Validation of Energy Characteristics in Flight Control System based on a Multidisciplinary Virtual Platform

Yuyuan Wang[1], Mingwei Sun[1] & Jian Fu[1]

[1]Fluid Power Transmission & Control Research Center, Beihang University 37 Xueyuan Road, Haidian District, 100191 Beijing, China

Abstract

The flight control system is pivotal to the operation of aircraft, confronting the requirement of higher integration in the evolving paradigm of more electric aircraft. The iterative design and optimization processes of the system are not only time-consuming but also costly, and there is a disconnection between models based on different methods and platforms. To overcome these issues, this communication introduces a multidisciplinary virtual validation platform for the design phase of the entire flight control system, encompassing actuators, the flight control computer, and the energy system.

The proposed platform is structured on a five-dimension system framework, featuring a distributed architecture with distinct layers for client interaction, application, execution, model, and physical representation. It utilizes the TCP/IP protocol for co-simulation and develops an intermediate platform in C language to facilitate communication between different models and platforms, overcoming FMI's limitations in aircraft simulation. Based on the platform, this communication presents a detailed flight control system analysis and modeling approach, employing incremental hierarchical modeling to represent the hydraulic actuation system, control system, and energy system. The spikes in hydraulic flow rate and corresponding pressure drops during High dynamic motion are verified in the platform. The simulation results demonstrate the platform's capability to verify the characteristics of flight control system.

Keywords: Flight control system of aircraft, Simulation, Energy characteristics, Virtual platform

1. Introduction

The flight control system is one of the most essential systems of aircraft. A typical flight control system mainly includes the flight control computer (FCC), actuation, hydraulic and other subsystems as shown in Figure 1. The modern flight control system faces higher level of integration demands under the trend of more electric aircraft. Consequently, there is a swift surge in electric power demand and load. The energy architecture of the flight control actuator system becomes increasingly complicated, confronting a variety of energy disturbances.

The heightened system integration and complexity could bring more problems during the preliminary design of the next generation aircraft such as hydraulic source insufficiency or electric disturbance. The iterative design and optimization of the flight control system are time-consuming and expensive. Moreover, constructing distinct testing platforms of the entire physical entity for design verification is impractical. To address these challenges, in the recent years, airframers have embarked on a paradigm shift toward Model-Based System Engineering (MBSE) methods. Multi-domain modelling and simulation provide a tool of flight testing before the prototype built. However, there is a disconnection between models based on different methods and platforms. Lacking of data interfacing and real-time interaction bring challenges for the practical application of the model-based systems engineering.

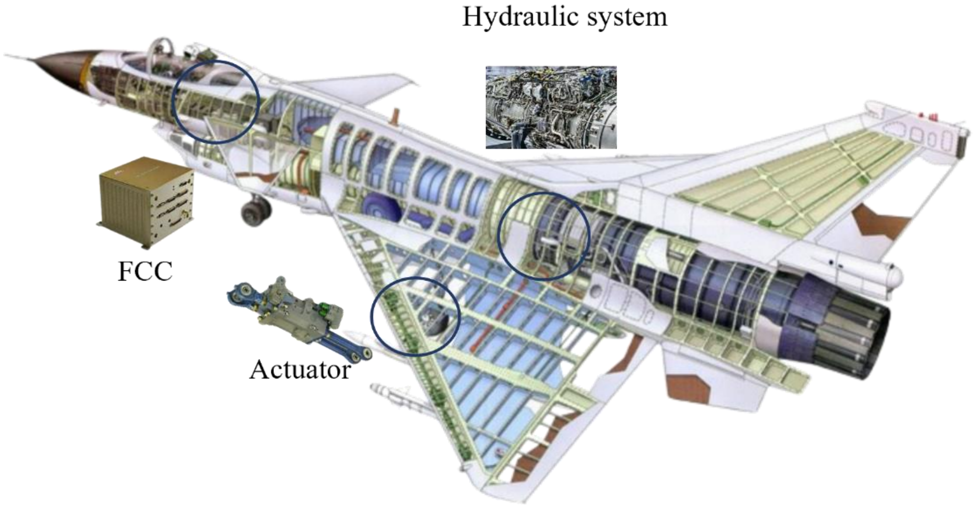


Figure 1 – Flight control system architecture

In order to deal with the co-existence of multiple simulation software in the co-simulation process, the EUROSIM[1] introduced the Functional Mock-up Interface(FMI) standard in the MODELISAR project. FMI serves as a universal data exchange protocol independent of any simulation software and has found widespread application in various fields. However, being a relatively new standard with evolving content, FMI currently cannot provide enough support for aircraft simulation. For this reason, airframers are still seeking methods to assess the interactions among systems in the design phase. Presently, many researchers resort to specific platform interfaces for co-simulation without compatible methods[2-4]. Some are actively engaged in constructing integrated platforms for simulation testing. For instance, Chengdu aircraft design and research institute[5] introduces a digital-twin assisted simulation for the electromechanical system of aircraft, supporting integrated virtual-virtual and virtual-real simulation. Airbus[6], in collaboration with several European research facilities, has initiated the development of the FlowSimulator suite, with the aim of harmonizing Computational Fluid Dynamics (CFD) workflows and establishing it as a cornerstone for CFD-based multidisciplinary simulations, as shown in Figure 2. Despite these advancements, there remains a notable absence of a dedicated simulation platform for the verification of flight control systems. The integrated simulation of flight control systems continues to pose significant challenges.

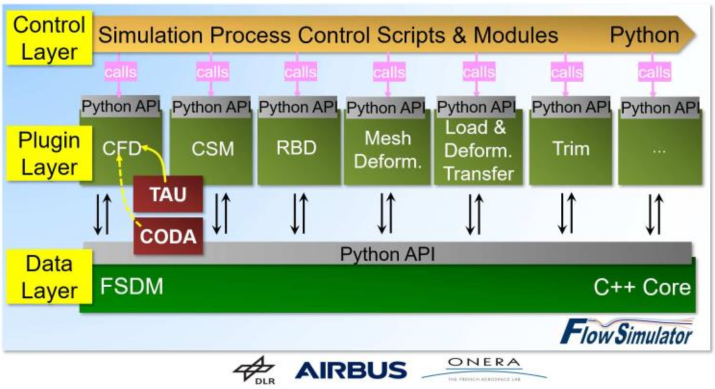


Figure 2 – Software architecture and layers of the FlowSimulator suite[6]

Addressing the aforementioned challenges, this communication introduces a multidisciplinary virtual verification platform for the entire flight control system of aircraft from the design phase. The research object includes the actuators (HSA), FCC and energy system of the whole aircraft. A complete virtual flight control actuator system will be constructed. The system and its associated control laws undergo efficient verification through virtual simulations in the early stages of the design process. System energy characteristics are also analyzed based on the platform.

