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MODELING AND SIMULATION APPLICATION THROUGHOUT THE AERO-ENGINE LIFE CYCLE

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Abstract

With the further improvement of system complexity and performance requirements of aero engine, modeling and simulation have increasingly become indispensable technical activities in aero-engine R&D process. Basic hierarchy of aero engine modeling and simulation and supporting relationship between levels were illustrated. The application scenarios of simulation in different stages were described in detail according to the significant development tasks of each stage in aero engine life cycle. With the rapid development of digitalization and intellectualization in the world, the future direction of aero engine modeling and simulation were summarized along with related development strategy.

Keywords: aero-engine， modeling and simulation, life cycle, hierarchy, application scenarios

1. Introduction

Aero-engine is a complex thermo-mechanical system that integrates the multi-disciplinary of aerodynamics, combustion, heat transfer, structural strength, control, testing, and material etc.， it operates in extremely harsh condition with high pressure, high temperature and high rotational speed and must satisfy the needs of maintaining mechanical simplicity, reliability, and minimum costs. In another word, aero-engine is an integration of almost all mechanics since the Newtonian mechanics era, and is considered as a complex product approaching the limit.

Traditionally aero-engine R&D is based on tests to verify the requirements and expose technical problems, needs recurrent iterations of “design-trial production-test -refine” through a large number of tests which resulting in long development cycle and high risks. With the further improvement of system complexity and performance requirements of aero-engine, the traditional R&D mode is not adapted to rapid development.

Early in the 1960s, single shaft turbojet and turboprop engine model such as SMOTE was developed to simulate aero-engine performance parameters. Since 1990s, aero-engine companies have recognized that modeling and simulation (M&S) is vital for the success of the project, M&S provides virtual visions to understand how the system works. In the development process, design verifications were conducted by using simulation results, possible faults and design defects were exposed ahead of time, which greatly shortened the development cycle and reduced development costs. According to Air Force Research Laboratory (AFRL), on account for advanced simulation applied in the aero engine design process, overall test hours reduced by 30% (to 7,000hr), correspondingly, the test engines decreased from 14 to 9, while the development cost decreased 50% from $1.5 billion to $0.7 billion[1]. Nowadays, modeling and simulations have increasingly become indispensable technical activities in aero-engine R&D process and lay a solid foundation for the transformation of development mode to “predictive” design.

The paper covers the following: scope and hierarchy of aero-engine M&S (Section 2), life cycle stages and main tasks of aero engine (Section 3), and highlight how models and simulations are used in each stage of aero-engine life cycle (Section 4), conclusions and future directions of M&S are given at the end.

2. Modeling and Simulation (M&S)

2.1 Aero-engine Simulation

There are different definitions and concepts about model and simulation, according to DoD Directive 5000.59, a model represents a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon or process, while a simulation is defined as a method for implementing a model over time [2]. In short, a model represents a real world system and the simulation shows how the system performs in a virtual world using computer codes. Hence, aero-engine simulation could be described as a method and an activity to establish virtual models for engine system, subsystem and components etc. according to specified scope and purpose, and run the models to simulate actual engine system characteristics and performance in operational conditions.

There are diverse ways of advanced modeling and simulation applied in aero-engine development process [3]. For the power system perspective, it includes the propulsion system, the whole engine, components and parts, control system and lubrication system and other subsystems simulations. For relevant subjects, they cover aerodynamics, combustion, fluid, control, structure, strength (life, reliability etc.) and cost analysis. And aero-engine simulations are applied for the engine design, test, manufacture and maintenance processes throughout the lifecycle. Meanwhile, for such applications above, aero-engine simulations also can be classified into diverse types according to the simulation methods, such as mathematical vs. semi-physic, static vs. dynamic, real time vs. non real time simulations.

Aero-engine simulations mainly focus on internal flow with aerodynamic, combustion, heat and mass transfer, while chemical reaction and multiphase flow and high speed rotation happens, the most critical simulation task is to analysis complex internal 3D flow characteristics by solving unsteady viscous 3D turbulence flow. Besides of engineering level simulations, there are also support models, cost models, manufacturing models to aid engine performance evaluation.

Fidelity and resolution are main aspects concerning the aero-engine simulation tasks. Engineering level simulations provide basis for design tradeoff for parts, component/subsystem and system. Fidelity and resolution depends on the concerned category of models and simulations and purpose of simulation tasks. An aero-engine simulation pyramid with hierarchical structure is shown in Figure 1, the pyramid is used not only to improve understanding on modeling and simulation, but also applied to plan the simulation experiments to support the bottom-up simulation verification and validation (V&V), which is vital for simulation credibility.

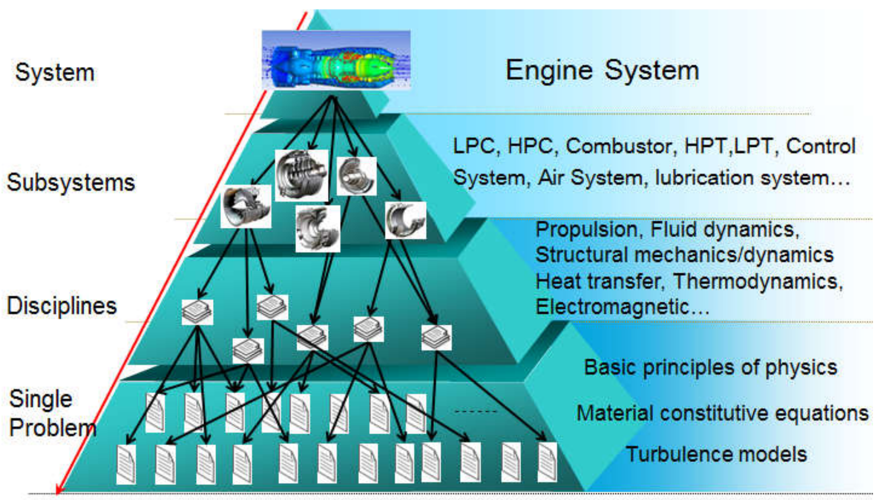


Figure1- Diagram of Aero-engine Simulation Pyramid

As shown in the pyramid in Figure 1, there are four levels of the hierarchy for aero-engine simulation. The top level is engine system, which corresponds to simulation of the whole engine in the respect of function, performance and structure. The next level is subsystem, which concerns component/subsystem simulation such as compressor, combustor, turbine, control system, etc. The third level focuses on simulation of discipline problems, which includes different subjects:

propulsion, fluid dynamics, structural mechanics/dynamics, thermodynamics, heat transfer, acoustic propagation, electromagnetic propagation, etc. The lowest level refers to single problems: basic principles of physics, materials constitutive equations, turbulence models and basic computer algorithm, which constitute the basis of aero-engine simulation. As the hierarchy moves to lower levels, the simulations tend to exhibit more resolution and longer time consumption, at every level of the hierarchy, models and simulations are applied consistent with development requirements in each stage of aero-engine life cycle.

