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Construction of Parametric System for Aircraft Conceptual Design Based on Simulink

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Abstract: Aircraft conceptual design is a complex system engineering, which makes it easy for aircraft designers to create confusion when constructing analysis systems. In order to solve the difficult problem of complex system modeling, we thought of making the flow diagram of aircraft conceptual design more intuitive and concrete than the ordinary method when design an abstract system. Simulink's block diagram modeling and online data transfer methods can visually develop complex systems, which are usually aimed at specific systems in most of related studies, like areoengine containing concrete component which can be constructed to block diagram framework in a so-called component level. Although the aircraft conceptual design system is an abstract system, we still can divide it into several parts based on its different sub-tasks which is like the component of the concrete system, greatly reducing the difficulty of modeling. In this paper, the aircraft conceptual design process was modularized to a framework using block diagram, and an intuitive aircraft conceptual design system according to the block diagram design frame was constructed through the visual development function of Simulink. According to the requirements of each stage of the flight mission envelope, an aircraft conceptual design parametric system based on constraint analysis subsystem and mission analysis subsystem is constructed, which advances layer by layer internally, merges and unifies externally, and finally completes the construction of the system. The developed system includes constraint analysis subsystem and mission analysis subsystem, which can analyze and calculate the overall parameters in aircraft conceptual design. In the process of system construction, we will encounter some problems due to negligence, but because we build the block diagram in a step-by-step design method, the structure is also very clear, it is easy to find the wrong module and correct it quickly. To evaluate the accuracy of the system, with the data of Airbus A318 as a reference, the design requirements were set, and the overall parameters of the conceptual design of the aircraft including takeoff weight, wing area, takeoff thrust, fuel amount, were calculated, and compared with the relevant parameters of A318, the deviation was within a reasonable range. It can be seen that after the framework of the aircraft concept design system is constructed, the aircraft parametric concept design system can be constructed intuitively through Simulink's block diagram modeling translation.

Keywords: Simulink, Aircraft Parametric Conceptual Design System, Block Diagram Modeling, Visual Development

1. Introduction

In the conceptual design stage of the aircraft, the overall parameters of the aircraft, including takeoff weight, wing area, takeoff thrust, fuel amount, etc., shall be preliminarily calculated according to the mission requirements and constraints of the aircraft [1, 8]. A large number of parameters, formulas and interfaces will be involved in the preparation of aircraft mission requirements analysis and constraint analysis program, such as reference [3], it uses the object-oriented programming method, many classes are written and divided into many levels that the relationship between objects looks very complex, and there are too many program fragments to manage. It is conceivable that it is difficult to build a more complex system with this method on my mine. For aircraft designers who are not software professionals and lack sufficient experience, it is difficult to establish a clear design framework, easy to make mistakes in the process of programming, and difficult to pass the data test.

Simulink can directly follow the development process after we construct the design principles into a series lined square frame that can easily re-construct so that can quickly verify the effect of innovative design and has achieved many successful cases in the field of automobile and industrial control [2]. In the aviation field, it has been used in Aeroengine dynamic simulation. Xia Fei uses Simulink's module library and s- function to build and puts forward a four-level structure for building engine model, which has the characteristics of model hierarchy, encapsulation modularization, structure diagram oriented and high visualization [4]. Zhu Shanshan establishes a component level model of an Aeroengine Based on MATLAB / Simulink, obtains the aeroengine dynamic model, and verifies the accuracy of the model [5]. Singh R developed a mathematical model of a laboratory engine using Simulink and the simulation result was found to be in good agreement with the experimental data [6]. Yu Yingjie studied the real-time modeling technology of aeroengine guide vane actuator. According to the design parameters of the actuator, the mathematical model was established in AMESim, and the mathematical model of fixed-step algorithm was established in Simulink and verified by simulation [7]. There are still many researchers who use block diagram combined with Simulink to design and analyze problems in the aviation field [12-20], but most of these studies are aimed at specific systems, like areoengine, rather than abstract systems, like this paper. The block diagram design mode of Simulink can clearly plan the requirements analysis module and constraint analysis module of aircraft design, and the data management and testing are flexible, which greatly reduces the additional burden of program structure planning and data testing for aircraft designers. This paper summarizes the aircraft conceptual design process into a frame diagram framework, and then translates it into a operable system by using Simulink. The mission requirements of the transport aircraft are relatively simple compared to fighter, and the transport aircraft are widely used in the market, and the parameters are easy to obtain from the public. This paper will analyze the mission requirements and constraints of the transport aircraft, as well as the payload evaluation, to calculate the overall parameters including takeoff weight, wing area, takeoff thrust, fuel amount in the conceptual design of the transport aircraft. It is used to prove that the block diagram design concept of aircraft conceptual design is intuitive and feasible.

