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Research on Aero-engine Collaborative Design Process Based on System Engineering

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Abstract

Taking the development of aero-engine external structure as an example, this paper briefly describes the problems in the development of aero-engine. Focusing on demand analysis and management, Structural control model, Design maturity, Top-down approach is introduced and a multi-disciplinary collaborative design process is established, with which the concurrent engineering in design and manufacturing is conducted, to improve iteration efficiency and shorten development cycle.

Keywords: Aero-engine System-engineering Maturity Collaborative-design

1. General Introduction

The development of aero-engine involves multiple disciplines, such as structure, strength, aerodynamics, heat transfer, noise, materials, manufacturing, assembly, etc. which need a lot of iterations and coordination. It is typical complex system engineering with the characteristics of great technical difficulty, wide coordination, long development cycle and high cost risk.

The external structure is a system that connects the various engine components, accessories, and transports the specified fluid media to complete engine operation, control, manipulation and other functions.

The space between engine and nacelle is limited, and the accessories, pipelines, and brackets of the fuel system, lubricating oil system, air system, and control systems are intertwined, so the external structure is regarded as an independent specialty in order to achieve a more compact layout, more efficient design iteration and more reasonable structure design. On the contrary, each system of the aircraft is responsible for its own structure, since the layout space is large enough.

According to incomplete statistics, about 50% of aero-engine failures in the 20th century were piping system failures. Except for occasional fracture failures, most of them were "dripping and leaking" problems, which will seriously affect the realization of the system functions of the aero engine, and then affect the overall performance of the aircraft.

Piping system failure is a very complex problem, with both design and manufacturing factors, such as insufficient design iteration, inadequate consideration of manufacturability, assembly and reliability, insufficient manufacturing accuracy, accumulation of errors, etc. All of these require the full iteration of each specialty, as well as the iteration of design and manufacturing.

2. Current status and problems of aero-engine development

The development stage of an aero engine mainly includes: requirements analysis and definition stage, conceptual design stage, preliminary design stage, detailed design stage, manufacturing and test verification stage. There are a lot of iterations and coordination in each stage, which requires the collaborative work of multiple people, disciplines and even enterprises.

The aero-engine development cycle is long and requires repeated iterative synthesis of multiple disciplines. Many enterprises have not yet established an effective development process in the aero-engine field. At the initial stage of project development, focus is often on program research, but the requirements analysis, functional architecture and system integration are not thoroughly developed. Problems such as insufficient tracking and verification of requirements, disjointed design and manufacturing, and inadequate integration and coordination in the development process would lead to frequent changes even performance degradation, schedule delay, and increased costs in the later stages of project development.

The external structure have interfaces with each component or system. Any changes from components or systems will require the redesign of the external structure; on the contrary, external changes often affect other components.

The external structure design is at the end of the aero-engine design chain, which needs input from other components, especially the 3-D (three-dimensional) model of the engine for the space layout and detailed design. This results in the design of external structures starting much later than other components, and there is not enough time to carry out iterative optimization and reliability analysis, which ultimately affects the final configuration, and even the engine transfers to the next stage.

In addition, the design and manufacturing professions are not sufficiently connected in the process, the designers lack manufacturing experience, and there is no effective mechanism to ensure adequate coordination and communication. Therefore, many design problems are only found during the manufacturing stage, causing the drawing revision and even manufacturing difficulties, which seriously affect the development schedule and quality.

In order to solve the problems above, a model-based collaborative design process based on system engineering is establised, to strengthen demand analysis and management, realize top-down online collaboration, design-manufacturing concurrent engineering, timely iteration and trade-offs for each profession, fully consider the needs of all stakeholders, thereby improving design efficiency and quality.

3. The Aero-engine development process based on system engineering

3.1 Requirements-based interdisciplinary coordination and management

Systems engineering is an interdisciplinary study and a method of achieving a successful system. It focuses on defining customer needs and functional requirements in the early development stage, and it considers the overall problems and conducts comprehensive design and system effectiveness analysis after recording these requirements.

In the initial stage of product development, requirement acquisition and analysis is conducted to ensure the integrity of engine functions. Requirements of each component are identified through top-level system requirements decomposition, boundary definition, and functional analysis, and then cross-professional coordination follows.

Take the engine bleeding pipeline as an example. The seven-stage bleeding air of the HPC (high-pressure compressor) mainly provides cooling air of the secondary guide vanes and blades, as well as the sealing air between the primary disc and the secondary disc. The air comes from the rear tip of the seven-stage guide vane of the HPC, then enters the air-collecting cavity at the end of the second guide of the HPT (high-pressure turbine) through the annular air collection cavity between the double-layer casings and the external air duct.

The main requirements identified are as follows. After the requirements are identified, the pipeline layout and structure design will be carried out, and the requirements changes and interface coordination will be continuously tracked throughout the whole life cycle of engine development.