2.2 Process of Modeling and Simulation

Modeling and Simulation in the design and development of aero engine need to follow strict process to ensure accuracy and credibility, despite emphasizing different aspects and diverse forms, most processes represent similar concepts or steps. Modeling and simulation itself is an integrated “Systems Engineering” process, which needs to start from problem recognition and requirement analysis, following with model implementation, verification and validation, testing, simulation and evaluation, during the process, iterations occurs when the simulation results cannot represent the real system, finally all the credible models are maintained by configuration management.

Figure 2 is an example of simulation modeling life cycle which introduces the modeling and simulation process and the interaction with actual system development process. In the solution domain, the life cycle model illustrates the loop of the model development process, besides that, the verification and validation process is also emphasized to ensure the simulation accurately represents the real world system and meets the intended uses.

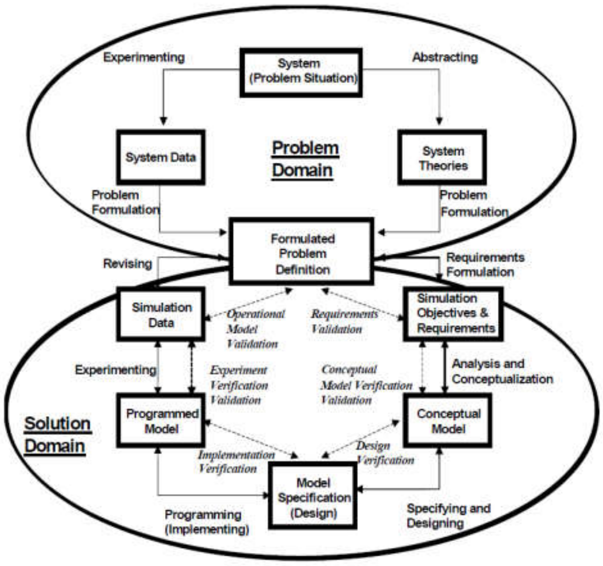


Figure 2 -Simulation Modeling Lifecycle [4]

3. Application of simulation in life cycle stages

3.1 Systems Engineering life cycle stages

The life cycle model defined in Systems Engineering process is used to guide all the life cycle activities, and ensure the system satisfies users’ needs for complex products development. In the INCOSE Systems Engineering Handbook[5], several different life cycle models and their stages are listed and compared. Ordinarily, life cycle model is constituted by several stages in serial sequence, however, the stages could overlap in practice according to the scope and complexity of the project.

According to characteristics of the activity sets in different life cycle stages, and also considering the highly correlated relationships and integrity of multiple activities within same stage, a generic aero-engine life cycle model with six stages is defined in Figure-3, which are the Requirement Analysis and Definition Stage, Concept Exploration Stage, Development Stage, Test and Evaluation Stage, Production Stage and Support Stage, however, the last two stages overlap in time sequence to a large extent. Main purposes of each individual stage are listed as follow.

Requirement Analysis and Definition	Conceptual Exploration	Development		Test and Evaluation	Production	Support
		Preliminary Design	Detailed Design			

Figure 3- Diagram of an aero-engine life cycle model

(1) Requirement Analysis and Definition Stage: starts from market and business analysis, captures user needs and stakeholder requirements, defines system requirements and initial aero-engine concept, and finally determines project feasibility.

(2) Concept Exploration Stage: explores and evaluates alternative aero-engine concepts and determines initial overall technical scheme.

(3) Development Stage: includes preliminary design and detailed design, the activities in this stage are located in the left side of the Systems Engineering “V” model, focuses on aero-engine top-down requirement allocating and design definition, finally finishes aero-engine detailed design.

(4) Test and Evaluation Stage: integrates the aero-engine components, tests and evaluates the engine according to airworthiness certification requirements, the activities in this stage are located in the right side of the Systems Engineering “V” model.

(5) Production Stage: produces the engines, and resolves production problems as well as reduces production costs.

(6) Support Stage: provides services to maintain reliability, availability to ensure aero-engines sustaining operational capacity.

3.2 Modeling and Simulation (M&S) and Systems Engineering (SE)

As it becomes more and more complex to develop a brand new aero-engine system, modeling and simulation is increasingly applied for the engineers to model the systems and analyze the system characteristics in the Systems Engineering (SE) life cycle. The simulation activities are embedded in the aero-engine development process, which are extremely useful for development interactions especially in the development stage, and the results also support the decision gate reviews to determine the project could move to next stage or not.

As an interdisciplinary approach and means, Systems Engineering emerges to enable successfully realization of the system and deal with complexity and change [5]. Although SE and M&S are distinct disciplines, M&S constitutes the core function of SE effort to integrate various engineering disciplines during system life cycle. The synergy of M&S and SE has been well established during past few decades [5-6], M&S helps manage complexity by modeling system characteristics, functions, performance and cost, it can help explore the entire solution trade space to support decision making.

As a result, in the process of complex aero-engine system development, modeling and simulation plays an increasingly vital role currently. Without M&S, the realized engine product will most possibly be technically risky and its development will suffer from exceeding the schedule and high risk of over-budget.

4. Modeling and Simulation in Aero engine life cycle stages

4.1 Requirement analysis and definition stage

A new aero-engine project starts from market analysis and prediction. In this stage, stakeholders and their needs of potential opportunities are identified, and initial aero-engine concept is developed based on reference architecture and used for feasibility analysis. In this stage, modeling and simulation is used to explore the effectiveness of new concept, function analysis, and cost estimation to support the feasibility analysis.

As most of the aero-engine architecture can be derived from a mature engine, it is necessary to focus on those new functions. Modeling tools such as IDEF0 diagrams or ULM/SysML language diagrams are applied to generate function breakdown. Once the operational scenarios is defined, models are developed to describe and analysis system or subsystem behaviors and characteristics in different flight missions and operational scenarios, and then compatible function requirements, function interface and architecture are developed to support system concept and future feasibility determination. In this stage, only low dimensional simulations are applied to support feasibility analysis.

As the functional architecture of the engine is established, basic aero-engine configuration such as turbo-fan, turbo-jet, or turbo-shaft engine with single spool, twin-spool is determined. Aero-engine performance is modeled and simulated to evaluate the critical performance parameters, such as thrust, specific fuel consumption, etc. Besides that, low detailed weight, size and rotor dynamics simulations are also applied to assess the feasibility of the aero-engine concept.

According to the aero-engine architecture and concept, initial product break down structure (PBS) can be built, which is the basis of cost estimation to forecast the life cycle cost, consequently work breakdown structure(WBS) and cost estimating models are formed based on the PBS and historical of similar aero-engine project.

Cost estimation occurs in each life cycle stage, and multiple methods, such as parametric, analogy, engineering estimate and actual cost etc., are used to get a relatively accurate result. In the early stages, like the Requirement analysis and definition stage, as there only little information is known about the aero-engine product, less detailed cost estimation models and parametric and analogy methods are applied to simulate the development cost as well as the life cycle cost. As the project proceeds to later stages, cost estimation tends to be more and more detailed and accurate.