2. Frame Construction

During flight, the aircraft is affected by thrust, gravity, lift, aerodynamic resistance and other forces. From different flight conditions, the active state of force is different. Integrating various states in the aircraft mission envelope, the takeoff thrust weight ratio and wing load are correlated to obtain the constraint formula (1):

$$\frac{T_{SL}}{W_{TO}} = \frac{\beta}{\alpha}\left\{\frac{qS}{\beta W_{TO}}\left[K_1\left(\frac{n\beta}{q}\frac{W_{TO}}{S}\right)^2 + K_2\left(\frac{n\beta}{q}\frac{W_{TO}}{S}\right) + C_{D0} + \frac{R}{qS}\right] + \frac{1}{V}\frac{d}{dt}\left(h + \frac{V^2}{2g}\right)\right\} \tag{1}$$

In this formula, $\beta = W/W_{TO}$, is the proportion of the remaining weight W of the aircraft in the takeoff weight W_{TO} during flight; for commercial transport aircraft, is the proportion of the remaining weight after fuel consumption in the takeoff weight. $\alpha = T/T_{SL}$ is the ratio of the aircraft operating thrust to takeoff thrust. $q = 1/2\rho V^2$ is the aerodynamic pressure. n is the overload factor. K_1 and K_2 is the polar curve coefficient of lift resistance. C_{D0} is the zero-lift drag coefficient. R is the additional resistance caused by the "smooth" fuselage. V is the aircraft speed. h is the flight altitude. g is the acceleration of gravity. Formula (1) can be deformed according to the characteristics of the mission segment. For details, refer to [1].

Mission analysis is to calculate the load change ratio at the end of each mission segment in the aircraft flight envelope. The key is to calculate the ratio of the aircraft weight at the end of a mission segment in the flight envelope to the initial aircraft weight W_f/W_i, because it can be used for calculating β, and then used for the calculation of formula (1). β_i recorded as the starting point value of a flight mission segment, β_f as the end point value, then $\beta_f = \beta_i$ (W_f / W_i), the calculation formula (2) of W_f/W_i is as follows:

$$\frac{W_f}{W_i} = \exp\left\{-TSFC\left(\frac{D+R}{W}\right)\Delta t\right\} \tag{2}$$

Among them, $TSFC$ is the ratio of installed thrust and fuel consumption, and the empirical formula is given in document [1]. D is the aerodynamic resistance, R is the additional resistance, and Δt is the running time of the mission section. Formula (2) can be deformed according to the characteristics of each mission segment. For details, refer to [1].

The takeoff thrust to weight ratio and wing load calculated in the constraint analysis shall be substituted into the mission analysis. The load ratio calculated in the mission analysis shall be re-substituted into the constraint analysis to calculate the takeoff thrust weight ratio and wing load. The iteration repeats until the takeoff thrust weight ratio and wing load data converge, and then, according to the load requirements in the design requirements, with formula (3), the takeoff weight of the aircraft is calculated. Finally, the overall parameters including takeoff weight, wing area, takeoff thrust, fuel amount can be calculated.

$$W_{TO} = \frac{W_P}{\Pi(W_f/W_i) - \Gamma} \tag{3}$$

Where, W_P is the load weight, and the weight of passenger plane is the crew, passengers and their luggage, $\Pi(W_f/W_i)$ is the product of each mission stage and Γ is the empty weight ratio.

