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Formulating Strategy and Technical Path for the Next-Generation Airworthiness Regulations of Aero-Engines

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Abstract: Airworthiness regulations are key for guaranteeing the safety of civil aviation products and are a significant indication of a nation's aviation power. A well-developed airworthiness regulation system is an effective technical and management means by which a country with an advanced aviation industry ensures the safety of its civil aviation products and occupies the broadest market share while complying with International Civil Aviation Organization (ICAO) rules. As major national science and technology projects for large aircraft, aero-engines, and gas turbines are implemented, it is imperative for China to further improve its airworthiness regulation system. In this study, we clarify the implications of aero-engine airworthiness regulations and summarize the problems regarding aero-engine airworthiness regulations, both in China and abroad. A formulating strategy and technical path for next-generation airworthiness regulations of aero-engines are then explored from the perspectives of the ICAO and China's civil aviation industry. The formulation strategy emphasizes the requirement for system safety, and specific principles include equivalence in safety, clarity in logic, international compatibility, and domestic applicability. Moreover, a new top-level framework for aero-engine airworthiness regulations is proposed. This framework inherits the international lessons learned, ensures a high safety standard, and can adapt to the progress of system safety technologies for aero-engines. Furthermore, we suggest that China should continuously deepen the level of research, synchronously expand the application, and synergetically develop the industry, thus promoting the construction of a robust aero-engine airworthiness regulation system in China.
Keywords: next-generation airworthiness regulations; aero-engines; new regulation framework; system safety requirements

1 Introduction

In 2018, the *Action Plan for Building a Strong Civil Aviation Country in the New Era* issued by the Civil Aviation Administration of China (CAAC) pointed out that, achieving the goal of building China into a strong civil aviation power requires focusing on eight major tasks, including strengthening the dominance and discourse power in formulating international civil aviation rules and standards, and cultivating the innovation ability to lead the development of the international civil aviation industry [1]. Throughout history, dominance and discourse power in international civil aviation standards have always been the highest level of competition among the

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world's civil aviation powers, as well as one of the fields with the fastest development. Therefore, having discourse power and initiative in standards is crucial for us to contribute to human safety.

Airworthiness regulations hold an important strategic position in China. They comprise the core guarantee for the safety of civil aviation products, being an important component of the civil aviation industry in developing core competitiveness, an important indication of a nation's aviation power, and the key to the successful implementation of major science and technology projects of large aircraft, aero-engines, and gas turbines. All civil aviation powers worldwide have placed the construction of airworthiness regulations at an extremely important strategic level and have expanded their influence to the maximum extent. At present, the United States, Europe, and China have established the world's most influential airworthiness regulation systems, namely, the Federal Aviation Regulations (FAR) of the U.S. Federal Aviation Administration (FAA), the Certification Specifications of the European Aviation Safety Agency (EASA), and the China Civil Aviation Regulations (CCAR) of the CAAC. Starting from the generation of the *Aircraft Engine Airworthiness* (CAR-13), the predecessor of the *Airworthiness Standards: Aircraft Engines* (FAR-33) in 1937, the aero-engine airworthiness regulations of the United States undergone thirteen revisions of CAR-13 and thirty-four revisions of FAR-33 before the latest amendment of the current FAR-33 [2] was finally formulated. The aero-engine airworthiness regulations in Europe can be traced back to the British Civil Airworthiness Requirements developed in 1926. Since the emergence of the *Joint Aviation Requirements for Engines*, the predecessor of the *Certification Specifications for Engines* (CS-E), this document has undergone twelve revisions and CS-E has now undergone six revisions before the latest amendment of the current CS-E came into shape [3]. China's aero-engine airworthiness regulations mainly refer to FAR-33 of the FAA. The first version of CCAR-33 was issued on February 9, 1988, and is technically equivalent to the amendment 33-11 of FAR-33. After that, it was revised twice on March 20, 2002, and March 15, 2011, and now CCAR-33R1 is technically equivalent to the amendment 33-20 of FAR-33, and the current effective CCAR-33R2 [4] is consistent with the amendment 33-30 of FAR-33 at the safety level. Overall, airworthiness regulations play a significant role in improving safety levels of aviation products.

Statistics show that, since the 1970s, the incidence of aircraft operation accidents has decreased to an improved safety level and has gradually stabilized. However, with the rapid growth in air traffic in recent years, the absolute number of aircraft operation accidents has also risen significantly, which is unacceptable to the public. Therefore, with the growth in air traffic, further reducing the incidence of accidents and increasing the safety level of civil aviation products are needed.

With the aim of improving safety, enhancing the economy, encouraging competition, and promoting technological progress to boost prosperous and sustainable development of the global aviation industry, we conducted an in-depth analysis of the technical connotation of aero-engine airworthiness regulations, systematically combing through the prominent problems existing in current aero-engine airworthiness regulations in China and abroad. Research was conducted on the formulating strategy and technical path for the next-generation airworthiness regulations of aero-engines from the two perspectives of the International Civil Aviation Organization (ICAO) and China's civil aviation industry. Finally, we put forward suggestions for a Chinese plan for next-generation airworthiness regulations.