Besides that, more simulations towards other critical system characteristics (measures of effectiveness, MOE) are implemented through on a set of low dimensional models, such as reliability models, maintainability models, etc. All the simulation are used to support the both the technical and economic feasibility decision.

4.2 Conceptual exploration stage

In the conceptual exploration stage, aero-engine system requirements are captured and allocated to component/subsystem hierarchy, multiple alternative system and component/subsystem concepts are created and analyzed, after trade-off studies on both technical and economic aspects, a sole initial overall technical scheme is selected, the critical technologies are identified, and initial cost breakdown structure (CBS) of the project is established. The main role of modeling and simulation in this stage is to analysis and evaluation the alternative concepts.

For the engine system, 0-D whole engine performance model (see Figure 4) is assembled by selecting modularized component reference models from the repository, where the different type of models such as intake, by-pass, compressor, combustor, turbine, secondary air system, etc. are preserved for reuse. In this simulation for derived new engine, characteristics are zoomed from exist component performance map in the repository, both the design point and off-design point performance are evaluated. As a result of performance simulation and trade-off, major concept parameters, such as thermodynamic cycle parameters (massflow, by-pass ratio, TET, etc.), regulation laws, the altitude and speed characteristics and are defined and verified. Initial engine main flow path is also defined as an output of performance design and analysis, and then weight estimation, air system analysis, load analysis and rotor dynamics analysis, and many other 0-D and 1D simulations are used to support the a alternative concepts selection.

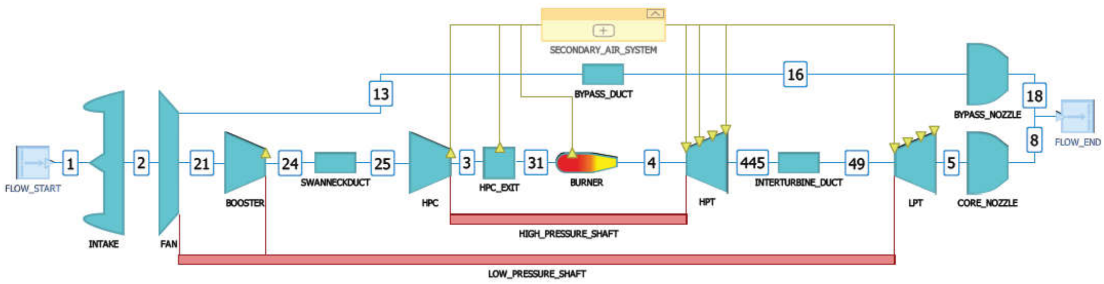


Figure 4-Diagram of the turbofan engine thermodynamic cycle model

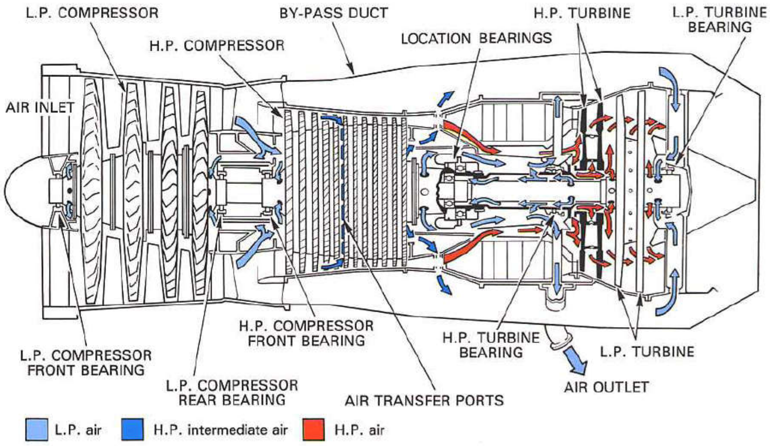


Figure 5-Flow path of aero-engine secondary air system [8]

In this stage, modeling and simulations mainly focus on the whole engine system and subsystem/component in less resolution. For the subsystem, such as the secondary air system(see Figure 5), alternative concepts are also formed and analyzed. Figure-x shows the internal flow path for the secondary air system, in the alternative concepts analysis, the flow path is discreted into a set of cells and units, which flow constitute a 0-D network model to represent the internal airflow; flow dynamics simulation based on the network model is applied to verify whether these air system concepts could satisfy air bleeding, cooling, sealing, control of bearing loads and other functional requirements, and analyze the mass flow, temperature and pressure distribution in every cell at the off-design points.

4.3 Development stage

In this lifecycle stage, system requirements and overall concept of the engine are determined and refined, a selected aero engine concept transforms into a realized system throughout long term iterations with several rounds of design definition, trail-manufacture and a set of tests, at the end this stage, system requirements have been verified and major technical problems exposed in trail-manufacture and engine tests have been fixed, the engine system development is ready for the following Test and Evaluation Stage.

In this stage, modeling and simulation play a critical role in the aero engine development process, numerous simulations are carried out within all hierarchy in the modeling and simulation pyramid as shown in Figure 1, and diverse models are created and integrated to verify the performance for the engine system, subsystems and also the critical components. Most of the simulations focus on the physical domain includes varied engineering disciplines such as aerodynamics, fluid and heat transfer, combustion, structural mechanics/dynamics, control, lubrication, materials and manufacturing processes, acoustic propagation, etc.

At the engine system level, the overall engine concept needs more refinement and trade-offs according to the system performance parameters in the flight envelope and subsystem design difficulties. In this process, low dimension (in 1D) whole engine model are applied to simulate both steady state performance and transient performance, and based on the components design and test results, those low dimension simulations are also used for the system performance analysis and iteration, components flow field matching, weight evaluation, rotor dynamics analysis, reliability evaluation, etc.

As the design definition moves forward, it is necessary to interacted main components and subsystems models to perform the 3D full engine simulation[9-14].Through the whole engine full 3D simulation, it simulates the performance of the whole engine under complex environment or extreme conditions, it helps to understand the flow field details of the whole engine, such as the gap leakage flow, the components matching, the distribution of cooling air, etc. it is also applied to verify the whole engine full 3D performance such as during over temperature or over speed, or performance at high altitude with low Reynolds number. Also, it helps to define the whole engine experimental scheme and partially replace the rig tests. The whole-engine simulation can be carried out after the detailed design of the components, to assess the matching status of the components in advance, assess the technical risk and guide the optimization of the whole-engine design.

Generally, there are three different ways for detailed full engine simulation wh1ch are (1) based on the 1D whole engine model and components multidimensional scaling, (2) the use of a single program for independent calculation and (3) the use of multiple programs coupled calculation, all three modes have their own advantages and disadvantages. Figure 6 shows the simulation result of the GE90 engine at Mach number (Ma) 0.25 and sea level take-off conditions at constant conditions.