Table 1 – Definition of aero-engine external structure requirements

No.	Requirements category	Requirements example
1	Functional Requirements	Air duct connecting the seven-stage gas collecting chamber of the HPC to the gas collecting chamber of the HPT; Required pipe diameter, medium temperature, medium pressure
2	Performance requirements	Minimum leakage, can withstand thermal expansion, vibration, tolerance accumulation due to manufacturing and installation tolerances
3	Interface requirements	Interface position, interface type and interface standard of the pipeline connection end
4	Environmental requirements	Vibration environment, ambient temperature distribution

5	Physical requirements	size limitation (gap with other systems), weight
6	Strength requirements	Vibration, pressure, fireproof, material properties
7	Other requirements	Manufacturability, assembly, maintainability, reliability, economy

3.2 Model-based online collaborative design

The traditional engine development process starts from the scheme design. The preliminary layout of the whole engine is established in the form of 2-D (two-dimensional) drawings, including the rotor support scheme, the load-bearing frame scheme, the accessory layout, etc., and the interface and preliminary boundary size requirements of each component are clarified in the conceptual design stage. Afterwards, the design of each component is carried out, and the whole engine scheme is completed after several iterations.

In the preliminary design stage, technical design is carried out based on the results of the whole machine scheme. Tasks that need to be completed include the cold and hot state analysis of the whole machine, the calculation of the dimensional chain, and the definition of dimensional tolerances, and finally it forms the overall 2-D engine coordination diagram and component diagram for the development of detailed design.

In the detailed design stage, each component determines the processing dimensions and tolerances, materials, surface treatment, manufacturing inspection and other requirements of all parts for manufacturing based on strength analysis and dimensional chain analysis.

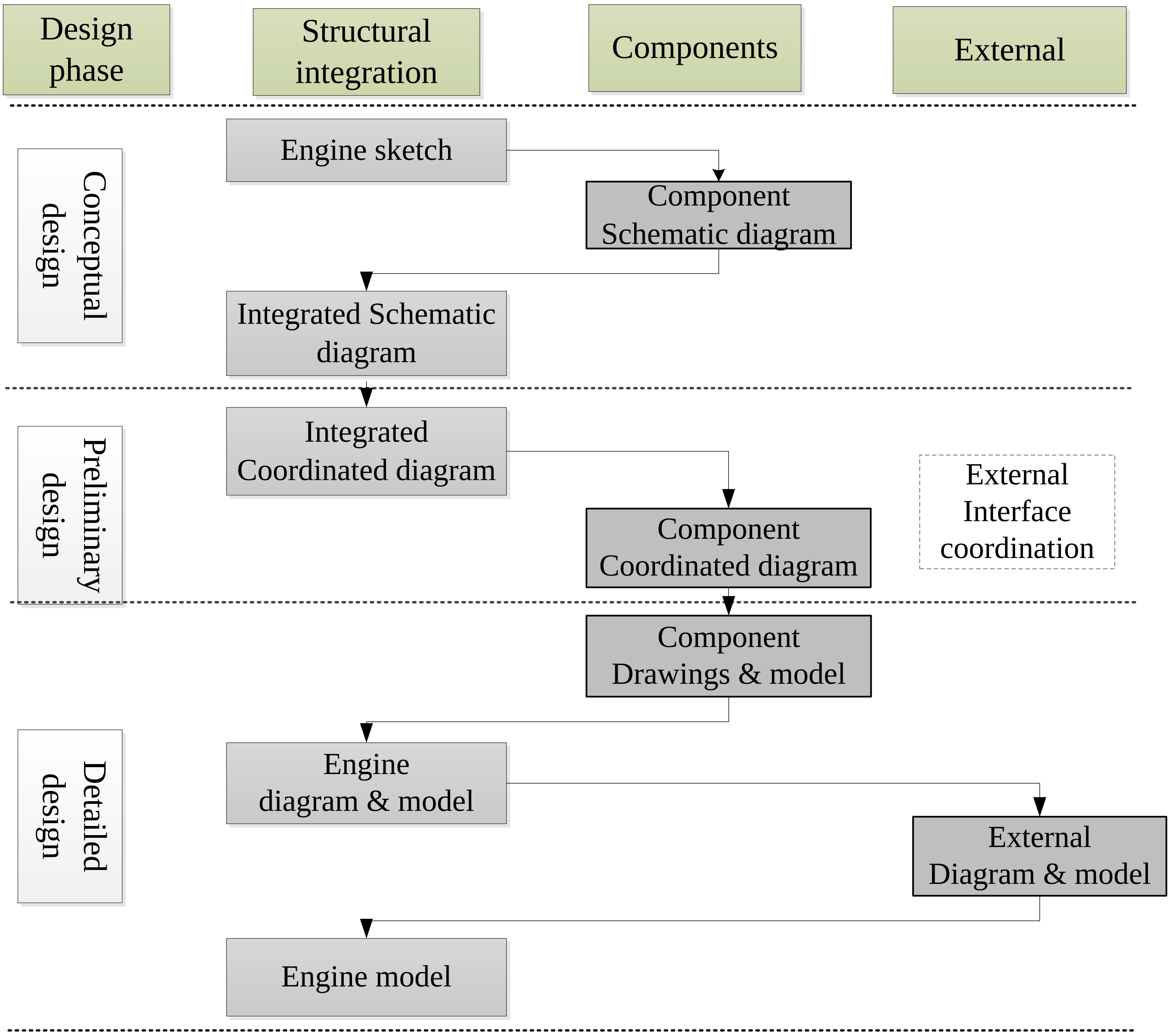

Figure 1 – Traditional 2-D-diagram-based development process

The traditional design process is shown in the following figure 1. The integration and component iterations are mainly serial, based on 2-D interface diagrams, assisted by 3-D models.