The communication is structured as follows: Section 2 depicts the archeticture of the virtural platform.

In Section 3 the models of flight control system are built. In Section 4, the system performance is simulated. Finally, Section 5 concludes the work and gives an outlook on further topics.

2. Mutidisciplinary virtual platform design

The virtual verification framework presented in this communication is founded on the five-dimension framework as shown in Figure 3.

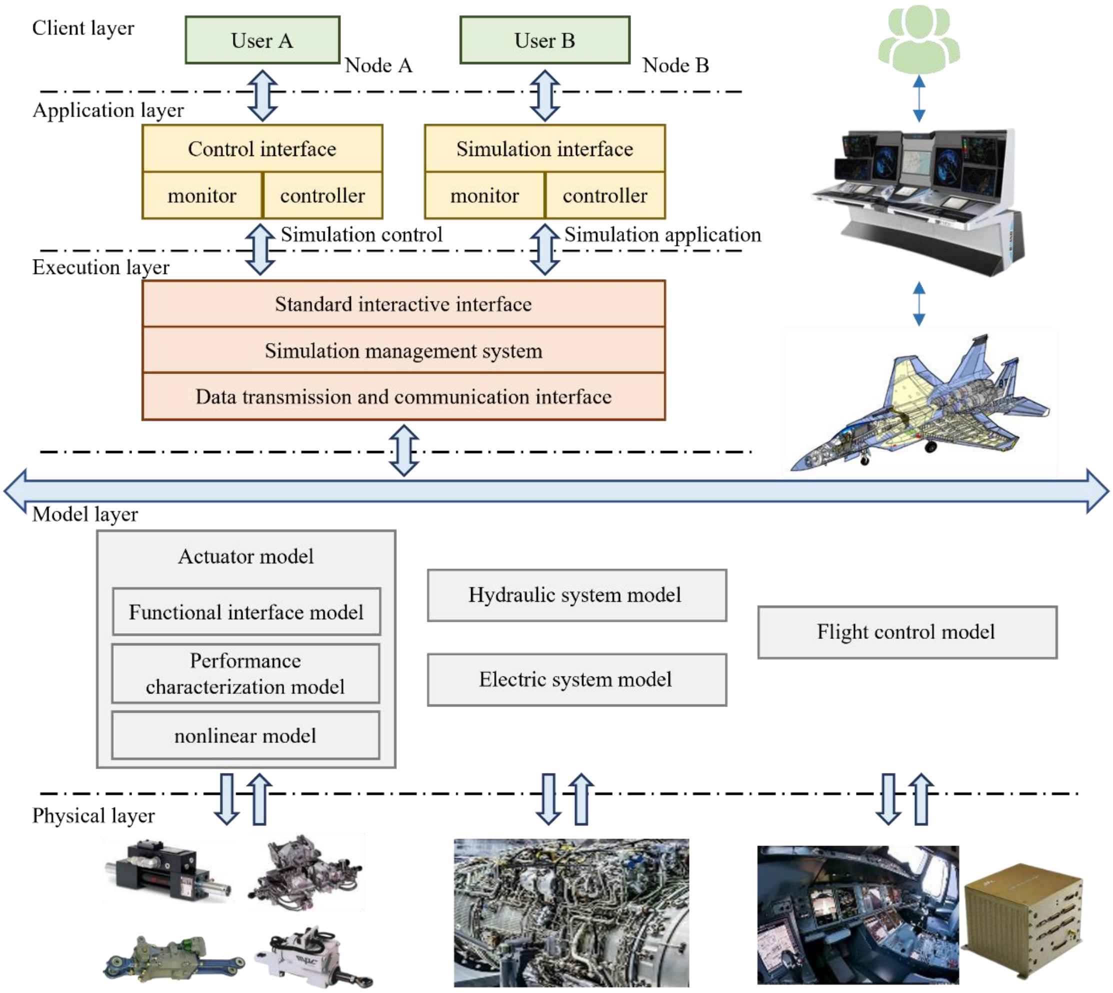


Figure 3 – Framework of the flight control system simulation

The virtual platform adopts a distributed structure, organized into five distinct levels: the client layer, application layer, execution layer, model layer and physical layer. Various components exchange data through standard interactive interfaces. The physical layer comprises several subsystems or components of the aircraft's flight control system. In the model layer, the system model is established to map the physical space and represent the shape, the behaviours, the processes, or the rules. It could be physical based simplified models, high fidelity models, and data-driven intelligent models. In this communication, the actuators, hydraulic system, electric system and flight control law are modelled using AMESim and matlab. The subsystems are described at different levels of abstraction to cater to diverse simulation demands.

The execution layer serves as the foundational backbone for the platform, responsible for the operation and communication of the entire system. This layer contains the standard interactive interface, simulation management system and data transmission interface. The interface functions as the communication middleware, facilitating the interconnection of models based on different methods and platforms. Large, real-time and efficient data transmission could be obtained through integration simulation.

Considering the compatibility of the system, the execution layer uses tcp/ip communication protocol, based on the Internet, which can simply and reliably realize the communication between different platforms and even different devices. Tcp/ip has been widely used in a variety of simulation software.

For example, Matlab provides an open communication interface, and communication can be established through socket and tcp/ip receive/send module. AMESim provides a conservative communication interface, and communication can be established through the library provided by AMESim and DYNCOSIMNETWORK module, which allows sharing values between Simcenter Amesim and a third party application. Although AMESim and matlab complie with FMI standard, the co-simulation is limited by software versions and is not compatible with other platforms. Therefore, an intermediate platform was developed using c language to realize the functions of the executive layer, as shown in Figure 4. The intermediate platform realizes the communication of model layer based on tcp/ip protocol and establishes the relation between model layer and application layer.