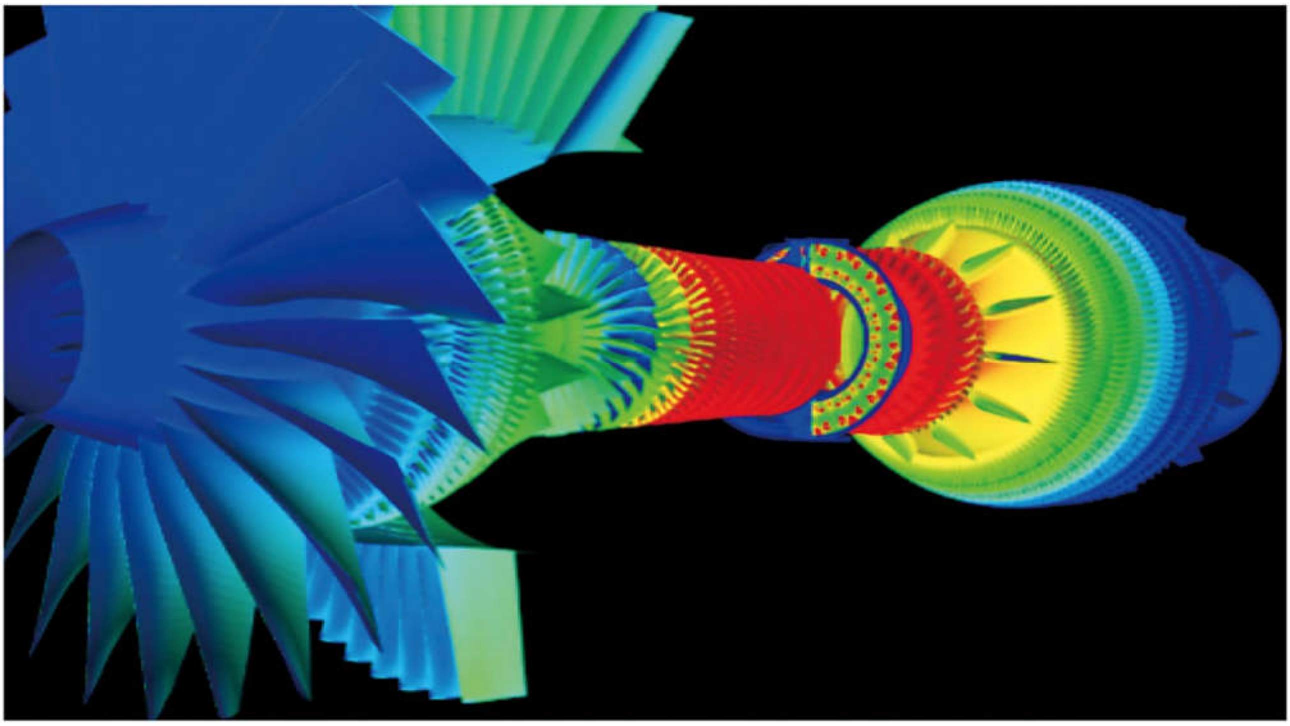
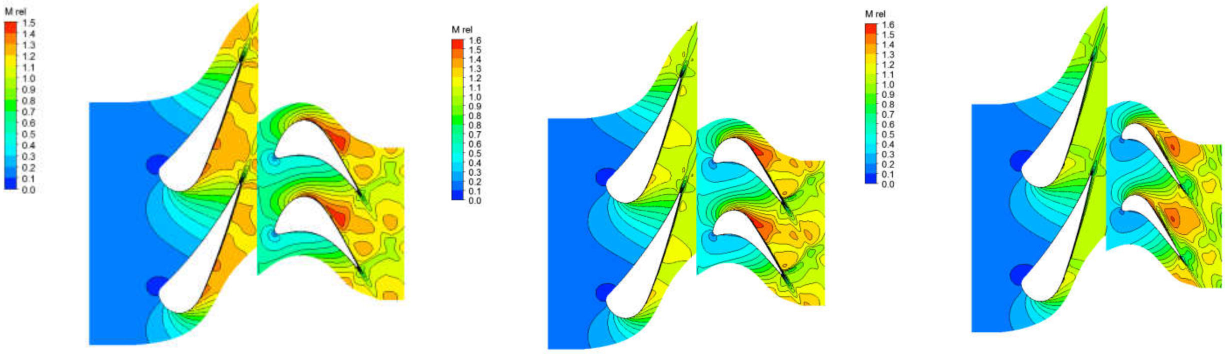


Figure 6- Result of GE90-94B full engine simulation[9]

For subsystem/component design, it is also important for applying models and simulations to analysis and verify subsystems/components design. Take turbine as an example, in the design process, as the design requirements are clearly defined and allocated down engine system requirements, it is the time to perform the aerodynamic design to complete the turbine flow path design and determine the aerodynamic parameters, and the structural design to design all the components to achieve the turbine aerodynamic performance and ensure overall compatibility and life-cycle reliability.

In engineering practice, the aerodynamic design of the turbine uses quasi-3D design to decompose the 3D flow in the radial runner and blade channel into 2D S1 flow surfaces and 2D S2 flow surfaces to solve for the turbine flow field, carry out turbine flow-path design and blade modeling, which provide the basis for subsequent cooling design, temperature field and strength analysis.

Due to the complexity of the flow field within the turbine, there are strong three-dimensional flow affecting turbine performance significantly, it is also very necessary to employ 3D flow field analysis to assess the turbine flow-path design and airfoil profile design and also verify the turbine design requirements. This includes the application of the 3D Euler equations to solve the flow field in 3D inviscid conditions and to study and analyze the pressure, temperature, streamline and velocity field distributions within the cascade. Figure 7 is a schematic diagram of the velocity field analysis carried out on the turbine blade, which shows that there is essentially no flow separation within the turbine blade grid.



(a) 10% blade height (b) 50% blade height (c) 90% blade height

Figure 7- Examples of turbine Mach number contours at blade tip, mid-section and root

Also, it is necessary to solve the three-dimensional viscous flow field of the turbine, both steady and unsteady simulation of the turbine component are applied to solve the velocity distribution within the boundary layer, the thickness of the boundary layer, the momentum loss, whether the separation exist and consequently the separation location, etc..As shown in Figure 8, the tailing edge flow characteristics analysis are also used to reveal the wake loss, the strength of the wave system, the composition structure of the vortex system, the excitation of the wake, etc. which is vital for deign optimization to reduce the trailing edge wake loss. Due the complexity of the boundary layer, separated flow and vortex system with in the viscous flow, it is necessary to generate a sufficient number of meshes to capture the flow details within the boundary layer.