2 Three implicit requirements of aero-engine airworthiness regulations

Existing aero-engine airworthiness regulations are continuously revised and formed under the framework of ICAO rules through the accumulation of industrial practice experience over a long period of time; by drawing experience and lessons from the application process; and through necessary demonstration, verification, and public consultation. The underlying technical requirements include the following three main aspects: minimum safety standard requirements, development process assurance requirements, and entire lifecycle requirements.

2.1 Minimum safety standard requirements

Aero-engines are mainly divided into generations according to their safety level in the airworthiness field. The FAA divides civil high-bypass-ratio turbofan engines into generations according to whether their type design reflects learning from the experience and lessons of relevant operating events. The first generation is defined as the turbofan engines designed in the late 1960s. The second, third, and fourth generations are all defined as the turbofan engines [5–7] with the understanding and incorporation of lessons learned from the previous generation (Table 1). The core of the FAA's generational division is "lessons learned". First, the lessons are identified through the analysis of the root causes of unsafe events in operation. Then, the lessons are converted into

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experience through the formulation and revision of regulations or explanatory documents, policy guidance documents, etc. Finally, the experience is absorbed through the design implementation and compliance verification of the engine. The first generation of high-bypass-ratio turbofan engines was in the "comprehensive birth period" (the late 1960s to the late 1970s), and the emergence of engines represented by JT9D, CF6, and other types marked the arrival of the era of civil high-bypass-ratio turbofan engines. During this period, the FAA was established, and it reedited and rearranged CAR-13 comprehensively and formed an amendment 33-0 of FAR-33. Currently, the provisions of airworthiness regulations are mainly based on experience. The second generation of high-bypass-ratio turbofan engines entered the "period of rapid development" (the early 1980s to the early 1990s). With the rapid development of civil engine design technology, a series of civil high-bypass-ratio turbofan engines appeared, represented by CFM56, V2500, PW4000, and other types. FAR-33 accordingly underwent two large-scale revisions, including the first introduction of low-cycle fatigue, electronic control systems, safety analysis, and other provisions. At this time, system safety requirements were introduced into the airworthiness regulations. The third and fourth generations of high-bypass-ratio turbofan engines entered the "period of fine design and integrated development" (the early 1990s to the early 2000s), with the appearance of high-bypass-ratio turbofan engines represented by GE90, GEnx, the Trent family, and other types and various advanced civil engine design technologies emerging one after another. With the rapid development of system safety technology, airworthiness regulations have gradually become both systematic and empirical. Simultaneously, after the founding of EASA and the publication of its CS-E regulations, FAA and EASA started a harmonization path of airworthiness regulations. This continuous development of aero-engine airworthiness regulations fundamentally represents the gradual improvement of their minimum safety standards, that is, the gradual improvement of the minimum safety level of certified engines that meet the requirements of the airworthiness regulations.

Table 1. Generational division of high-bypass-ratio turbofan engines by FAA.

Generations [7]	Definitions [7]	Typical engine types [7]	Scope of FAR-33 amendments of the certification basis	Characteristics of typical airworthiness requirements
First generation	Those designed in the late 1960s.	JT9D、RB211-22B、CF6-6、CF6-50、CF34-3	33-4 and earlier (with a few 33-9)	FAA was established, and CAR-13 was recodified into FAR-33.
Second generation	Those designed in the 1980s with the understanding and incorporation of lessons learned from the first generation.	ALF502、ALF507、AE3007、CFE738、CF34-8、TFE731-20/40/60、CF6-80、CFM56-2/-3/-5、V2500、PW2000、RB211-535C、RB211-524B4、Tay、PW4000 94″	33-4 to 33-15 (With a few 33-19 or 33-20)	Underwent two large-scale revisions of regulations. Typical changes in provisions included: the introduction of low cycle fatigue requirements of rotors, electronic control system requirements, safety analysis requirements, foreign object ingestion requirements, etc.; the verification requirements for rotor containment were modified.
Third generation	Those designed to incorporate the lessons learned from the second generation.	GE90-94″/115″、CFM56-7、CF34-10、PW4000 100"/112"、PW6000、Trent 500、Trent 700、Trent 800、BR710、BR715	33-15 to 33-20	The harmonization process of FAA and EASA regulations was started. Typical changes in provisions included: the environmental adaptability requirements for foreign object damage were refined, and separate provisions for bird, rain and hail ingestion were established.
Fourth generation	Those designed to incorporate the lessons learned from the third generation.	GEnx、GP7000、Trent 900、Trent 1000、BR725	33-20 and later	Further refined and improved the requirements of provisions: comprehensively refined the safety analysis requirements; set higher safety level requirements for bird ingestion and icing environment; introduced for the first time the requirements for the Extended-range Twin-engine Operational Performance Standards (ETOPS); requirements were added for damage tolerance assessment of life-limited parts, transient fuel icing, composite fan blades, Single Event Effects, model-based development methods and tools, etc.