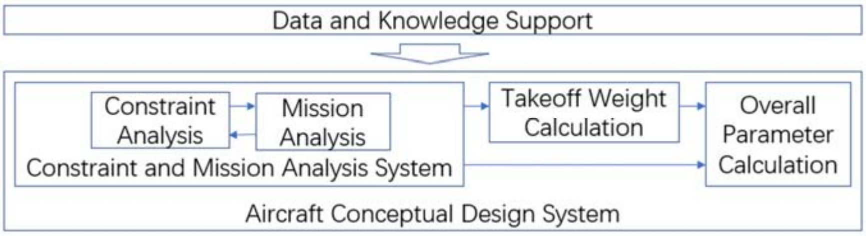

Figure 1. *Basic framework of aircraft conceptual design.*

Figure 1 shows the basic framework of aircraft conceptual design based on the principle of aircraft conceptual design. Using the Simulink block diagram system construction function, the framework is intuitively translated into the aircraft conceptual design parametric system. The block diagrams are connected by lines, which can easily observe and test the data flow, so that the aircraft designers focus on the aircraft design itself. That's to say, the design process can easily construct and re-construct using the block, and what we can focus on more is that what parameter or algorithm can improve the performance of the aircraft. The parametric system of aircraft conceptual design includes constraint analysis subsystem and mission analysis subsystem, which can analyze and calculate the overall parameters in aircraft conceptual design.

3. Simulink System Construction

The basic flight mission of the transport aircraft includes four Mission segments: warm-up and take-off, climb, cruise and landing, which constitute the flight mission envelope of the aircraft. According to the requirements of each stage of the flight mission envelope, an aircraft conceptual design parametric system based on constraint analysis subsystem and mission analysis subsystem is constructed, which advances layer by layer internally, merges and unifies externally, and finally completes the construction of the system.

3.1. Constraint Analysis Subsystem

It can be seen from the formula (1) that the mapping relationship between aircraft takeoff thrust weight ratio and takeoff wing load is related to the changes of force, flight speed, atmospheric conditions and potential energy. Therefore, the requirements for aircraft takeoff thrust weight ratio and takeoff wing load are different for each flight mission. The purpose of constraint analysis is to synthesize the constrained boundary conditions in all flight processes and obtain the optimal solutions of takeoff thrust weight ratio and takeoff wing load. Combined with the flight status of each mission segment and formula (1), a Simulink constraint analysis subsystem composed of a takeoff constraint module, climb constraint module, cruise constraint module and landing constraint module can be built, as shown in Figure 2.

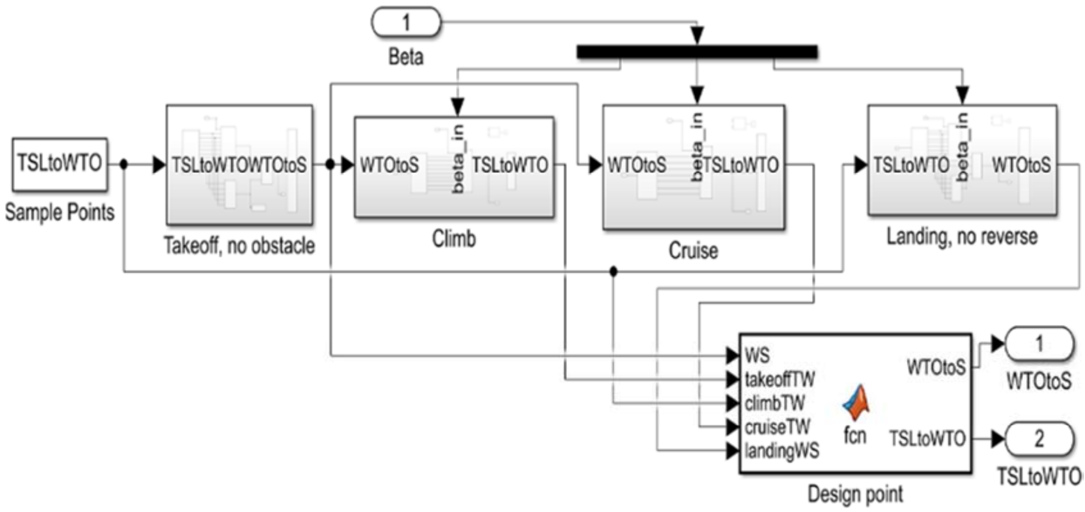

Figure 2. *Constraint analysis subsystem.*

3.2. Mission Analysis Subsystem

It can be seen from the formula (2) that the mission analysis needs to calculate the ratio of the end weight and the starting weight of each flight mission segment of the aircraft, such as the ratio of the end weight to the starting weight in the climbing mission segment. The main function of W_f/W_i is to calculate β. Obviously, the β value of the starting point of the warm-up process is 1. Through formula (2), combined with the specific state and parameters of the aircraft in the warm-up stage, the end point β of the warm-up process equal to the starting point β of the take-off process can be calculated. Assuming that the fuel at the end of the cruise phase is just consumed, the calculation process of each mission phase is written into a module and connected in series to obtain the Simulink mission analysis subsystem composed of warm-up, takeoff, climb and cruise modules as shown in Figure 3.