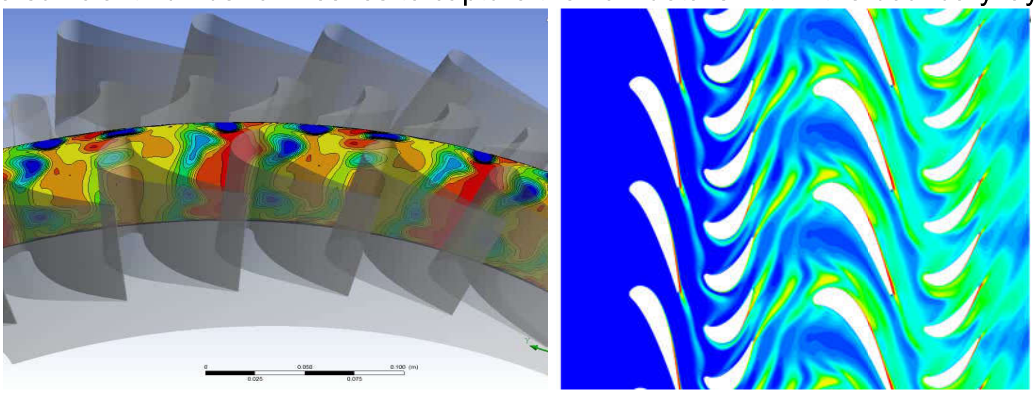


Figure 8-Unsteady simulation of turbine wake flow field

For the critical parts design, take the cooled turbine blade as an example, the external heat transfer analysis of the airfoil is the basis for the blade cooling design. It is necessary to use the S1 results of the blade aerodynamic calculation as the raw data for the analysis, boundary layer flow of compressible and non-compressible fluid is analyzed, so as the external heat transfer coefficient distribution along the chord length of each section of the blade is solved (Figure 9) for the blade cooling design.

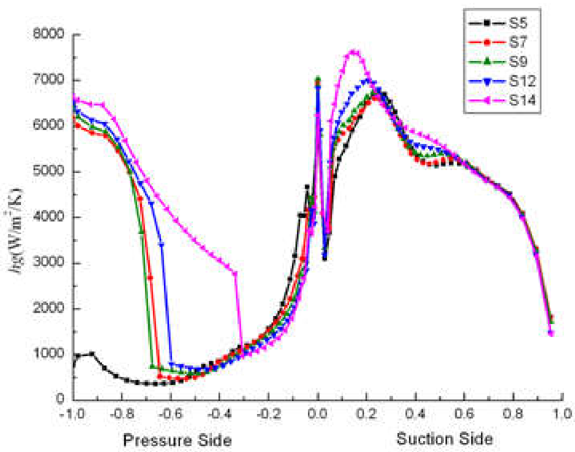


Figure 9- Analysis of the external heat transfer of the turbine blade

According to the external heat transfer distribution, gas temperature and pressure distribution, coolant temperature, pressure, cooling structure design can be defined and hence the detailed turbine blade 3D model will be created, which can be used for the internal air system analysis and blade thermal analysis. The internal air system analysis is a discrete one-dimensional flow network of the entire inner cavity, which yields the pressure and temperature distribution and flow distribution along the cooling passage, thus verifying whether the cold air flow meets the design requirements. Using the external and internal heat transfer as boundary conditions, a temperature field analysis can be carried out to obtain the 2D or 3D temperature field of the blade and verify the cooling design of the blade meets the requirements. Film cooling is widely used as an effective cooling method in the blade design process, the effect of film cooling on external heat transfer cannot be ignored, therefore, film cooling corrections to the external heat transfer coefficient of the blade are also required before applying boundary conditions.

In addition, the CFD-based 3D air-thermal coupling simulation also plays a huge role in the turbine blade temperature field analysis, taking into account the influence of coolant flow, external heat transfer and heat conduction in the coupled analysis, the flow field of both the internal and external flow and the temperature distribution of the blade are solved and assessed, which is able to capture sufficient flow field details, hence helps the blade cooling design optimization, as shown in Figure 10.

As a critical part of the engine, the turbine blade is subjected to thermal stresses in addition to complex aerodynamic and centrifugal loads during operation, the strain and stresses, creep life estimation, vibration analysis and other strength simulations must be performed to verify the blade design.

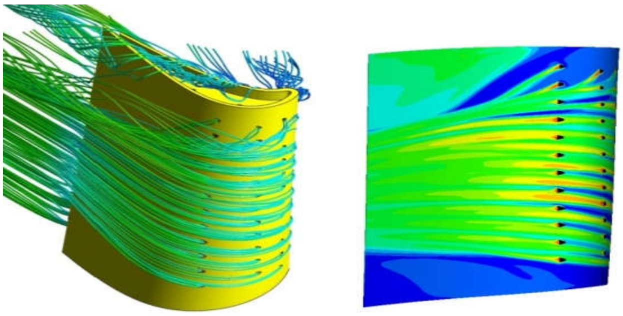


Figure 10- 3D air-thermal coupling simulations used for film cooling design optimization

Simulation is also applied to the component prototyping process, especially for the single crystal blades casting, the mechanism of the solidification process is more complex and the role of simulation in this is more obvious. As shown in Figure 11, the casting process of single crystal blades is simulated to reveal the temperature distribution during solidification, and the solidification process and grain growth process at different drawing speeds are also simulated, and also the grain structure and recrystallization locations, which provides a basis for the casting process parameters optimization.

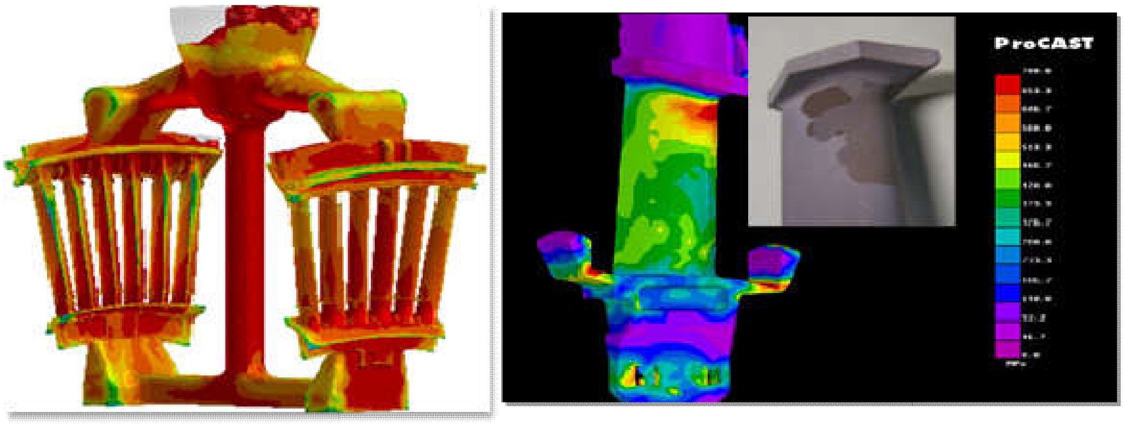


Figure 11- Blade casting process simulation

At present, much of the component and system tests can be replaced by simulations, but tests are still the direct and final means of verifying that the design meets the design requirements, and the large amount of data obtained from tests can provide authoritative information for the verification and validation (V&V) of simulation models. Through modeling and simulation of complex test equipment and test processes, test results can be predicted in advance so that test design can be optimized, and test risks can be mitigated in advance to make the tests successful.

4.4 Test and Evaluation Stage

In this lifecycle stage, test and evaluation have to be performed to validate whether the aero engine system design satisfy the user's needs. The main task is to all required qualification rig tests and flight tests, which include validations in different hierarchies such as whole engine system, subsystems/components and parts, and resolve any technical problems or design defect that exposed during the rig tests and test flights in time.