2.2 Development process assurance requirements

By taking the control system, a typical internal system of the aero-engine, as an example, the most revolutionary change in the engine control system in the late 20th century was the transformation from hydro-mechanical control to digital electronic control. With the increasing complexity of aircraft engine electronic control systems and other systems, the possibility of engine electronic control systems failure directly or indirectly caused by design errors increases significantly, and the design and analysis technology traditionally applied to deterministic risks or traditional noncomplex systems cannot provide a sufficient safety guarantee for complex systems. Therefore, the development process assurance based on demand, development, and system safety design and verification has become an effective method for aircraft/engines and their systems, thereby solving the problems caused by the increasing system complexity and meeting the safety objectives of engine airworthiness regulations. The essential technical connotation of aero-engine safety design is to design and verify complex engine systems and to perform safety analysis and verification matching with engine development activities according to the double “V” systems engineering (Fig. 1) of the SAE ARP4754A [8] and SAE ARP4761 [9] standards established by the Society of Automotive Engineers. Currently, EASA has, in its recent aero-engine-type certification projects, officially determined the EUROCAE ED-79A standard of the European Organization for Civil Aviation Equipment (the European standard corresponding to SAE ARP4754A) as the means of compliance for the development process assurance and safety requirements of the airworthiness provisions related to engine control systems and safety analyses. Therefore, aero-engine airworthiness regulations essentially imply the requirements for development process assurance accompanying the safety design of the engine system.

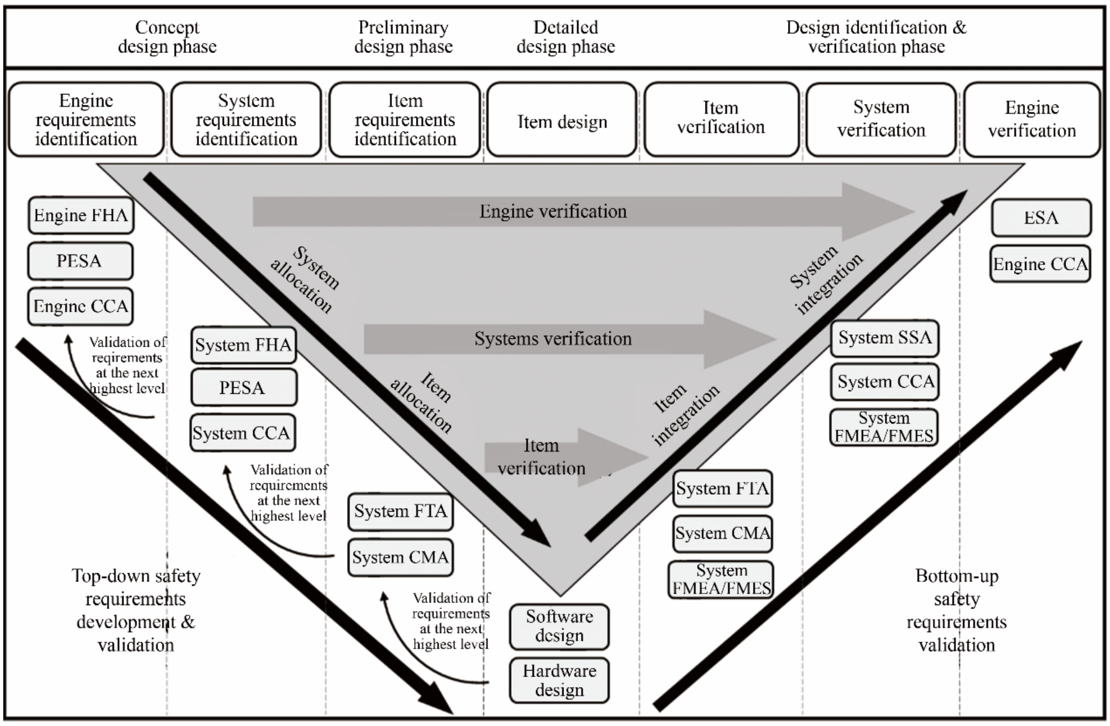

Fig. 1. Interaction between safety and development processes for aero-engines (Re-plotted from associated graph in [8]).

*Notes***:** FHA: functional hazard assessment; PESA: preliminary engine safety assessment; CCA: common cause analysis; PSSA: preliminary system safety assessment; FTA: fault tree analysis; CMA: common mode analysis; FMEA: failure mode and effect analysis; FMES: failure mode and effect summary; SSA: system safety assessment; ESA: engine safety assessment.

2.3 Entire lifecycle requirements

Airworthiness management is technical management that aims to ensure the safety of civil aviation products. Based on formulating a variety of minimum safety standards, it entails scientific and unified review, appraisal, supervision, and management of the design, manufacture, verification, service, and maintenance related to the entire lifecycle safety of civil aviation products to ensure that civil aviation products achieve and continue to maintain a safe and usable state. Although aero-engine airworthiness regulations are mainly applied to the initial airworthiness stage, their provisions involve various activities aimed at ensuring the safe operation of the engine, such as design, manufacture, verification, service, and maintenance, throughout the lifecycle of the aero-engine. For example, in China’s current effective Aero-Engine Airworthiness Regulations (CCAR-33R2) Section 33.4 “Instructions for continued airworthiness” and Section 33.5 “Instruction manual for installing and operating the engine,” both specify the relevant requirements related to safety in the process of operating and maintaining the engine. FAA Advisory Circular for Section 33.28 “Engine control systems” [10,11] specifies that software and

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complex electronic hardware shall complete the development process assurance activities of the entire life cycle respectively in accordance with the standards of RTCA DO-178 [12] and RTCA DO-254 [13] of the Radio Technical Commission for Aeronautics. Section 33.70 “Engine life-limited parts” requires that corresponding engineering, manufacturing, and service management plans be formulated to ensure that the engine structural parts have sufficient low cycle fatigue life, thereby preventing the occurrence of seven top events that could result in hazardous engine effects caused by the failure of life-limited parts, including noncontainment of high-energy debris and uncontrolled fire during the operation of the engine. In addition, when performing the engine compliance verification test, it is necessary to fully consider the structural and performance degradation in the operating process to prove that the entire engine and its systems and components meet the design expectations in terms of their functions and durability within the expected operating envelope and service limits of the entire lifecycle and can continue to operate safely.