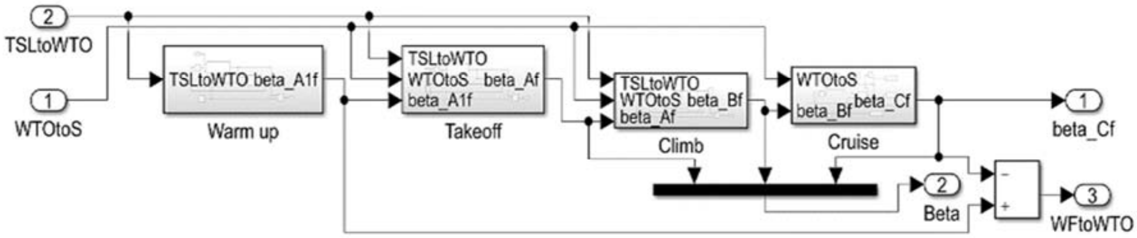

Figure 3. *Mission analysis subsystem.*

3.3. Integration of Constraint and Mission Analysis System

The constraint analysis system calculates the takeoff thrust weight ratio and wing load by knowing the residual weight ratio of each flight stage. The mission analysis system is to calculate the proportion of aircraft residual weight to takeoff weight after each flight mission by knowing the takeoff thrust weight ratio and wing load. The two systems are integrated, and the initial takeoff thrust weight ratio and wing load are set according to experience. After several iterations, the data converge to obtain the final design point of takeoff thrust weight ratio and wing load. Figure 4 shows the constraint and mission analysis subsystem integrated with Simulink.

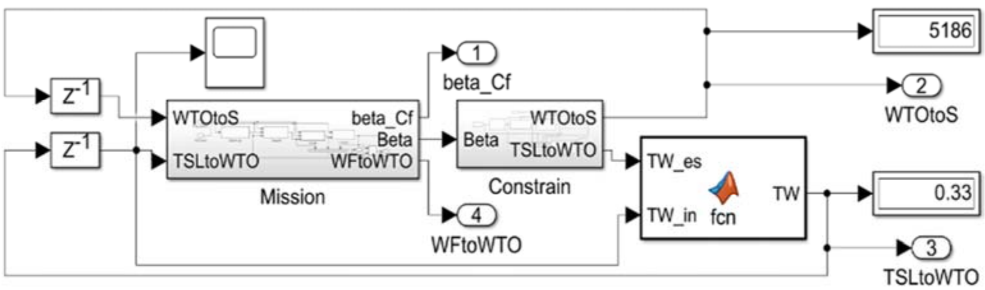

Figure 4. *Integrated constraint and mission analysis subsystem.*

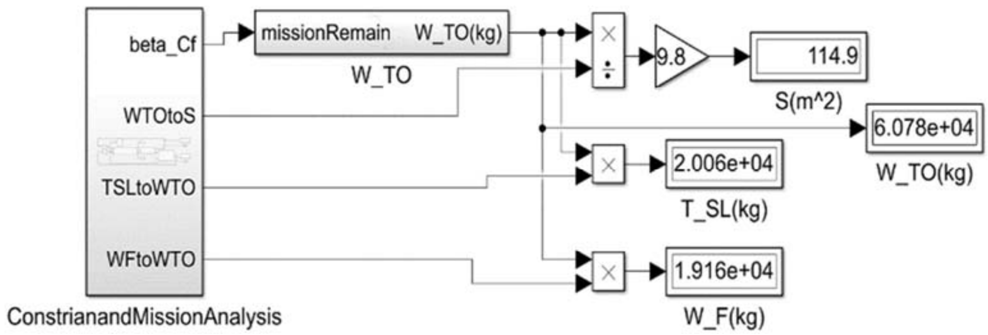

Figure 5. *Aircraft parametric conceptual design system.*

3.4. Aircraft Parametric Conceptual Design System

After the integration of constraint and mission analysis system, given the boundary design requirements of the aircraft, the takeoff thrust weight ratio T_{SL}/W_{TO}, wing load W_{TO}/S, fuel to takeoff weight ratio W_F/W_{TO} and other parameters can be calculated. Then, a calculation module is built using formula (3) to calculate the aircraft takeoff weight W_{TO}. Finally, the overall parameters can be calculated according to these data. Figure 5 shows the final aircraft parametric conceptual design system.