In this stage, many of the engine requirements have been verified through extensive simulations and test verifications in the last lifecycle stage, modeling and simulation mainly focus more off-design point verification in the flight envelop, help to accomplish various qualification tests; carry out analysis for failures or problems occurred during the tests and re-evaluate the consequent design improvements. It is also important to employ multiple components simulation and or 3D full engine simulation to predict the performance and assess the components matching during operations.

According to the airworthiness regulations, there are also many special engine environment tests required to assess the engine performance and reliability in the harsh environmental conditions of the adaptability, such as high and low temperature starting and acceleration test, icing test, corrosion sensitivity test, in addition to birds strike test, foreign object damage test, swallowing sand test, etc. As shown in Figure 12 is a birds strike simulation compared with real rig test. Throughout the simulation, the effects of different parameters on impact damage can be analyzed, which can be beneficial for the experiment scheme establishment to ensure test success. Also, the impact of the bird with the fan blade is simulated, including the deformation and failure of the fan blade after the bird strike, to provide a visual reproduction of the test process.

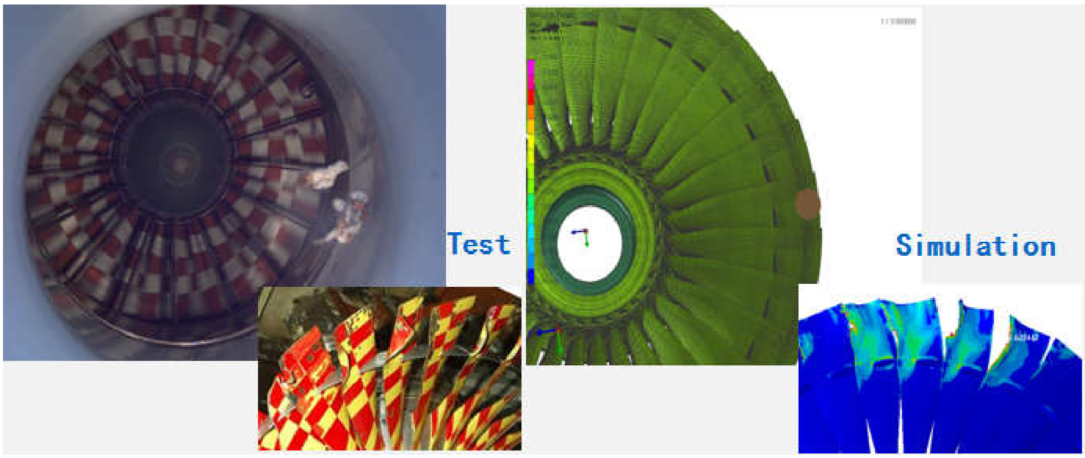


Figure 12- A comparison of birds strike test and simulation

4.5 Production Stage and Support Stage

The last two lifecycle stage overlap in the timeline to a large extent, product and service improvements are required to resolve production/reliability/supportability problems, reduce production and deploy costs and enhance the capacity of the engine systems, at the end of the lifecycle, ensure all the disposal requirements are satisfied.

Modeling and simulation may be applied to optimize the production process and improve production efficiency. By modeling and monitoring tens of thousands of square meters of space and thousands of objects on the production site in real time, using a combination of real data and virtual models for analysis, companies such as Airbus, Dassault, GE and Pratt & Whitney can get a real-time picture of the exact location of marked parts/tools and equipment and plan where they will need to be used in the future, thus reducing production interruptions, planning and scheduling assets in advance and planning future activities through simulation. Figure 13 shows an example that an assembly simulation applied to verify design for assembly of the engine and support for assembly process design and the assembly line layout.

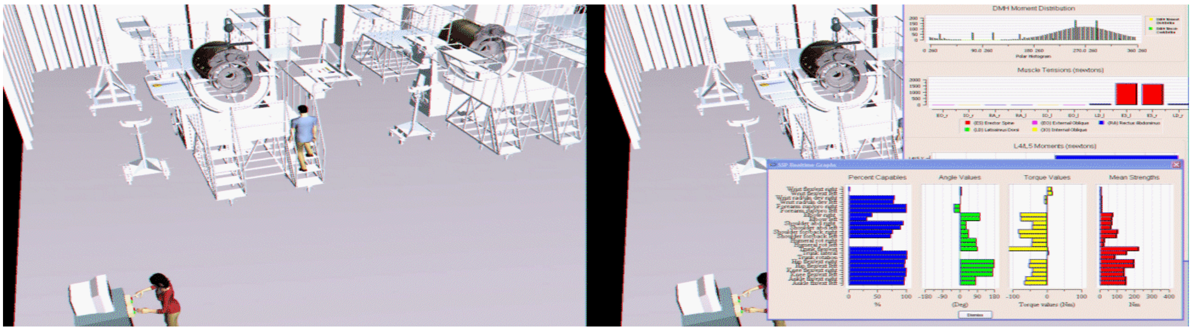


Figure 13-Example of aero engine assembly simulation

During the engine utilization and support, modeling and simulation are required to resolve supportability problems and reduces maintenance costs, it should be noted that these modeling and simulation do not start in this stage only, but is already carried out in parallel with the design process from the Development Stage, and is reflected in the design iteration process.

An virtual maintenance simulation, as shown in Figure 14, can be used as a DFX tool to support engineers in the design process for iterative maintainability design, besides that, the application of technologies such as visualization and VR, providing electronic interactive manuals for engines and animated demonstrations of the maintenance process, etc., can provide maintenance training and simulation exercises for users in advance. The basis for virtual maintenance is a single data source model generated during the design process, with key physical attributes and precise 3D geometric features, integrated into a prototype for virtual maintenance. In the virtual maintenance process, interference checks take into account not only the interference between components, but also the human and virtual environment, such as the maintenance site, tools, etc..

Figure 14- Example of aero engine virtual maintenance

4.6 More considerations

(1) M&S VV&A

Nowadays, it is widely recognized that modeling and simulation Verification, Validation, and Accreditation (VV&A)has become indispensable to provide sufficient information to determine if the simulation can meet their needs and ensure simulation credibility and accuracy. [15]

Verification, Validation, and Accreditation (VV&A) supports establishing the credibility of models and simulations. It also helps reduce risk by identifying potential problems and errors early in the modeling and simulation development cycle. VV&A processes are performed to establish the credibility of the models and simulations. In one words, Verification answers the question "Have we built the model right?" while validation answers the question "Have we built the right model?”.