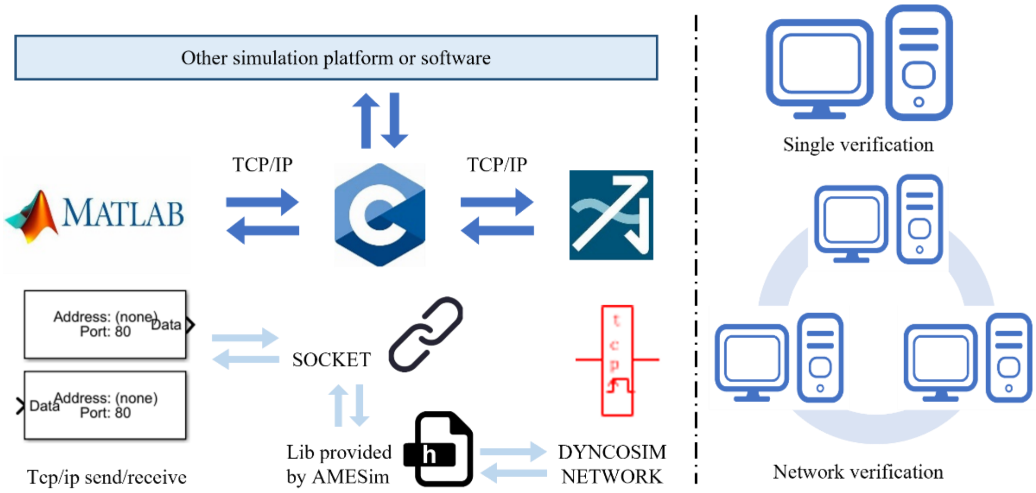


Figure 4 – Framework of execution layer

The application layer realizes management of the simulation system, encompassing the human-computer interaction of system performance monitoring and simulation control. It encapsulates the execution layer and provides user friendly interface. Based on the software, the application layer communicates performance data and pertinent information to the user, while also regulating system operations based on user commands. A highly integrated virtual test environment is constructed based on the five-dimension system framework.

3. Flight control System analysis and modeling

Flight control actuation system can be divided into control system, energy system and actuation system. This communication mainly considers HSA and hydraulic source, and simulates the hydraulic load characteristics.

The control system adopts the Non-Linear F-16 Aircraft Model provided by the Department of Aerospace Engineering and Mechanics of the University of Minnesota. This model can simulate the response of an actual F-16 using one of two models as described by Stevens and Lewis and the NASA Report. It will trim according to the flight attitude and output corresponding commands to the actuator model to complete the simulation.

There are usually two ways to model a complex system: the decremental method and the incremental method. The decremental approach is to create the most complex model firstly and then simplify it step by step. Incremental approach, by contrast, progressively increase the complexity of the model based on requirements and known parameters, which can be consistent with the system engineering process. In this communication, the incremental hierarchical modeling method is used to analyze and model the whole HSA and its components. Complexity of each level model increases gradually, while the specific interfaces of the model (signal and power) remain the same to ensure that the model is replaceable.

Based on the requirements of different simulation scenarios, The system model is divided into three levels, as shown in Figure 5. The first-level functional interface model uses simple formulas to express the energy flow relationship. This model clarifies the basic mathematical relationship of the actuator system and give the interface between each component. It can be used to verify the performance of the actuator in the preliminary design stage.

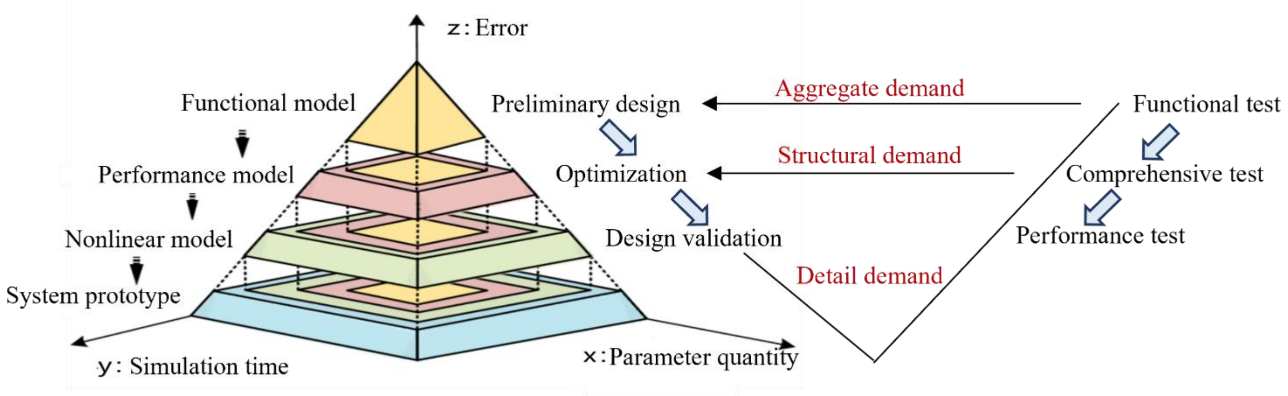


Figure 5 – Architecture of incremental method

The second level is the performance characterization model, which is to refine each component under interface constraints and establish a more detailed model to represent the performance of the system under different parameters. Because the number of parameters and the simulation time are relatively small, this model is suitable for optimization that involves a large number of performance calculation.

The third level typical nonlinear model adds a variety of nonlinear factors and can establish thermal module to be closer to the actual prototype. The simulation time of the model is long and the number of parameters is large. Due to the small error between the horizontal model and the prototype of the flight control actuator system, it is often used in the validation of the designe scheme which can accept a longer simulation time.