3 Problems existing in current aero-engine airworthiness regulations

3.1 Major international problems

FAR-33 and CS-E are currently the most representative aero-engine airworthiness regulations worldwide. With the promotion of major international engine manufacturers, the terms and contents of FAR-33 and CS-E have gradually converged, but their frameworks have always maintained their own characteristics. However, FAR-33 and CS-E both have great historical burdens. While constantly evolving, they are also experiencing crises.

3.1.1 The airworthiness regulation framework has been unfit for the requirements of system safety technological progress, and it is difficult to implement system safety requirements.

With the rapid development of system safety technology, the system safety requirements of aero-engine airworthiness regulations have undergone a process of change from nothing to something and from qualitative to quantitative. In 1974, FAR-33 introduced the qualitative requirements of 33.75 “Safety analysis” [14] and, in 2007, Section 33.75 further added the quantitative requirements for the probability of occurrence of hazardous top events [15], which marked a significant transformation of aero-engine airworthiness regulations from experience-oriented in the past to the coexistence of systematicness and empiricism. However, under the double constraints of the FAA’s legal rigor and the historical burden of the logical structure of the regulations, the logical structure of FAR-33 remains in its early state. In addition to Section 33.75, other quantitative system safety requirements are scattered in the revision of other airworthiness provisions because of the limitation of the original framework, resulting in an increasing number of overlapping contents among the provisions of FAR-33, making it difficult to implement system safety requirements in practice.

3.1.2 The airworthiness regulation framework is not suitable for the development of aero-engine technology and lacks the flexibility to adapt to new technologies and innovations.

Driven by the experience and lessons from accident cases, the application of new technologies, technological progress in safety analysis, international consistency promoted by aero-engine manufacturers, and other factors, FAR-33 and CS-E regulations have undergone multiple amendments or revisions. Restricted by the framework of early airworthiness regulations, the process of regulation revision has witnessed an increasing number of interrelated and overlapping contents among provisions with the aim of ensuring their self-consistency and completeness, and regulations have thus become increasingly cumbersome. In addition, with the continuous development of aviation power technology, especially the emergence of new power technologies, such as open rotors, electric propulsion, and hybrid power, the design features of aero-engines have changed significantly. The existing regulations and provisions, especially those based on means of compliance, cannot adapt well to the latest aero-engine design features and technical level and lack the flexibility to accommodate the development and innovation of new technologies, which adds extra burden to the work of airworthiness certification and obtaining airworthiness certificates.

3.2 Major domestic problems

FAR-33 and CS-E have evolved in the background the industrial standards of Europe and the United States, whose division of provisions and technical requirements are compatible with their industrial systems. For Russia, China, and other late starters in civil aero-engines, there is an objective problem of maladjustment. With specific local industrial systems and industry characteristics, late starter countries are facing problems such as insufficient basic accumulation and lack of compliance indication when they are conducting design, manufacture, verification, review, and maintenance of aero-engines under the aero-engine airworthiness regulation framework modeled upon FAR-33 and CS-E.

3.2.1 The accumulation of local data makes it difficult to support the airworthiness design and compliance indication of current regulations.

To demonstrate the provision compliance of current regulations, such as 33.15 “Materials,” 33.70 “Engine life-limited parts,” and 33.75 “Safety analysis” of CCAR-33, a large amount of material data and component reliability data will be used. These data can be obtained under the European and American data accumulation mechanism, and, with the long-term serial development of European and American civil engines, the database is growing. For late-starter countries, because the local industrial systems and industry characteristics are not very compatible with European and American regulations, their local data accumulation may be insufficient or nonstandard in meeting the requirements of current regulations, resulting in great difficulties in demonstrating the airworthiness of self-developed or co-developed civil engines using European and American methods. More importantly, without the feedback obtained after commercial operation, it will be difficult to form a sustainable development situation for civil aero-engines.

3.2.2 The innovation of local safety design and airworthiness compliance indication means is in urgent need of reform within the regulation framework.

The late starter countries were relatively late in developing their civil aviation industry, and their amount of technical accumulation of the part of requirements development on the left side of the “V” in Fig. 1 is relatively small. In particular, they have not fully mastered the allocation method from system safety requirements to subsystem and component safety requirements, and the safety requirements fail to be integrated into and run through the entire aero-engine design process. While taking a systematic and in-depth study on the safety design and airworthiness compliance indication means and gradually improving the data accumulation mechanism, we should make full use of the existing local development experience data and innovative research results, explore new means and ways for safety design and airworthiness compliance indication, and gradually form an airworthiness regulation system that is compatible with the local industrial level and technical characteristics. This is the only way to alleviate the current situation of “following” and “learning from” European and American airworthiness regulations. However, the framework design of the existing regulations, especially some “prescriptive-based” provisions and requirements (i.e., whose means of compliance and determination criteria are specified), to a certain extent, restricts the innovation of safety design and compliance indication means, and it is imperative to reform the aero-engine airworthiness regulation framework.