Strict VV&A process (Figure 15) and specification has been established during past few years. If the development of the model is carried out in strict accordance with the VV&A process and specifications, consequently both the correctness and confidence of the simulation results are increased as well as the simulation accuracy.[16-18]

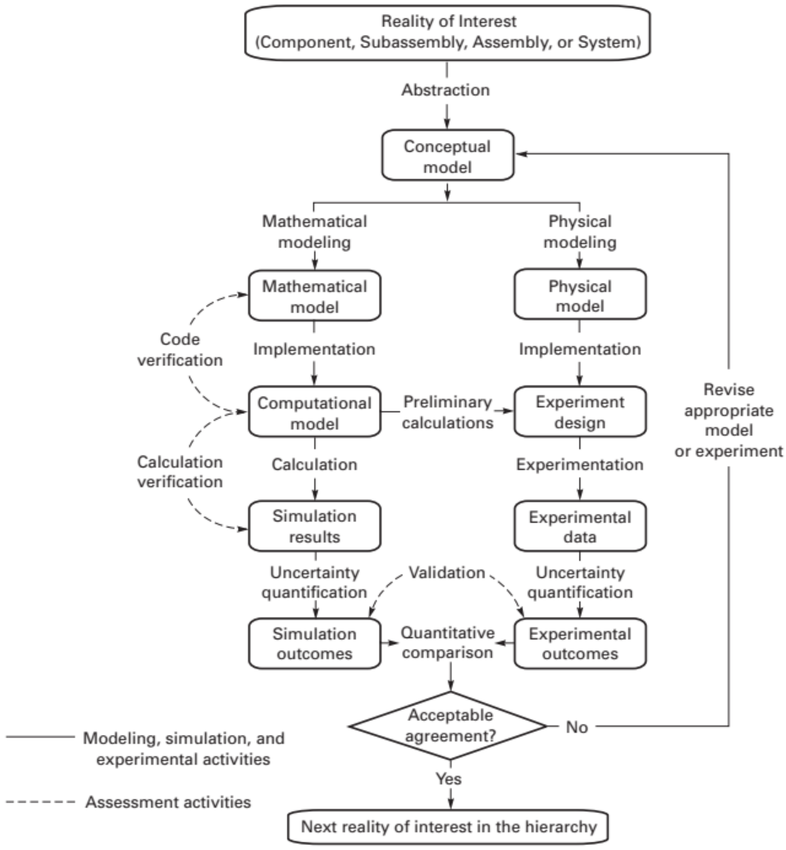


Figure 15- V&V process[17]

(2) Simulation data management

Simulation data is becoming increasingly important as the basis for supporting the modeling and simulation and even the entire R&D process. Firstly, models and simulations require rigorous verification, validation and accreditation (VV&A) to ensure accuracy and confidence in the modeling and simulation, which is based on a large amount of data sources from engine design, manufacturing, assembly, testing and field operation. On the other hand, each simulation task generates a range of simulation data. The types of data are also diverse, both parametric and file-based, and may be in the form of individual parameters, parametric tables, 1D/2D/3D model data, or pictures and diagrams, making it difficult to manage and utilize simulation data in a standardized manner.

Therefore, it is necessary to manage the scattered simulation-related data reasonably and effectively in accordance with certain logical relationships, realize the close integration of simulation data with simulation processes and simulation platform tools, promote the transmission, sharing and reuse of simulation data in the simulation process, extract data values through algorithms of data analysis, improve simulation accuracy and confidence, and enhance simulation efficiency.

(3) Digital twins

Digital twin [19] is considered as a huge leap of modeling and simulation and the IT technology, the aerospace industries consider digital twin as a great opportunity to optimize performance, gain insights, and reduce costs, they have made huge efforts to explore the research and application of digital twins in the aircraft system lifecycle. By establishing an accurate mapping and feedback mechanism between physical and digital space, digital twin enables real-time exchange of data/information between physical and digital space, and captures changes in the physical space environment and ontology during the evolution of complex systems, continuously updating the twin models in digital space to predict and evaluate system behaviors.

The US Air Force has worked with Boeing to build a digital twin model of the F-15C airframe[20], enables multi-scale simulations and structural integrity diagnostics that can track individual airframe structures, along with advanced modeling and simulation tools to manage and predict residual stresses, structural geometry, loads and boundary conditions, finite element analysis network dimensions and material microstructural uncertainties.

Rolls Royce create digital twin models[21] for each of the composite fan blades during UltraFan Low Pressure System (ALPS) testing, collecting a large amount of data during testing for engineers to predict how each blade would perform over the course of its life.

Figure 16 is a concept of GE digital twin[]. GE Aviation created a digital twin for the GE90 engine to look specifically at the maintenance of an aircraft engine to monitor and predict blade erode from the part. This is more prevalent in places like the Middle East, in which planes encounter sandy conditions. [22]