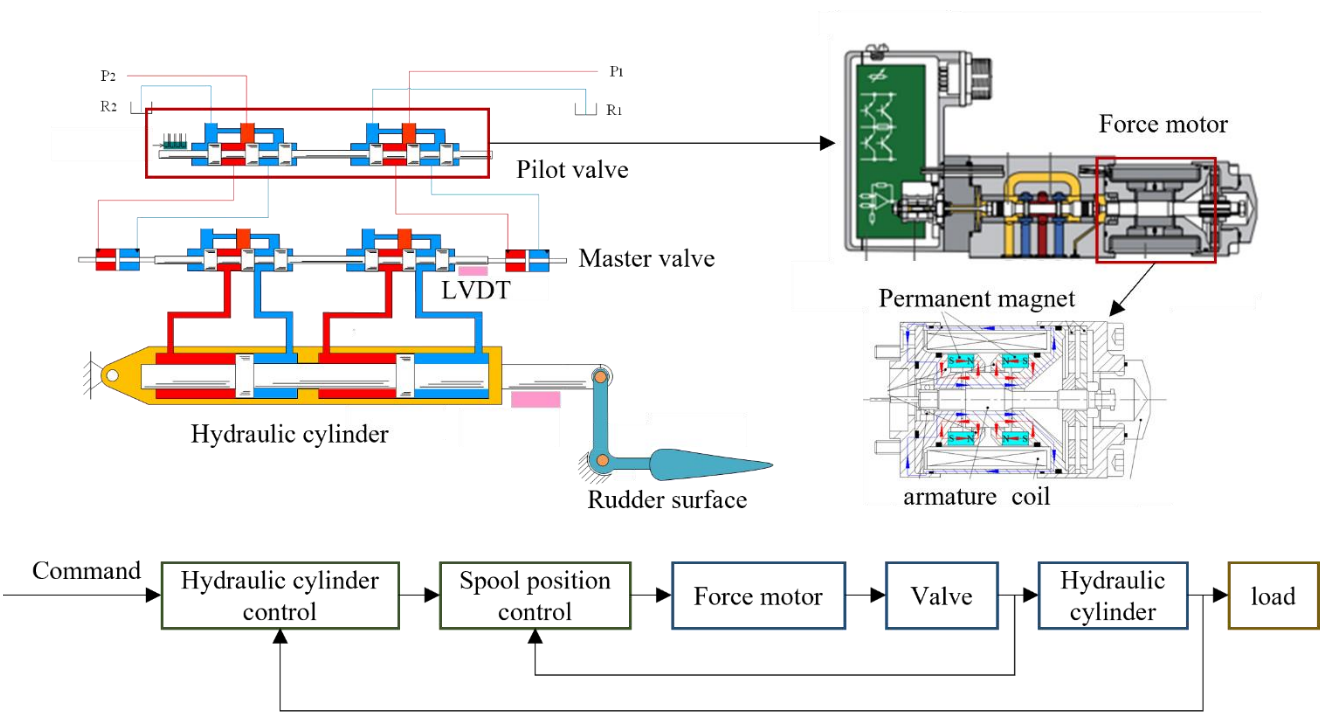
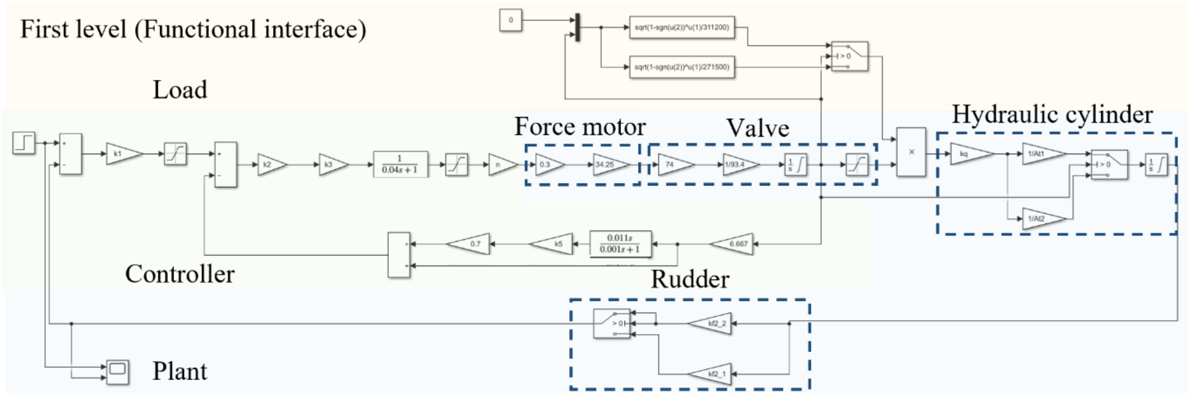


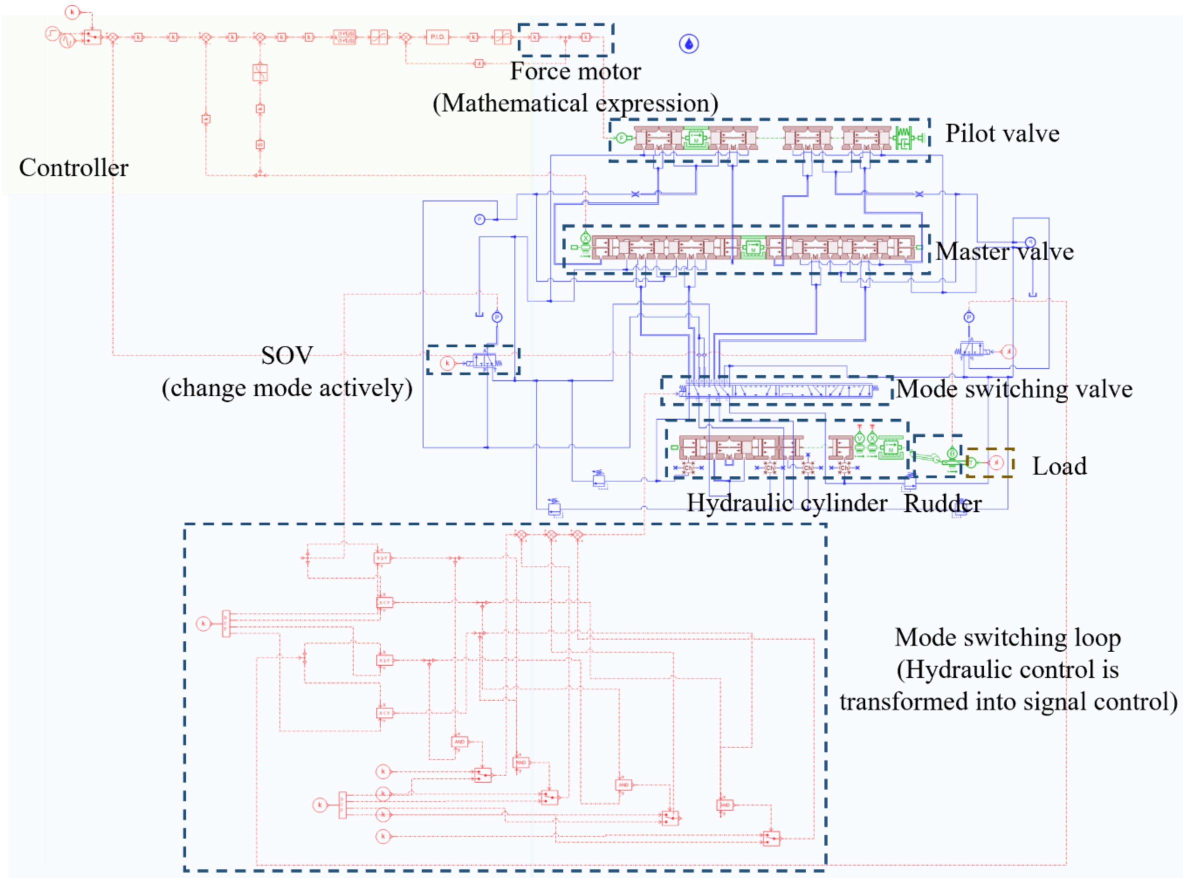
Figure 6 – Structure of the direct drive servo valve control actuator system

This communication studies the direct drive servo valve control actuator system, which is mainly composed of direct drive servo valve, actuator cylinder and other accessories, as shown in Figure 6.The direct drive electro-hydraulic valve, the key factor of the system using force motor and other linear electro-displacement conversion mechanism directly drive the valve spool. The valve system consists of two hydraulic redundancy, mechanically connected in series. In the secondary system, the main valve spool is driven directly by the hydraulic oil output from the pilot valve at both ends of the spool, without other mechanical interfaces on the spool. The hydraulic oil from the main valve drives the hydraulic cylinder to control the angel of rudder surface.