3.2.3 Research on the substantive safety intent and basic principles of airworthiness regulations promotes the reform of the regulation framework.

Promoted by their local civil engine airworthiness certification projects, late-starter countries have accumulated considerable experience in airworthiness regulation research and practice. In the early stage, this research and these practices mainly focused on the requirements of the existing regulations and provisions in Europe and the United States and their means of compliance and technologies, yet there remains a lack of targeted and systematic research on substantive safety intent and the basic principles hidden behind those provisions. As a result, the basic theories related to airworthiness are disconnected from engineering problems and technical standards, and the existing local aero-engine basic research reserves and engineering practice data cannot give full play to their due roles in actual type certification, especially in proposing new means and ways to indicate airworthiness compliance. This directly hinders the process of type certification of domestic civil engines and the independent formulation and revision of regulations. With the continuous enrichment and accumulation of practical experience in the development of civil engines, late starter countries have begun to emphasize the systematic and in-depth study of substantive safety intent and basic principles of airworthiness regulations, thereby further promoting the optimization and reform of the framework for airworthiness regulations of aero-engines.

In summary, to adapt to the major progress of the aero-engine industry in system safety technology, promote the healthy development of the global civil aero-engine industry, and solve problems such as the incompatibility between the technical requirements of airworthiness regulations and the local industrial system and industry characteristics in late starter countries, it has become a top priority to conduct research on the next-generation airworthiness regulations of aero-engines and to reorganize the framework for aero-engine airworthiness regulations in accordance with the latest understanding and progress of the industry.

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4 Formulating strategy and technical path for the next-generation airworthiness regulations

Research on next-generation airworthiness regulations for aero-engines needs to be conducted from two perspectives. First, from the perspective of the ICAO, the future image of aero-engine airworthiness regulations needs to be examined. In view of the problems existing in current international mainstream aero-engine airworthiness regulations, a Chinese plan for future international engine airworthiness regulations should be formed to address the needs in the development of technology, legislation, and industry and to promote the healthy development of the civil aviation sector around the globe, including China. Second, from the perspective of China's civil aviation industry, in view of the current problems facing domestic civil engines in obtaining airworthiness certificates and going through airworthiness certification, the entire industry should coordinate and interact to collectively achieve a robust pattern in which airworthiness standards are deeply integrated in coordinated development with basic research and engineering practices, gradually form an airworthiness regulation formulation and revision system that meets the needs of China's civil aviation development, and actively support the sustained and high-quality development of China's civil aviation industry.

4.1 Formulating strategy

To address the problems confronting current international and domestic aero-engine airworthiness regulations, we put forward the regulation formulating principles of "equivalence in safety, clarity in logic, international compatibility, and domestic applicability."

4.1.1 Equivalence in safety

Always adhere to the core elements of airworthiness. Namely, we need to ensure the safety of civil aviation products, strictly observe the minimum safety level of civil engines represented by aero-engine airworthiness regulations, which ensures that the safety level of the new regulations is not reduced compared with that of the existing regulations, and consider economic efficiency based on ensuring the safety level.

4.1.2 Clarity in logic

Under the guidance of system safety, it is necessary to replan and reorganize the top-level framework setting and ways of provision division of the regulations. The difficulties in airworthiness technology and management, such as operational limitations, equivalent level of safety, and exemption, should be integrated to achieve a clearer logic in the overall framework of the regulations.

4.1.3 International compatibility

Establish a mechanism that promotes compatibility with the industrial systems of other countries. Opinions and suggestions should be regularly solicited from aero-engine research, development, and production enterprises around the globe. This will enable formulation of a regulation system with "one core and multiple expressions" and eventually achieve international mutual recognition of the new regulations.

4.1.4 Domestic applicability

In close combination with the existing and ongoing civil aero-engine development practices in China, and in accordance with the characteristics of domestic research, development, and production, different acceptable means of compliance with a level of safety equivalent to those of the existing regulations and provisions should be formed. This will enable compatibility between the regulations and China's industrial level and technical characteristics to be gradually realized.

4.2 Technical path

Based on the principles of equivalence in safety, clarity in logic, international compatibility, and domestic applicability, general guidelines can be adopted in which the top-level framework is designed first to guide the formulation and revision of various technical provisions and then further improve the establishment of the airworthiness regulation system, which includes regulations and explanatory documents. The specific technical path is described in the following.

4.2.1 Top-level framework design

Guided by system safety requirements, the mode of "safety analysis requirements and other requirements in parallel" in current FAA and EASA regulations would be adjusted to a new regulation framework "guided by system safety requirements" (Fig. 2). Meanwhile, provisions of Section 33.75 "Safety analysis" of the existing

CCAR-33 regulations would be incorporated into the section of system safety requirements, with safety-analysis-related events of other provisions being extracted and integrated into the overall framework of system safety requirements. Other existing provisions would be logically reorganized under the premise of equivalent safety standards.