Due to the different focus of expression, it is generally impossible to directly apply the part design drawing to the integration drawing, and it is necessary to find and redraw the relevant information; on the contrary, each component cannot directly apply the information in the integration interface diagram to the component interface diagram, so there are different data sources and the design iteration cycle is long.

Since the 2-D diagram cannot express the 3-D interface information in detail, the coordination results based on the 2-D diagram in terms of interference and spatial orientation evaluation will be frequently changed in subsequent designs.

As the design process shows, during most of the preliminary design stage and the detailed design stage, the External engineer can only carry out the interface coordination, but cannot officially start the accessory layout and the 3-D routing of the pipeline.

Unlike compressors, combustion chambers and other rotating body structures, 2-D drawings can be used to conveniently express design information, aerodynamic evaluation, and strength calculations; the External requires a 3-D model to carry out spatial orientation evaluation, interference inspection, strength evaluation, assembly analysis, etc. because the pipelines and brackets are intertwined in space.

Since the 3-D model of the whole machine can only be provided in the detailed design stage, the components are usually almost finalized when the external design starts, and the time left for the external design is very tight.

When the interface needs to be changed for optimization, the components usually have already started the verification test, and the cost of change is very high, which affects the freezing of the whole engine model. In many cases, the non-ideal engine configuration is transferred to the next stage, resulting in poor assembly, maintainability and reliability.

In order to improve the efficiency and quality of iterations, it is necessary that each component, especially External, can carry out designs, iterations and evaluations in parallel based on the 3D model.

Different from traditional design, online collaborative design means that technicians of different professions can carry out designs in parallel on the same platform and based on the same model for real-time interaction.

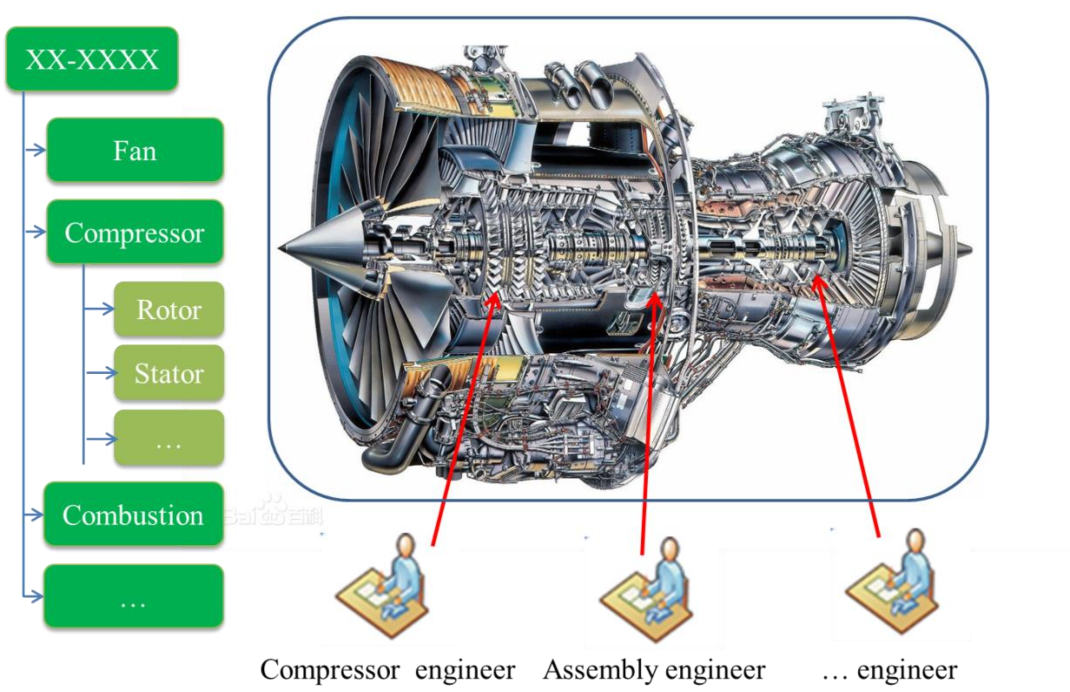

Figure 2 – Model-based online collaborative design

The development of full 3-D digital technology also provides technical conditions for "model-based design" to replace "2-D drawing-based design". MBD (Model Based Definition) technology integrates the geometric structure design information (geometric model, size), production process manufacturing information (geometric tolerance) and product attribute management information. Using it as the only data source in the entire product development process can achieve a high degree of integration of design, process, manufacturing, inspection and other disciplines.