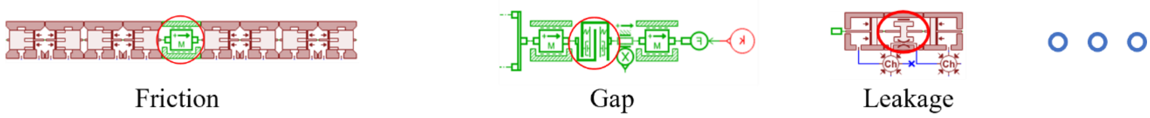
Based on the incremental method, the model of HSA is built as shown in Figure 7. For the validation of energy load characteristics, the accuracy of the model is important, and the simulation time should be reduced as much as possible. Therefore, the communication focuses on the second level.



(a) Functional interface model



(b) Performance characterization model



(c) Factors of typical nonlinear model

Figure 7 – Model of hydraulic actuator

The first level model is built in simulink, reflects the basic transfer function relationship of the system. On this basis, the second level model is constructed by refining the first level model. This model adopts three-ring control. Controller realizes the closed-loop control by controling the motor voltage with pid algorithm, collecting signals of force motor current, main valve spool displacement and rudder deflection angle. A mode switching valve is added to the model, which can be actively controlled by electrical signal or passively controlled by pressure. If the system pressure is normal, the dual redundancy works simultaneously. If a redundancy failure results in a reduction in pressure, the mode switch valve cuts off this redundancy, and the system only work in single redundancy. In the event of a complete failure, the system switches to the return mode, keeping the rudder stable. Since the force motor and the mode switching valve have little influence on the load characteristics of the system, they are simplified to the ideal model in the secondary model to improve the simulation efficiency.

The hydraulic energy system consists of three independent subsystems, left, right and center. These systems supply fuel to different actuators to improve the reliability of the system. Taking the left system as an example, the hydraulic energy system model is established as shown in Figure 8. The system uses dual pump to supply hydraulic oil, and maintains the pressure at 35MPa by the load sensitive constant pressure pump. When the required flow rate of the system exceeds the oil supply capacity, the pressure is reduced.

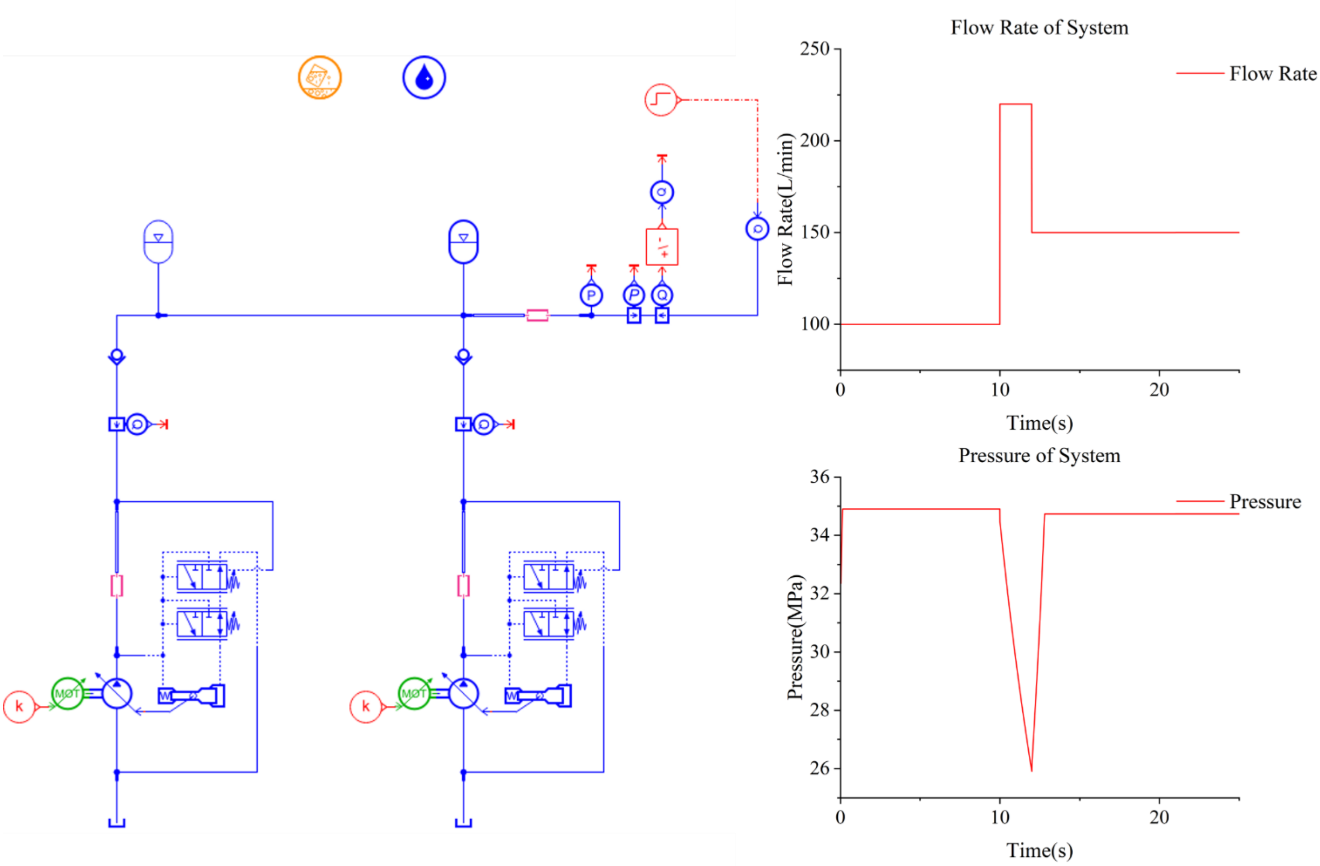


Figure 8 – Model of hydraulic system

4. Simulation and result analysis

Based on the virtual platform and simulation model above, the interaction between the execution layer and the model layer is established to provide conditions for the validation of system energy characteristics, as shown in Figure 9. Three cross-platform actuator control loops (aileron, elevator, and rudder) are established. The actuator instructions are issued from the flight control law model of matlab, passed into the intermediate platform, and then distributed to different actuator models in AMESim. The angel from actuator model is fed back to the flight control law simultaneously. Moreover, the hydraulic model and the actuator model exchange flow and pressure data through the virtual platform to form the a single-platform energy loop.