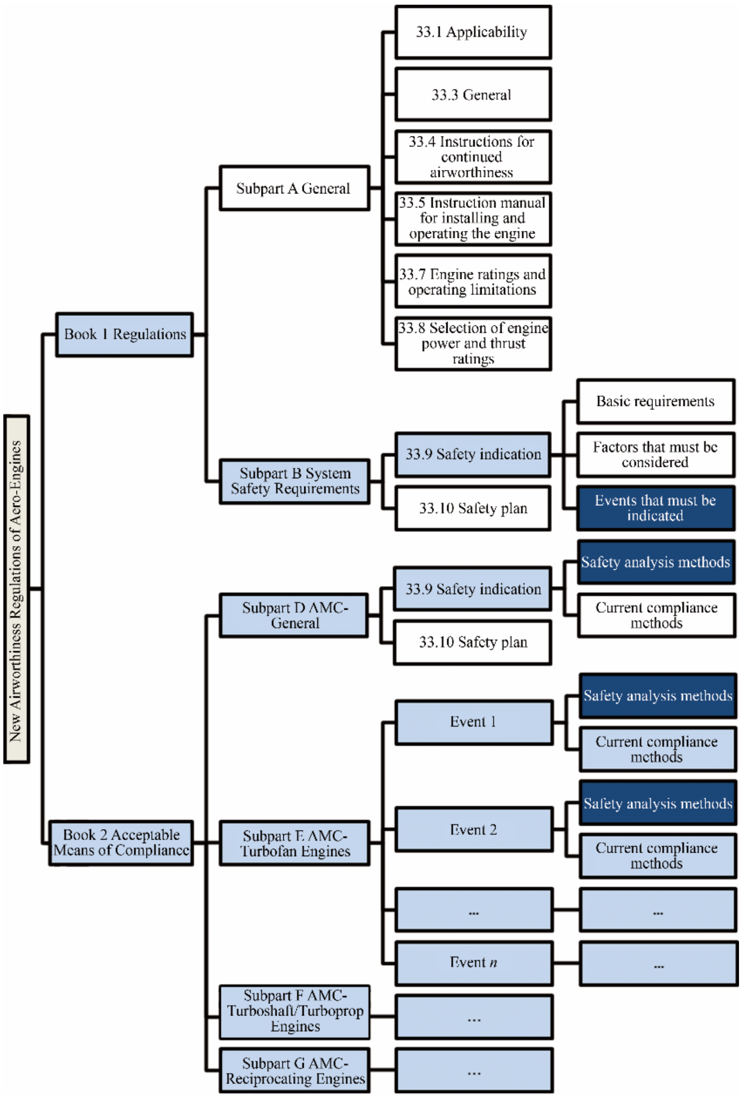

Fig. 2. Proposed new framework for airworthiness regulations of aero-engines.

The requirements and means of compliance would be expressed separately. The regulation framework would be reorganized in the form of “regulations + acceptable means of compliance”. The contents of existing regulations and provisions would be sorted and divided into parts based on requirements and those based on means of compliance. The system safety requirements in Book 1 “Regulations” mainly include the contents of provision requirements. “Performance-based” expressions would be adopted (i.e., only the safety results that must be achieved would be specified, rather than the means to achieve the results), the results of the safety objectives would be focused upon, and the requirements would provide flexibility while ensuring that the safety standards are not reduced. Book 2 “Acceptable Means of Compliance” mainly contains the contents of methods of compliance of the provisions. In it, “prescriptive-based” expressions would be adopted. The book would lay particular emphasis on ways and means to achieve safety objectives, which are presented separately according to different engine types.

The external interface remains unchanged. Having fully considered the interrelationship between CCAR-33 regulations and other management and technical airworthiness regulations, such as the impact on relevant provisions of CCAR-21, CCAR-23, CCAR-25, CCAR-27, CCAR-29, CCAR-35, and other regulations, research

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would be conducted synchronously in combination with the formulation and revision of these regulations to ensure consistency or compatibility with the interface of other regulations and provisions.

4.2.2 Setting of provisions

The safety intent would become explicit, whereas the safety level would not be reduced. The substantive safety intent behind the provisions would be deeply explored and then re-sorted and converted into the events that must be indicated in Section 33.9 "Safety indication" in system safety requirements, which are itemized in the form of provision requirements, thereby ensuring a level of safety equivalent to current airworthiness regulations. However, possible safety-related top events not covered by the existing regulations can be derived through system safety analysis to ensure that the safety level of the regulations is not reduced, as shown in Fig. 3.

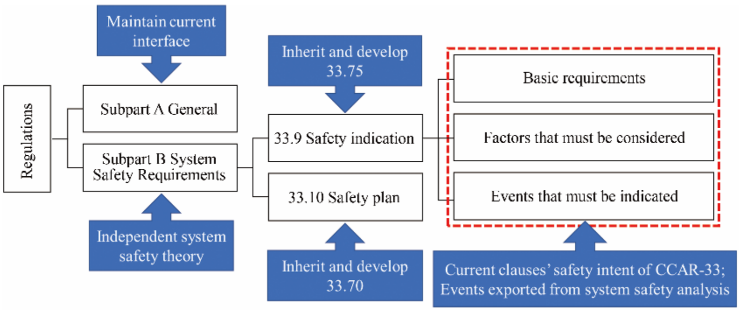

Fig. 3. Proposed new framework for airworthiness regulation of aero-engines (Book 1).