The model-based online collaborative design process is shown in the following figure 3. The conceptual engine model is established by structural integration designer. Based on this conceptual model, structural designers of each component conduct structural iteration, interface refinement and model improvement. The entire design process is simplified into a continuous updating process of the same model, from concept to detail. It reduces the mistakes and omissions caused by poor communication between components (and within components), and improves the design efficiency and quality. The serial design process becomes parallel design process, and traditional data distribution changes into data access, ensuring the uniqueness of the design data.

In the conceptual design stage, based on the component gas flow path and interface, the engine coordinate system and the component coordinate system are established to form the shape of the component and the main part.

Based on the scheme design of each component, the engine layout, the basic outline dimensions, and the preliminary structure scheme of each component are formed, including the preliminary scheme of the load-bearing system, the layout scheme of the accessory, and the main structure forms of the components, etc.

In the preliminary design stage, based on the technical design and strength evaluation of each component, the component structure scheme, outline size, assembly relationship, main part shape and materials are determined, such as the stator connection scheme, the engine assembly and size.

In the detailed design stage, based on component structure refinement, strength analysis, dimensional chain calculation, the interface type and size, as well as the precise shape, material, dimensional tolerance, surface treatment, manufacturing inspection requirements of all parts would be completed.

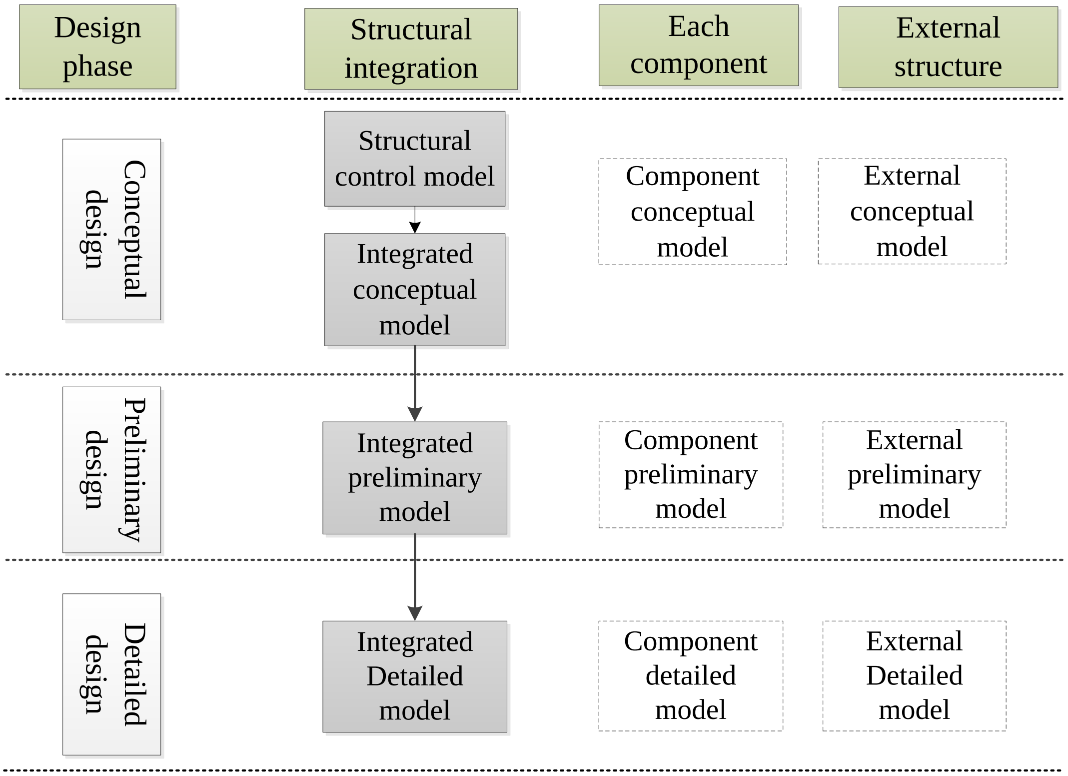

Figure 3 – Model-based online collaborative process

In order to support the up-down structural design, the aircraft skeleton model is used for reference, and the engine control model is introduced to control the interface between each component.

The structure of aero-engines is complex, and there are a large number of geometric relationships between components and parts. Often the change of one model affects several nearby models, and the single parametric definition of the model cannot meet the need for changes in the associated structure caused by the iteration of the design process. Through the establishment of Control Model, the relevant influence and constraints of the upstream design requirements on the downstream design can be realized, and the requirements can be transmitted quickly and accurately.

The control model mainly describes information such as the datum, spatial position, important installation position and partial profile of the key components, serving as the basis for the design and positioning of the component model. It can be geometric elements such as points, lines, surfaces, or topological elements such as points, edges, and surfaces extracted from entities, or entities, depending on specific needs.

With top-down approach, the control model is established and maintained layer by layer by the integral and component engineers. The lower-level control model associates the upper-level control model with the necessary decomposition, and finally and finally controls the associated changes. With the control model to control components boundaries, installation locations, and space occupation, all models are controlled by the engine functional requirements, and the risk of errors and conflicts with adjacent parts is significantly reduced.