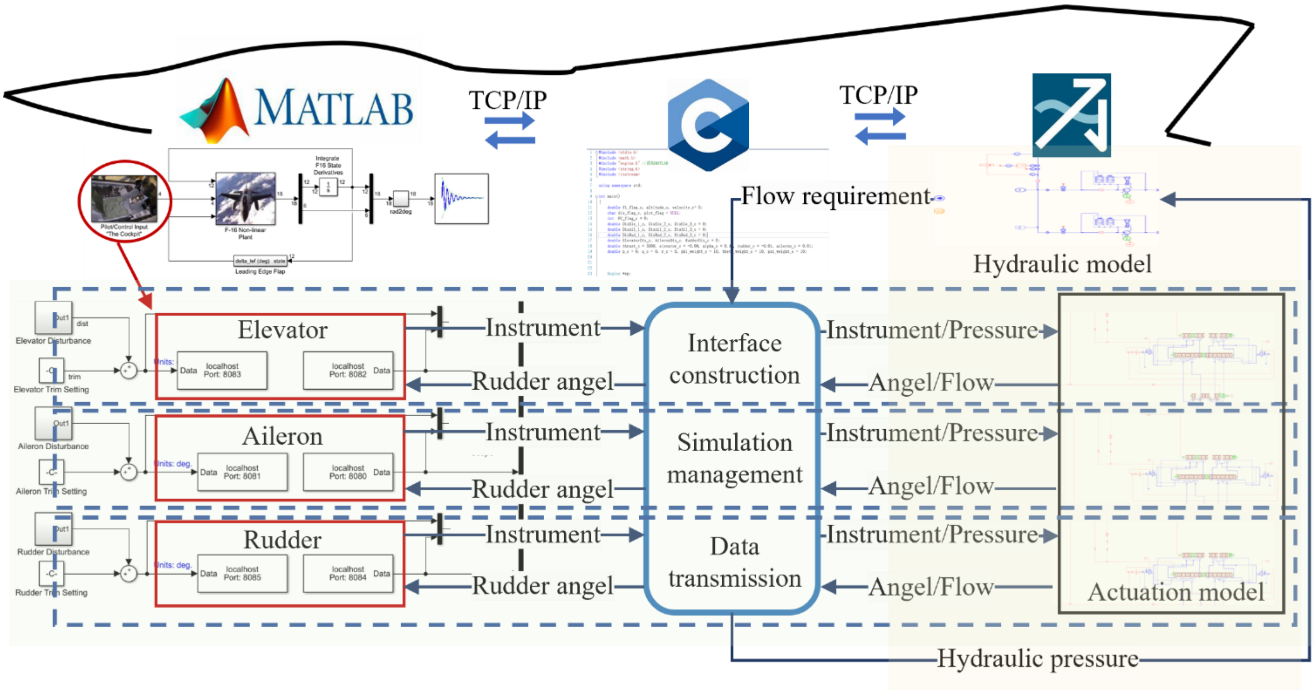


Figure 9 – The architecture of simulation

Within this architecture, the low-altitude and high-dynamic maneuvers of the aircraft is simulated to verify the load characteristics of the actuator system under extreme operating conditions. In the flight control model, the range of parameters is shown in the Table 1.

Table 1 – The range of parameters

Parameter	Min	Max	Unit
Altitude	5000	40000	ft
Velocity	300	900	ft/s
Elevator	-25	25	degree
Aileron	-21.5	21.5	degree
Rudder	-30	30	degree

Establish the aircraft's flight altitude at 5000 feet and velocity at 300 feet per second to systematically simulate the yaw, roll, and pitch maneuvers, thereby exploring the aircraft's dynamic responses in these critical flight configurations. With the yaw rate set to 170 degrees per second, the instructions calculated by the flight control law model are shown in Table 2.

Table 2 – System instructions for yaw

Parameter	Value	Unit
Elevator	1.8234	degree
Aileron	6.5309	degree
Rudder	25.1764	degree

The response of system is shown in Figure 10. At the one-second mark, the system initiates a yaw maneuver; At the five-second mark, it sustains level flight; and at the six second, it executes a reversal of the yaw. The actuator system follows the instruments to govern the aircraft's orientation. At this time, the system flow rate is mainly determined by the rudder. When the rudder is deflected, the flow rate surges and the system pressure decreases.