The number of ways of compliance indication would be increased to provide flexibility without lowering safety standards. The requirements of the existing CCAR-33 provisions that essentially provide the means of compliance would be reorganized, and one of the acceptable means of compliance would be given one by one for the corresponding events that must be indicated in the provisions of Section 33.9 "Safety indication," thereby ensuring that the safety standards of the regulations are not lowered. However, for the events that must be indicated, their safety can also be ensured from the perspective of the occurrence probability of top events through system safety analysis methods. Therefore, corresponding to all events that must be indicated, there are three ways to indicate compliance (Fig. 4): (1) methods of compliance derived from current regulations, (2) methods of compliance of safety analysis, and (3) a combination of the above two methods. The three methods are equivalent under the premise of ensuring the same level of safety and simultaneously providing a new degree of flexibility for adapting to the development and innovation of new aero-engine technologies.

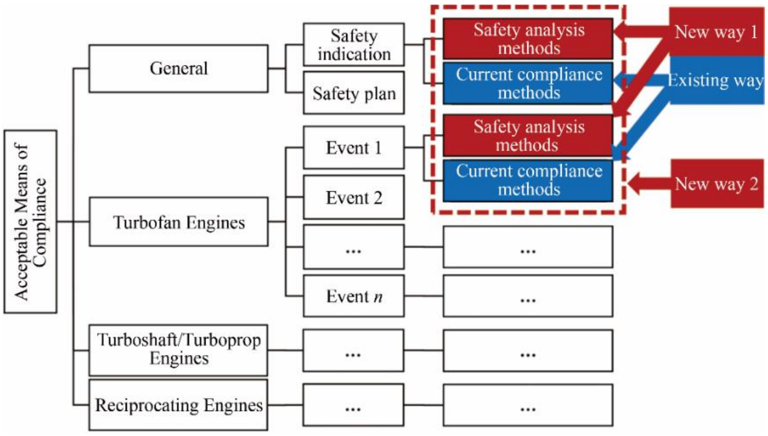

Fig. 4. Proposed new framework for airworthiness regulation of aero-engines (Book 2).

The provisions would make full use of the existing experience in Europe and the United States and strictly ensure equivalence of safety standards. This would entail a comprehensive and systematic study of FAA and EASA airworthiness regulations, explanatory documents, policy guidance documents, and others, reflecting the current international experience and lessons in the development and operation of aero-engines. The information gathered would then be analyzed and transformed into compliance verification means under the new regulation framework. It would later be incorporated into the framework of acceptable means of compliance divided by different engine types and events that must be indicated and thus strictly ensure that the safety standards of the new regulations are equivalent to those of the existing airworthiness regulations.

The provisions would closely integrate with domestic development practices and strengthen the local applicability and anti-monopoly restrictions of regulations. Domestic applicants would conduct in-depth research on means of compliance, enhance technical accumulation, and indicate compliance in strict accordance with airworthiness regulations. Meanwhile, when the engine type design and compliance verification activities cannot strictly follow the existing path and indicate compliance with specific provisions of current regulations, the current domestic experience and data related to the design, manufacture, verification, service, and maintenance of civil aviation engines can be used to summarize and refine them in combination with the actual domestic situation and form the requirements and their compliance verification means with a level of safety equivalent to current regulations and provisions. The requirements and acceptable means of compliance with the new regulations and provisions would be incorporated by considering economic efficiency while ensuring the safety level, enhancing the local applicability and anti-monopoly restrictions of the regulations, and boosting China's international discourse power and influence in civil aviation standards formulation.

4.3 Comparison of regulation frameworks

By considering the formulating strategy and technical path for next-generation airworthiness regulations, the framework differences between new and current regulations are mainly reflected in four aspects.

4.3.1 General context

Current regulations are mainly divided into chapters and sections according to the engine type, provision requirements, or type of means of compliance; the new regulation framework, led by the system safety ideology, would be divided into chapters and sections under the guidance of system safety requirements.

4.3.2 Reflection of safety intent

The safety intent of the provisions of current regulations is mainly hidden behind the provisions and is not clearly reflected in the contents of the provisions; the new regulation framework would make the safety intent of the provisions fully explicit.

4.3.3 Methods of compliance

The methods of compliance with current regulations have poor selectivity (in fact, there is only one way designated by the regulations). The new regulation framework, in addition to the method of compliance in current regulations, adds two new ways: the use of safety analysis to indicate compliance and the combination of safety analysis and methods of compliance in current regulations.

4.3.4 Formulating basis

Current regulations are formulated based on the European and American industrial systems and technical paths and have fully absorbed the accumulated experience and lessons of aero-engines in the current world; the new regulations, on the basis of inheriting the existing international experience and lessons, will further learn from the experience in domestic basic research and type development.

In summary, with continuous and in-depth research based on the new airworthiness regulation framework and technical path proposed in this study, the Chinese plan for the next-generation airworthiness regulations of aero-engines thus formed will be guided by system safety requirements, exhibit flexible adaptability to new technologies, be compatible with and inherit the existing practical experience in China and abroad, consider economic efficiency while ensuring the safety level, and enhance anti-monopoly restrictions of airworthiness standards.

5 Measures and suggestions

The study of airworthiness regulations is an important part constructing a strong civil aviation industry. It is a long-term task for China to support the construction of a strong transportation infrastructure with high-quality development of the civil aviation industry. Moreover, the development of airworthiness regulations will promote prosperity and safety in the global aviation industry. To guarantee and promote the construction of the aero-engine airworthiness regulation system in China and continue to conduct research on the next-generation airworthiness regulations of aero-engines, the following suggestions are made.