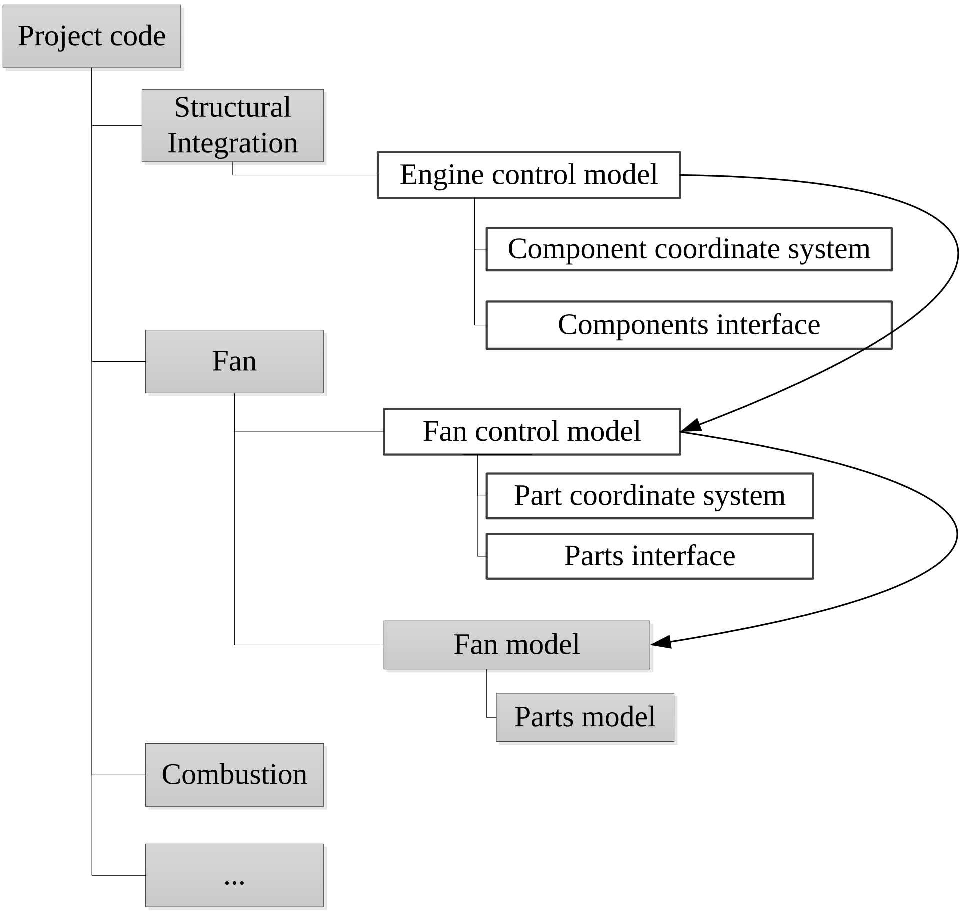

Figure 4 – Control model based up-down collaborative process

Taking the pipeline design as an example, the process of model-based online collaborative design is described.

In the conceptual design stage, the coordinate system of the external is established, which inherited from the coordinate system of the engine.

According to the design input from the air system, the routing path of the air system pipeline can be determined to complete the pipeline layout. As shown in Figure 5, the red pipeline is the seven-stage bleeding air pipeline. The next step is to determine the sealing scheme. Due to the high temperature of the medium, a metal sealing structure is adopted for the air pipeline. Considering reliability and economy, we choose mature standard parts. Some parameters of the sealing parts are as follows:

1) Material: Inconel 718 (AMS5596);
2) Dimensions: the free thickness of the gasket x;
3) Leakage rate: according to the working pressure, the leak rate is required to be no more than y;
4) Compliance verification test: sealing ring life test, sealing performance test (compression rebound curve, leakage rate)