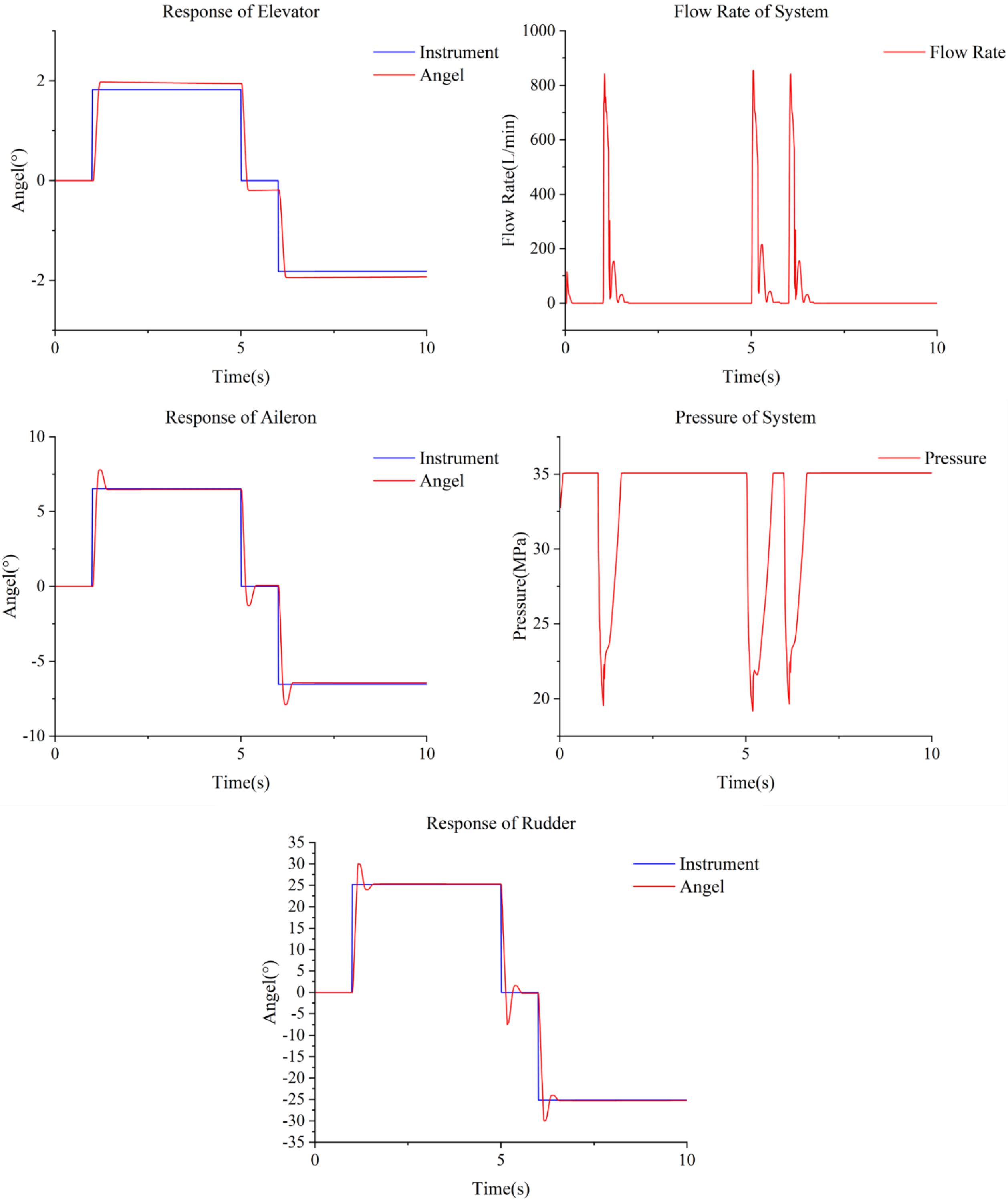


Figure 10 – System response on yaw

With the pitch rate set to 95 degrees per second, the instructions calculated by the flight control law model are shown in Table 3.

Table 3 – System instructions for pitch

Parameter	Value	Unit
Elevator	18.7468	degree
Aileron	3.8618e-9	degree
Rudder	1.8106e-7	degree

The response of system is shown in Figure 11. At this condition, only the elevator is operated, and the aileron and rudder have no obvious action and are not considered. The elevator angle was initially set to deflect by 18 degrees, subsequently returned to the neutral position, and finally deflected to -18 degrees. When the elevator is deflected, the flow rate surges and the system pressure decreases.

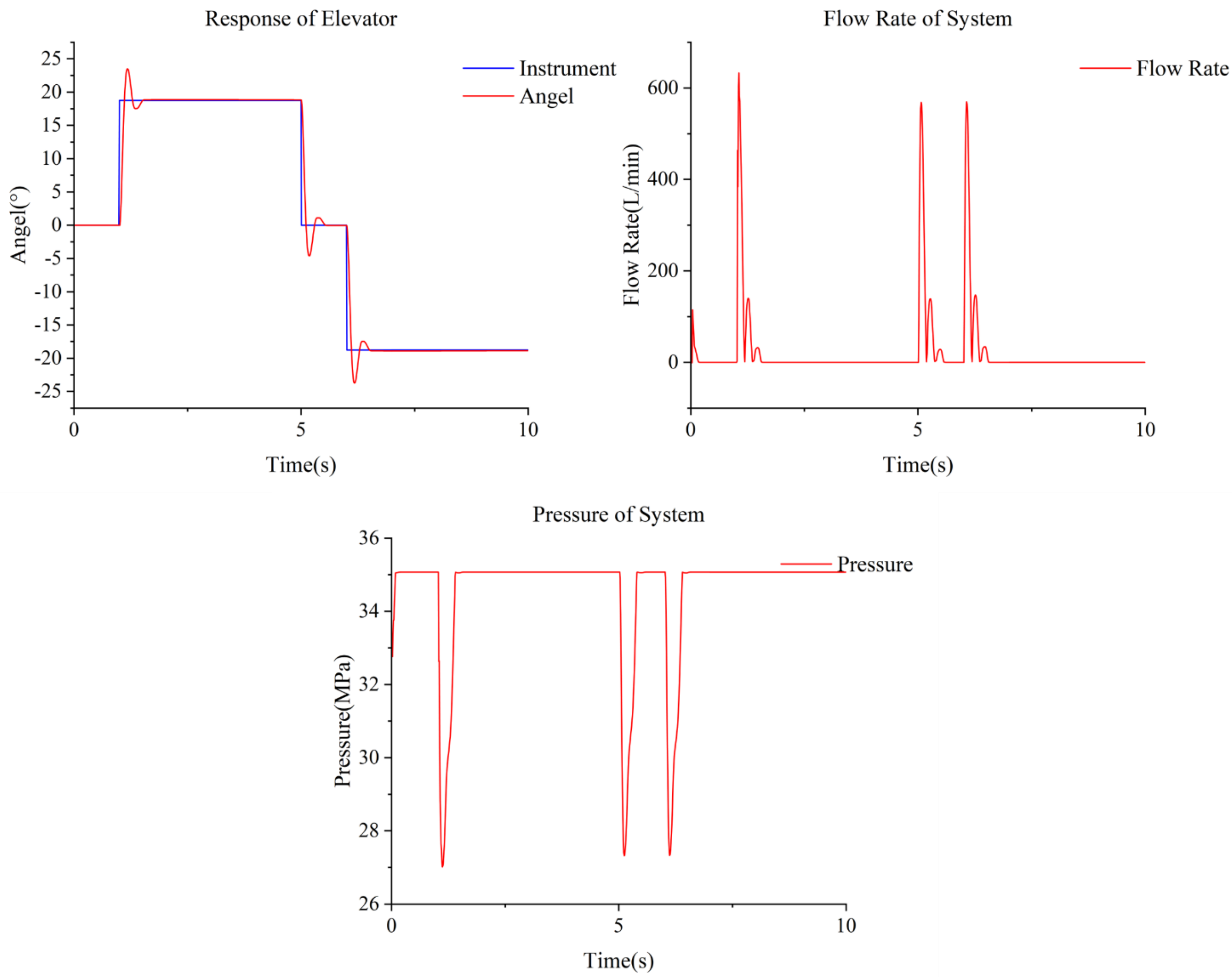


Figure 11 – System response on pitch

With the roll rate set to 120 degrees per second, the instructions calculated by the flight control law model are shown in Table 4.