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5.1 Continuously deepening the level of research

We suggest that competent authorities of airworthiness regulations and the civil aviation industry incorporate research on airworthiness regulations of aero-engines into the planning of long-term scientific research projects. The civil aircraft research project, Civil Aviation Safety Fund project, and the "two engines" (i.e., aero-engines and gas turbines) project should jointly support research on aero-engine safety and airworthiness technology in China. All ministries and commissions should deploy in stages and continue to deepen research on the Chinese plan of next-generation airworthiness regulations, research on the formulation and revision of China's airworthiness regulations, and basic research on type development based on existing regulations, thereby gradually establishing a long-term mechanism for the construction of China's aero-engine airworthiness regulation system.

5.2 Synchronously expanding the application

We suggest that industrial departments further strengthen the close integration of "research on aero-engine airworthiness regulations" and "research and development of civil aviation power." Based on the existing joint demonstration mechanism between the regulation research team and the type engineering team, we should further expand the scope of the engineering team of civil aviation power for the joint demonstration, strengthen the integration of the joint demonstration, guide engineering practice with regulation formulation and revision, and promote regulation research through type development and certification so that a normal mechanism will gradually be formed for the coordination and integration of the formulation of aero-engine airworthiness regulations and the type engineering practice.

5.3 Synergetically developing the industry

We advise that the CAAC, together with the Ministry of Industry and Information Technology, industrial departments, colleges, universities, and relevant foreign institutions, systematically study the formulation of aero-engine airworthiness regulations and their compliance technology. With the transfer and transformation of intellectual property rights and achievements as the link, we should establish a technological innovation system featuring a deep integration of "industry, university, and institute" with the "four-in-one" model, that is, the close cooperation among civil aircraft airworthiness departments, industrial departments, colleges and universities, and international resources. These should work in a coordinated manner to tackle major constrictions in aero-engine safety design and airworthiness compliance technology and thus lay a technical foundation for the establishment of China's aero-engine airworthiness regulation system.

References

[1] Civil Aviation Administration of China. Action plan for building a strong civil aviation country in the new era [EB/OL]. (2018-11-26) [2022-06-20]. http://www.caac.gov.cn/XXGK/XXGK/ZFGW/201812/t20181212_193447.html. Chinese.

[2] Federal Aviation Administration. FAR Part 33 Amendment 33-34 airworthiness standards: Engines [S]. Washington DC: Federal Aviation Administration, 2014.

[3] European Aviation Safety Agency. CS-E Amendment 6 Certification Specifications and Acceptable Means of Compliance for Engines [S]. Cologne: European Aviation Safety Agency, 2020.

[4] Civil Aviation Administration of China. CCAR-33R2 Aeroengine airworthiness regulations [EB/OL]. (2016-03-17) [2022-06-20]. http://www.caac.gov.cn/XXGK/XXGK/MHGZ/201606/t20160622_38639.html. Chinese.

[5] Federal Aviation Administration, Aerospace Industries Association. Technical report on propulsion system and Auxiliary Power Unit (APU) related aircraft safety hazards [R]. Washington DC: Federal Aviation Administration, 1999.

[6] Federal Aviation Administration, Aerospace Industries Association. 2nd technical report on propulsion system and Auxiliary Power Unit (APU) related aircraft safety hazards [R]. Washington DC: Federal Aviation Administration, 2005.

[7] Federal Aviation Administration, Aerospace Industries Association. 3rd technical report on propulsion system and Auxiliary Power Unit (APU) related aircraft safety hazards [R]. Washington DC: Federal Aviation Administration, 2017.

[8] Society of Automotive Engineers. SAE ARP4754-2010 guidelines for development of civil aircraft and systems [S]. Washington DC: Society of Automotive Engineers, 2010.

[9] Society of Automotive Engineers. SAE ARP4761-1996 guidelines and methods for conducting the safety assessment process on civil airborne systems and equipment [S]. Washington DC: Society of Automotive Engineers, 1996.

[10] Federal Aviation Administration. AC 20-115D Airborne software development assurance using EUROCAE ED-12( ) and RTCA DO-178( ) [S]. Washington DC: Federal Aviation Administration, 2017.

[11] Federal Aviation Administration. AC 20-152 RTCA, Inc., document RTCA/DO-254, design assurance guidance for airborne electronic hardware [S]. Washington DC: Federal Aviation Administration, 2005.

[12] Radio Technical Commission for Aeronautics. Software considerations in airborne systems and equipment certification: RTCA DO-178C-2011 [S]. Washington DC: Radio Technical Commission for Aeronautics, 2011.

[13] Radio Technical Commission for Aeronautics. Design assurance guidance for airborne electronic hardware: RTCA DO-254-2000 [S]. Washington DC: Radio Technical Commission for Aeronautics, 2000.

[14] Federal Aviation Administration. FAR Part 33.75 amendment 33-6 safety analysis [S]. Washington DC: Federal Aviation Administration, 1974.

[15] Federal Aviation Administration. FAR Part 33.75 amendment 33-24 safety analysis [S]. Washington DC: Federal Aviation Administration, 2007.