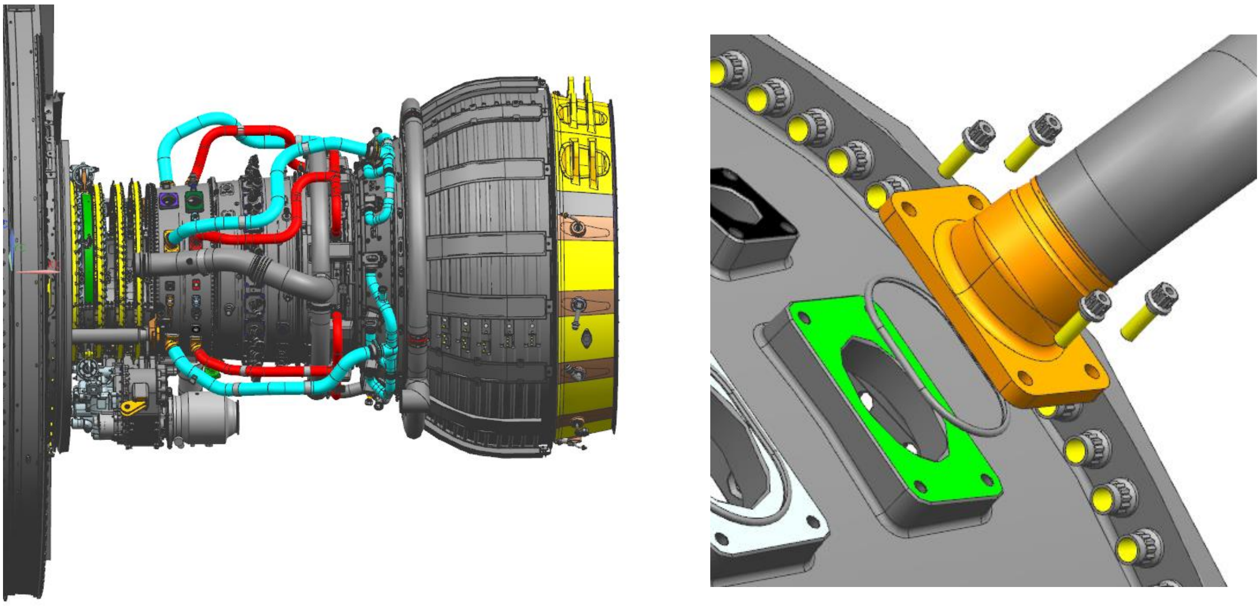

Figure 5 – Conceptual design of air system pipeline

In the preliminary design stage, according to the envelope and interface information, the engine-level control model is completed, as shown in Figure 6. The component-level control model (external control model) waves interface information from the engine-level control model to constrain the pipeline. According to the interface information in the external control model, we can position and complete detailed design of the interfaces at both ends of the pipeline.

After the pipeline design is completed, it is necessary to carry out iterations with the strength team and the assembly team to determine the basic configuration and carry out manufacturability analysis (see section 3.3 for details).

Strength analysis mainly includes: pipeline static pressure analysis, modal analysis, frequency response analysis, etc. In addition, due to the high ambient temperature, it is necessary to carry out thermal stress analysis to evaluate low-cycle fatigue life based on information such as the temperature load of the pipeline components, the thermal expansion of the casing, and the pipeline pressure load.

It is important to note that the strength analysis needs to consider the influence of processing (tube wall thickness reduction) and assembly error (assembly stress). If the strength analysis does not meet the requirements, it is necessary to change the pipeline direction or add the compensation design.

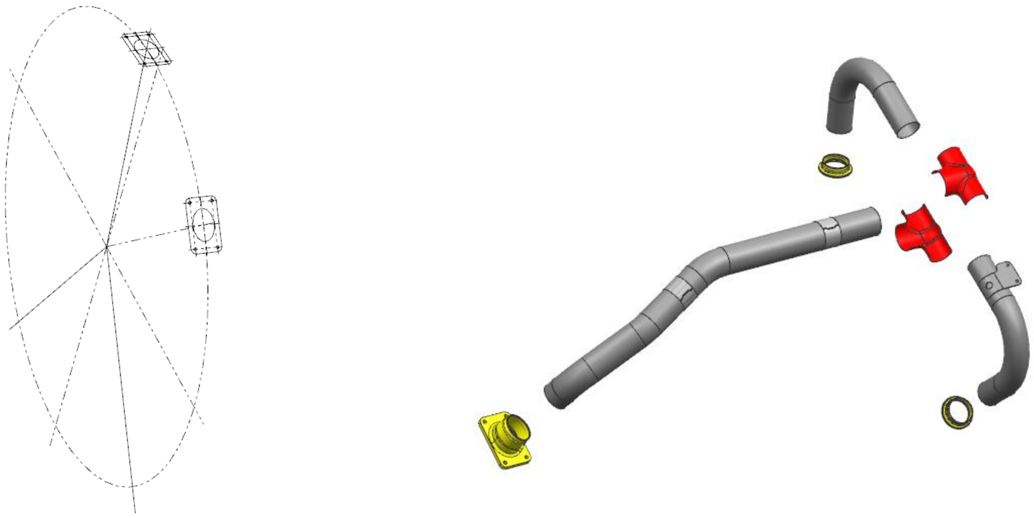

Figure 6 – Preliminary design of air system pipeline

In the detailed design stage, according to the iterative results of assembly analysis, strength evaluation, and manufacturability analysis of all components, the position and tolerance of the interface are determined in the engine-level External control model, as shown in Figure 7. The External engineer complete the structural model according to the updated External control model, complete the PMI marking of the components and parts, and release the design status.