4. System Evaluation

The evaluation object of the system is medium and short-range passenger aircraft. The data refer to A320 series, while the A318 has the least passenger capacity and the range data is closest to the maximum load range. Therefore, the boundary design requirements of this example are given with reference to the relevant requirements data [9] of A318, as shown in Table 1.

Table 1. *Requirements refered to A318.*

Items	Requirements
Payload (ton)	11.1
Cruise Mach Number (Ma)	0.8
Max Range (km)	2800
Cruise Level (m)	12000
Runway Length (m)	1600

According to the empirical value, the value range of thrust to weight ratio is 0.2 ~ 1.5, and the initial value of takeoff thrust to weight ratio is set to 1.25. After several iterative calculations, the calculation result of takeoff thrust weight ratio is 0.33, the convergence process is shown in Figure 6, and the corresponding wing load result is 5186 Pa. The solution space of the design point is located above the takeoff, climb and cruise constraint curve, on the left side of the landing curve, the large wing load should be selected as much as possible to reduce the wing weight. However, the transport aircraft has low requirements for flight performance and high requirements for carrying capacity, so the thrust weight ratio should be selected as small as possible. Figure 7 shows the position of the design point (5186, 0.33) in the solution space.

Whether the design point calculated by the constrain and mission subsystem is reasonable can be compared with A318 data. The maximum takeoff weight of A318 is 59 tons, two pw6000 engines can be selected and the maximum thrust of a single engine is 23000 pounds [10], i.e. 10.43 tons. The thrust weight ratio is 10.43*2/59 ≈ 0.35, which is compatible with 0.33 in this case, and a certain margin is reserved. It is difficult to obtain the wing load data of A318 from the literature, but according to its passenger capacity of 107, ref [1] just gives the wing load data of 737-600 of being the same level with 110 passengers, which is about 110 lbf/ft^2, i.e. 5266 Pa. The calculated result 5186 Pa in this case is also within the acceptable range. Therefore, the design point (5186, 0.33) calculated in this case is reasonable.

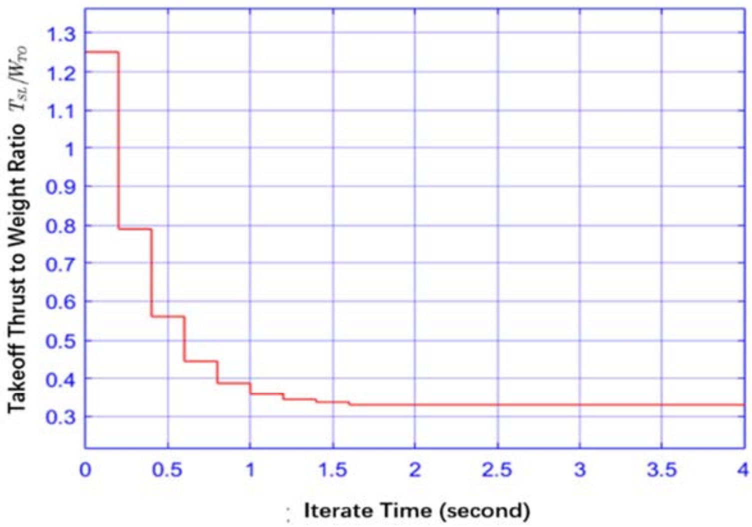

Figure 6. *The convergence process of* T_{SL}/W_{TO}.