Table 4 – System instructions for roll

Parameter	Value	Unit
Elevator	-3.8708	degree
Aileron	16.4523	degree
Rudder	-6.2248	degree

The response of system is shown in Figure 12. At the initial second, the system embarks on a rolling maneuver; and precisely at the six second, it initiates a reciprocal rolling action. The system flow rate is mainly determined by the aileron. When the Aileron is deflected, the flow rate surges and the system pressure decreases.

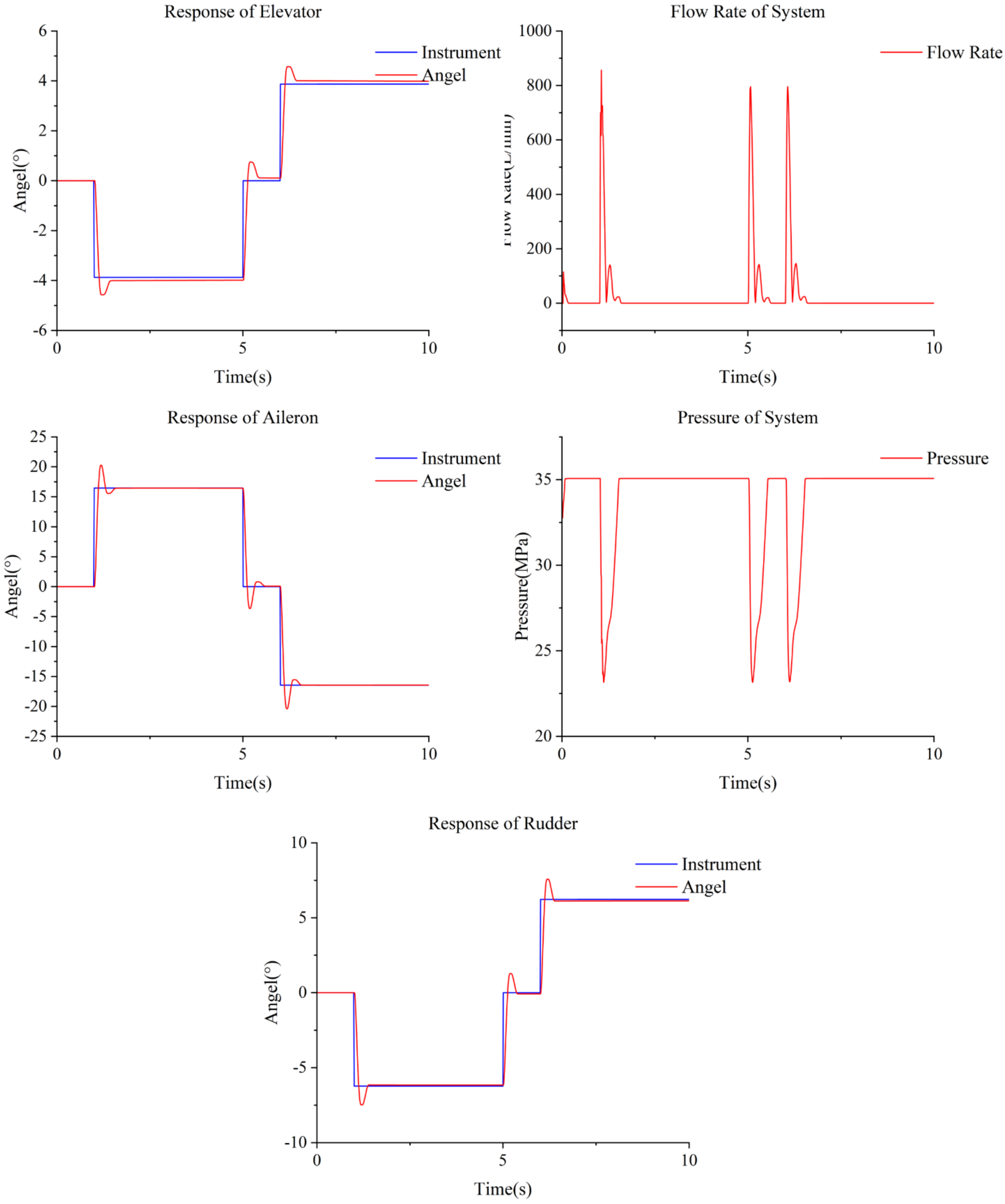


Figure 12 – System response on roll

Upon analysis of the aforementioned simulation outcomes, it is evident that during the execution of high-dynamic maneuvers by the aircraft, abrupt deflections of the control surfaces at significant angles lead to a precipitous surge in the hydraulic system's flow rate, surpassing its specified threshold. Therefore, the system pressure drops sharply, which is consistent with the test results. The sudden drop of pressure is dangerous to the aircraft, and it is necessary to verify the energy characteristics of the aircraft during the whole flight.

5. Conclusion and outlook

This communication introduces a comprehensive five-dimension architecture for a virtual validation platform tailored to the flight control system. The architecture encompasses the physical, model, execution, application, and client layers. In accordance with the specifications of the model layer, an in-depth analysis of the flight control actuation system was conducted. Employing an incremental modeling methodology, the flight control law, actuation system, and hydraulic energy system are individually modeled. Ultimately, within the platform, information exchange among the flight control model, the actuator model, and the hydraulic energy model was achieved. Throw the simulation of the aircraft's high-dynamic maneuvers at low altitudes, the following conclusions have been drawn:

(1) During the execution of high-dynamic maneuvers by the aircraft, abrupt deflections of the control surfaces at significant angles lead to pressure drop sharply, which is dangerous to the aircraft.

(2) The model response of the flight control consistent with the test. The virtual validation platform is verified.

Due to limited time, the research conducted in this communication is relatively preliminary and has several areas for improvement. Future work can focus on optimization in the following areas:

(1) Flight control actuation system is a highly integrated system, The simulation of the system should adopte specific flight control law model for the aircraft studied and higher level actuation models to improve the accuracy.

(2) Future research should employ a more complete control law to simulate the entire flight trajectory, thereby assessing the impact of pressure drop characteristics on the aircraft's performance comprehensively.

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