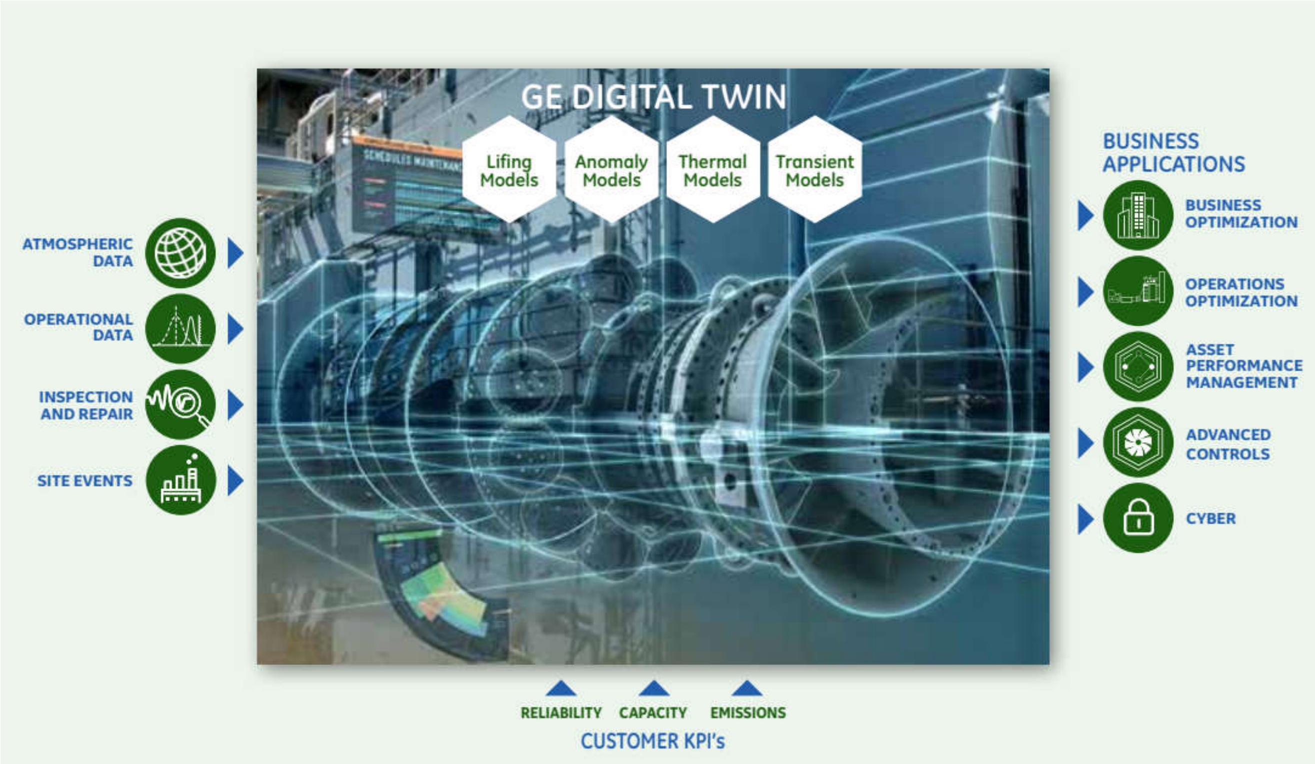


Figure 16- GE digital twin concept

5. Conclusion

Modeling and simulation technology is a necessary tool for the development of advanced aero-engines, and greatly reduce the development costs of engines and shorten the development cycle. This paper illustrates the applications of modeling and simulation throughout the life cycle of an aero-engine, which is important to promote the overall understanding of modeling and simulation in the R&D process. However, as thermal cycle parameters and system complexity keep increasing for the future aero-engines, it is necessary to improved modeling and simulation application capabilities so as to accelerate the transformation of aero-engine development from the traditional mode to the "predictive" mode:

1) Focusing on advanced simulation methods, such as multi-dimensional scaling, multidisciplinary coupled simulation, multi-components/systems integration simulation, integrated flight and aero-engine simulation, semi-physical simulation, etc., to solve the urgent modeling and simulation problems in the aero-engine development so as to improve the capacity of simulation as a verification tools.

2) Research on modeling and simulation VV&A methods and tools, improve data analysis and processing capabilities, verify and modify simulation tools, models and algorithms based on reliable test data, and consequently improve the accuracy and confidence of simulations.

3) Explore the "requirement-function-logic-physical (RFLP)" modeling method based on MBSE for future development, Enables model-based system design, simulation verification, model integration, virtual testing and collaborative R&D.

4) The digital twin will establish a strong connect between the virtual world and the physical engine,

bring in a paradigm shift in research and development. It is necessary to research the methods to realize a digital twin model of the aero-engine, modify the model based on real data, develop various analytical and predictive models with the support of technologies such as big data and artificial intelligence, and increase understandings about the complex system. As a result, an accurate, comprehensive and dynamic simulation of the aero-engine will be achieved, thus it is able to accelerates the design verification process, make in time predictions of operational performance status and trends, and lead to more efficient decision-making and system optimization.

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7. Copyright Statement

References

[1] Skira C A. Reducing Military Aircraft Engine Development Cost through Modeling and Simulation. RTO AVT Symposium on Reduction of Military Vehicle Acquisition Time and Cost Through Advanced Modeling and Virtual Simulation, Paris, 2002.

[2] DoD Directive 5000.59, DoD Modeling and Simulation (M&S) Management, January 4, 1994

[3] CAO Jian-guo. Status, Challenges and Perspectives of Aero-Engine Simulation Technology, Journal of Propulsion Technology, Vol.39, No.5,pp 961-970,2018 (in Chinese)

[4] Walden, David D., Garry J. Roedler, and Kevin Forsberg. INCOSE Systems Engineering Handbook Version 4: A guide for system life cycle processes and activities. 4th edition, Wiley, 2015.

[5] Ören, Tuncer I., Levent Yilmaz. Synergy of systems engineering and modeling and simulation. In Proceedings of the 2006 International Conference on Modeling and Simulation-Methodology, Tools, Software Applications (M&S MTSA), pp. 10-17. 2006.

[6] Hollenbach, J. W., & Alexander, W. L.. Executing the DoD modeling and simulation strategy—making simulation systems of systems a reality. In Proceedings of the 29th conference on Winter simulation, pp. 948-954.1997

[7] Reitenbach, Stanislaus, et al. "Collaborative Aircraft Engine Preliminary Design using a Virtual Engine Platform, Part A: Architecture and Methodology." AIAA Scitech 2020 Forum. 2020.

[8] Royce, Rolls. The jet engine. John Wiley & Sons, 2015.

[9] Turner M. Lessons learned from the GE90 3-D full engine simulations. 48th AIAA aerospace sciences meeting including the new horizons forum and aerospace exposition, January 4-7, 2010. Virginia: AIAA, 2010.

[10]Claus R W, Lavellf T, Townsend S, et al. Coupled high-fidelity engine system simulation. 26th international congress of the aeronautical sciences: September, 2008.

[11]Schluter J, Apte S, Kalitzin G, et al. Unsteady CFD simulation of an entire gas turbine high-spool. Proceedings of GT2006, ASME Turbo Expo 2006: Power for land, sea and air, May 8-11, 2006. New York: ASME, 2008.

[12]Schluter J, Wu X, Weide E, et al. Integrated LES-RANS of an entire high-spool of a gas turbine. 44th AIAA aerospace sciences meeting and exhibit, January 9-12, 2006. Virginia: AIAA, 2006.

[13]Medic G, Kalitzin G, You D, et al. Integrated RANS/LES computations of an entire gas turbine jet engine. 45th AIAA aerospace sciences meeting and exhibit, 8-11 January, 2007. Virginia: AIAA, 2007.

[14]Teixeira M, Romagnosi L, Mezine M. A methodology for fully-coupled CFD engine simulations, applied to a micro gas turbine engine. ASME Turbo Expo: turbomachinery technical conference and exposition, Junary 11-15, 2018. New York: ASME, 2018.

[15]Cook, D. A., and J. M. Skinner, How to Perform Credible Verification, Validation, and Accreditation for Modeling and Simulation, CrossTalk: The Journal of Defense Software Engineering. 2005

[16]Sanders, P.DoD modeling and simulation (M&S) verification, validation, and accreditation (VV&A). OFFICE OF THE UNDER SECRETARY OF DEFENSE (ACQUISITION AND TECHNOLOGY) WASHINGT ON DC, 1996.

[17]ASME V&V 20-2009-R2016, Standard for Verification and Validation of Computational Fluid Dynamics and Heat Transfer, 2016

[18]ASME V&V 10.1-2012, An illustration of the Concepts of Verification and Validation in Computational Solid Mechanics, 2012

[19]Grieves M. Product lifecycle management: the new paradigm for enterprises. International Journal of Product Development, 2(1-2):71, 2005

[20]Tuegel, E., The airframe digital twin: some challenges to realization[C]. Proceedings of the 53rd AIAA/ASME/ASCE/ AHS/ASC Structures, Structural Dynamics and Materials Conference, VA.USA：AIAA, 2012,:1812

[21]Rolls-Royce UltraFan one step closer as Advanced Low Pressure System (ALPS) testing gets underway, available at: https://www.rolls-royce.com/media/press-releases/2019/25-02-2019-rr-ultrafan-one-step-closer-as-advanced-low-pressure-system-alps-testing-gets-underway.aspx

[22]GE Aviation, Digital Twin Creation, available at https://www.ge.com/research/offering/digital-twin-creation