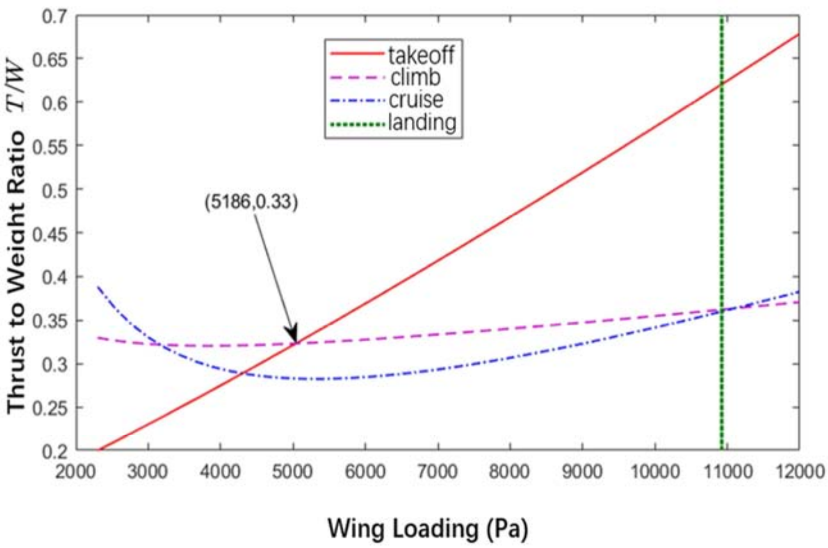

Figure 7. *Position of the T/W and wing loading design point (5186, 0.33).*

After the design points of takeoff thrust to weight ratio and wing load are determined, combined with the parameters such as by-product fuel proportion in constraint mission analysis to the iterative calculation of maximum takeoff weight, the overall parameters including takeoff weight, wing area, takeoff thrust and fuel amount, can be finally obtained. The comparison between the results calculated by the aircraft parametric conceptual design system and A318 data [9-11] is shown in Table 2.

Table 2. *The comparison between the results and A318 data.*

Overall Parameters	System Results	A318 Data	Defference
Takeoff Weight (ton)	60.78	59	+3%
Wing Area (m^2)	114.9	122	-5.8%
Takeoff Thrust (ton)	20.06	20.86	-3.8%
Fuel Amount (L)	23950	23860	+0.38%

It can be seen that there is a certain gap between the calculated value of this case and A318 data, but they are relatively small. As a conceptual design stage, a single data does not need too accurate values, but a set of data combination is within a reasonable range, which is the most important to have reference value for the system engineering, so that the subsequent detailed design process has a reasonable initial design value. Even if there is a deviation, it only needs to be slightly modified to meet the design requirements. In fact, the pw6000 engine used in A318 has a single takeoff thrust value of 16000 pounds to 23000 pounds. Based on the upper limit, the maximum deviation can reach (23000-16000) / 23000 ≈ 30.4%, which shows that in the detailed design process, the lower limit of takeoff thrust can be reduced by 30.4% through reasonable design, such as the design of the wing and its lifting device. Therefore, the calculation result of this case is reasonable.

5. Conclusion

Based on Simulink, an intuitive and modular aircraft parametric conceptual design system was established by using aircraft conceptual design theory. Through the evaluation of the system, the overall parameters of takeoff weight, wing area, takeoff thrust and fuel volume were calculated. Compared with the actual aircraft model data, the results are in an acceptable range. This shows that in the face of complex aircraft conceptual design parametric system, designers can first use its principle to build a modular framework, and then use the block diagram modeling method of Simulink to intuitively translate the modular framework into an operable system. This method is convenient that simplifies the complicated process of formulating development rules in the general software development process, and make the designer focuses on the aircraft design itself. In engineering application, it can simplify the development process and shorten the development time, which has practical significance.

6. Recommendations

Block diagram design is a very intuitive design method. Many researchers are used to apply the block diagram to design the system with specific components and use the mode of software engineering for the abstract engineering design process. However, in the practical engineering application, the complex aircraft design process also requires the design process to be fast and flexible, so as to shorten the development time and quickly modify the design when the market demand changes suddenly. The block diagram design method is undoubtedly in line with this design feature. In this paper, the principle of aircraft conceptual design is summarized into a block diagram design process. Combined with the block design function of Simulink, the calculation of aircraft conceptual design data is realized. The construction process of summarizing the aircraft conceptual design principle into a frame diagram design framework is heuristic, without methodical rules, but summarizes the principle into a usable block diagram design framework in the process of continuous attempts. The disadvantage of this direct method is that it is lack of efficiency to build a framework when it involves a more complex design system or a high reuse rate of the modules. For specific systems, such as aeroengines, components can be used as the design basis of modules, but the abstract system does not have this natural and intuitive division benchmark, which may require an efficient evaluation standard to guide the establishment of block diagram design principles. It is expected to enrich this content in the future.

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