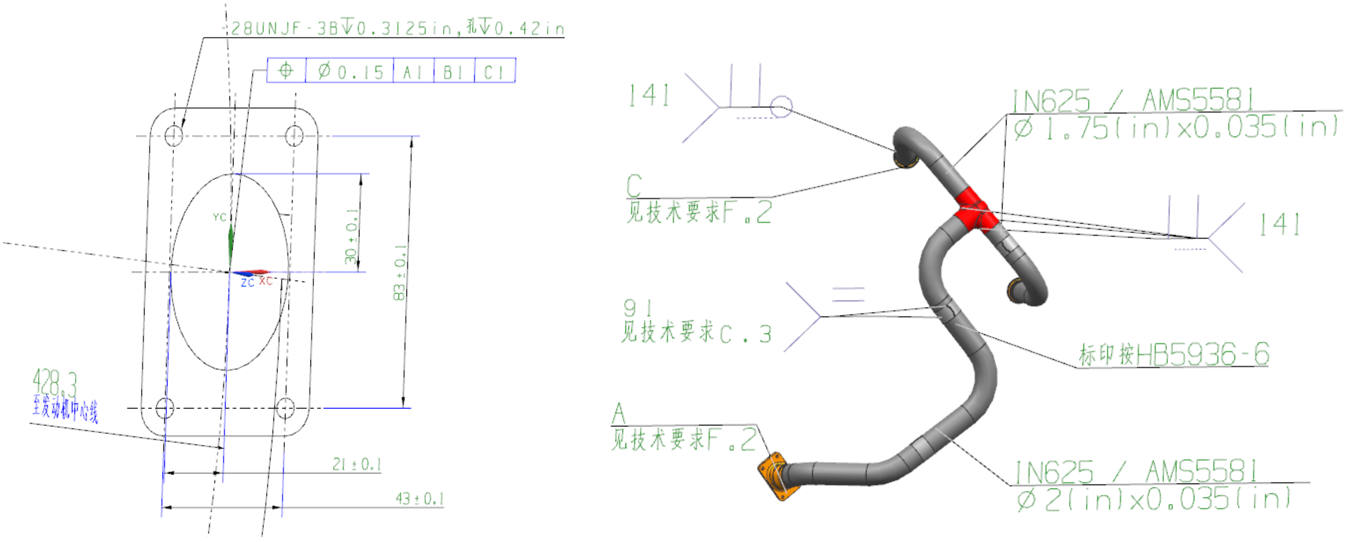

Figure 7 – Detailed design of air system pipeline

3.3 Maturity-based design and manufacturing Concurrent Engineering

Maturity refers to the degree of completeness of the product, which reflects the degree of detail and completeness of the product information at different stages, and facilitates the development of all cross-professional and cross-enterprise collaborative work before the processing and manufacturing stage.

Aero-engines have complex structures, numerous parts, diverse processing techniques, and lots of suppliers. Insufficient coordination between design and manufacturing, leads to inadequate consideration of process issues at development stage. Many design problems are only found during the manufacturing stage, resulting in modification and even manufacturing difficulties, which seriously affects project schedule and cost.

Collaboration between design and manufacturing is very critical for aero-engine development. Design and manufacturing collaboration is mainly based on the idea of concurrent engineering, which allows process designers to participate in structural design as early as possible. Process designers and structural designers work together based on product maturity to achieve manufacturing-oriented design and advancement of process preparation.

Design-manufacturing collaboration mainly includes two aspects: on the one hand, process personnel participate in the product design to ensure that the feasibility and rationality of the process are fully considered at the beginning of product design, and key technical research is carried out when necessary; on the other hand, it is a preparation for manufacturers to understand design ideas as early as possible and start manufacturing in parallel.

On the one hand, there should be process personnel in the design team to provide process support, assisting structural designers to optimize the craftsmanship of products, and finally realize manufacturing-oriented design.

On the other hand, manufacturers can make necessary preparations in advance according to different product maturity, rather than waiting for the final release of design drawings.

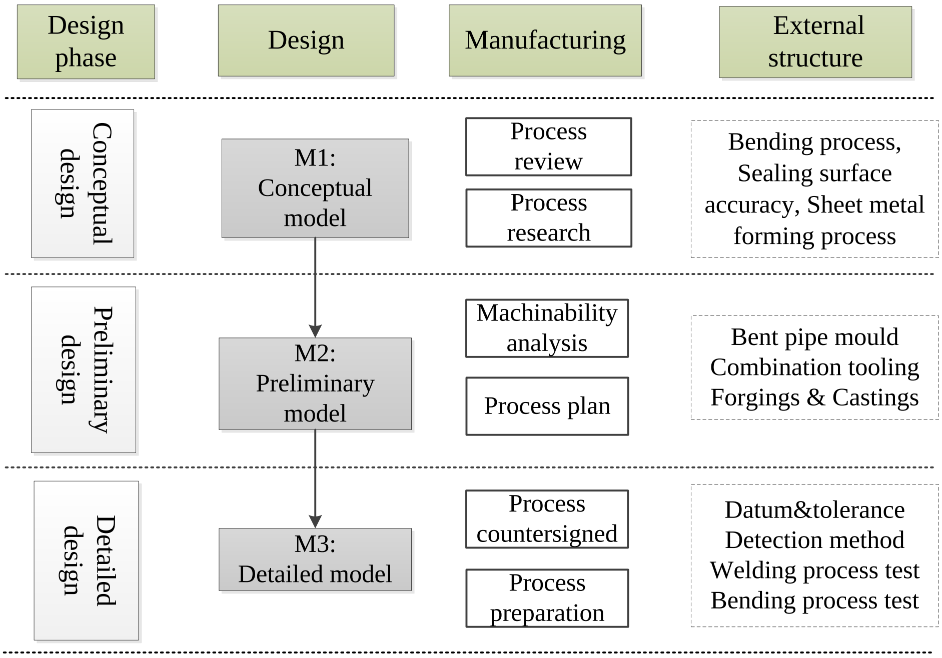

Figure 8 – Maturity-based design and manufacturing Concurrent Engineering

The collaborative process of design and manufacturing based on maturity is shown in Figure 8. In the conceptual design stage, the designer completes the conceptual model (M1) according to the product requirements, which mainly includes the following information: the general direction of the external pipeline, the material range of the parts, surface treatment requirements, pipeline sealing structure, pipeline thermal compensation scheme, etc.

For the conceptual model (M1), the manufacturing supplier inspects the production line of the factory to confirm whether the equipment capacity, the heat treatment line, the welding capacity, or other special process capability can meet the design requirements, and carry out the process research according to the actual situation.

In the preliminary design stage, the designer complete the detailed design based on the interface refinement and strength evaluation, and establish a preliminary model (M2), including precise shapes, materials, dimensional tolerances, etc.

Manufacturing process personnel need to complete machinability analysis, processing difficulty analysis, and process plans:

1) Machinability analysis: including the size and consistency of the pipe bending radius, the length of the straight section, the processing plan of the casting and forging, and the processing cycle;
2) The main process of components: is there a need for molds, forgings and castings, special processes, whether combined processing is required;
3) Purchasing plan preparation, cycle estimation, assembly preparation, preliminary process planning;

In the detailed design stage, the designers complete and release the PMI model. The manufacturer s carry out the process countersignature, MBOM establishment, raw material procurement, detailed preparation of process regulations, tooling design and process verification tests.

Also take the pipeline as an example, collaborative process of design and manufacturing based on maturity is described in Table 2.

Table 2 – Example of collaborative process of design and manufacturing based on maturity

Design stage	Design/ Maturity	Manufacturing
Conceptual design stage	M1: Conceptual model 1) Design plan: the bleed air pipeline adopts tube bending, sheet metal butt welding and fusion welding technology. 2) Part material: tube blank material UNS N06625 or UNS S321, 2in outer diameter, 0.035in or 0.028in wall thickness; 3) Surface treatment: no need for passivation, fluorescence, heat treatment; 4) Sealing scheme: the pipeline and casing are sealed with metal gaskets; 5) The pipeline adopts a large bending angle for thermal compensation (90 degree bend); 6) 6) Special process plan (none, the bending radius is estimated to be 2D, the pipeline length is estimated to be 1.5 meters)	Process review, process research, and production line evaluation: 1) Equipment capacity (CNC pipe bender can process 625 and 321 pipe fittings); 2) No surface treatment requirements; 3) The production line is capable of sheet metal forming, pipe bending, component welding and testing capabilities; 4) AS1895 flange welding requires a flatness of 0.1, and the factory has welding ability (notes for processing sealing parts); 5) There is no special process, the overall pipeline shape is guaranteed by tooling, and the tooling is checked. There is no problem with the 2D bending of the 2in pipeline;
Preliminary design stage	M2: Preliminary model 1) Conduct: UNS N06625, φ2inX0.035in, φ1.75inX0.035in; bending radius: 2D 2) Tee: sheet metal material UNS N06625; 3) Joints: rectangular flange, round flange 4) Sealing: metal C-ring seal, metal E-ring seal	Machinability analysis, process plan formulation 1) Pipeline manufacturability (bending radius 2D, straight section 100mm, 5 bends, equipment capacity meets requirements) 2) Component process (bending, sheet metal forming, welding, X-ray, hydraulic test, shape correction, etc.) 3) Part manufacturability (mechanical processing, non-forging castings) 4) Estimated processing cycle (4

Design stage	Design/ Maturity	Manufacturing
		weeks for parts processing, no special technology, 2 weeks for raw material procurement, 4 weeks for component processing, and estimated total cycle time of 10 weeks)
Detailed design stage	M3: Detailed model (PMI model) 1) Technical requirement F.2 2) Technical requirement C.3 3) Processing requirements 4) Inspection requirements	Process countersignature, process preparation work 1) MBOM construction; 2) Preparation of raw material procurement quota; 3) Tooling mold design; 4) Preparation of process specifications (bending process test, welding process test); 5) Product scheduling and processing;

With concurrent engineering based on model maturity, design and manufacturing engineers can fully communicate with each other. New process requirements would be identified in time and the processing difficulties would be solved as soon as possible. It will significantly save development cycle, reduce project risk, and improve processing efficiency.

4. Conclusion

In order to solve problems of aero-engine development, a model-based collaborative design process is established. This process is based on MBD method, Structural control model, Top-down approach and maturity-based design and manufacturing concurrent engineering.

Through the initial application, the design iteration efficiency can be significantly improved and the development cycle can be shortened.

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