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ON THE THEORY OF AREOCRAFT STRUCTURAL OPERATIONAL INTEGRITY CONTROL

Yuting He[1] and Rui Bao[2]

[1]Air Force Engineering University; Xi'an 710038, China; email: heyut666@126.com
[2]Beihang University; Beijing 100083, China; RBao@buaa.edu.cn

Abstract: From the perspective of performing and completing the functions and missions, for aerocraft structure, its more comprehensive general quality characteristic, structural operational integrity (SOI), shows the inherent attribute which exists when a structure is sound and unimpaired in service or operational processes. In this paper, a brief introduction to aerocraft structural operational integrity (ASOI) is introduced firstly, including the concept of aerocraft structural operational integrity, the categorization of aerocraft structural operational integrity, and basic characterization methods of aerocraft structural operational integrity. As a general quality characteristic of aerocraft structure, aerocraft structural operational integrity can be controlled in structural life cycle time. Then, the basic concept of aerocraft structural operational integrity control (ASOIC) is presented. Consequently, the connotation of aerocraft structural operational integrity control is analyzed, which can be expressed by means of the control activity-wheel of aerocraft structural operational integrity formed by design/establishment, manufacture/achievement, evaluation/validation, monitoring/sustaining, recovery/increasement and inspection/exploitation activities of aerocraft structural operational integrity. Furthermore, the basic modes of aerocraft structural operational integrity control are shown here, which include open-loop control, coordinated control, and balanced control of aerocraft structural operational integrity. Finally, aerocraft structural operational integrity control strategy (ASOICS) was discussed briefly, which is to establish and apply an aerocraft structural operational integrity program (ASOIP) to all aerocraft structures.

Keywords: aerocraft structure, structural operational integrity, connotation of control, control mode, control strategy

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1. INTRODUCTION

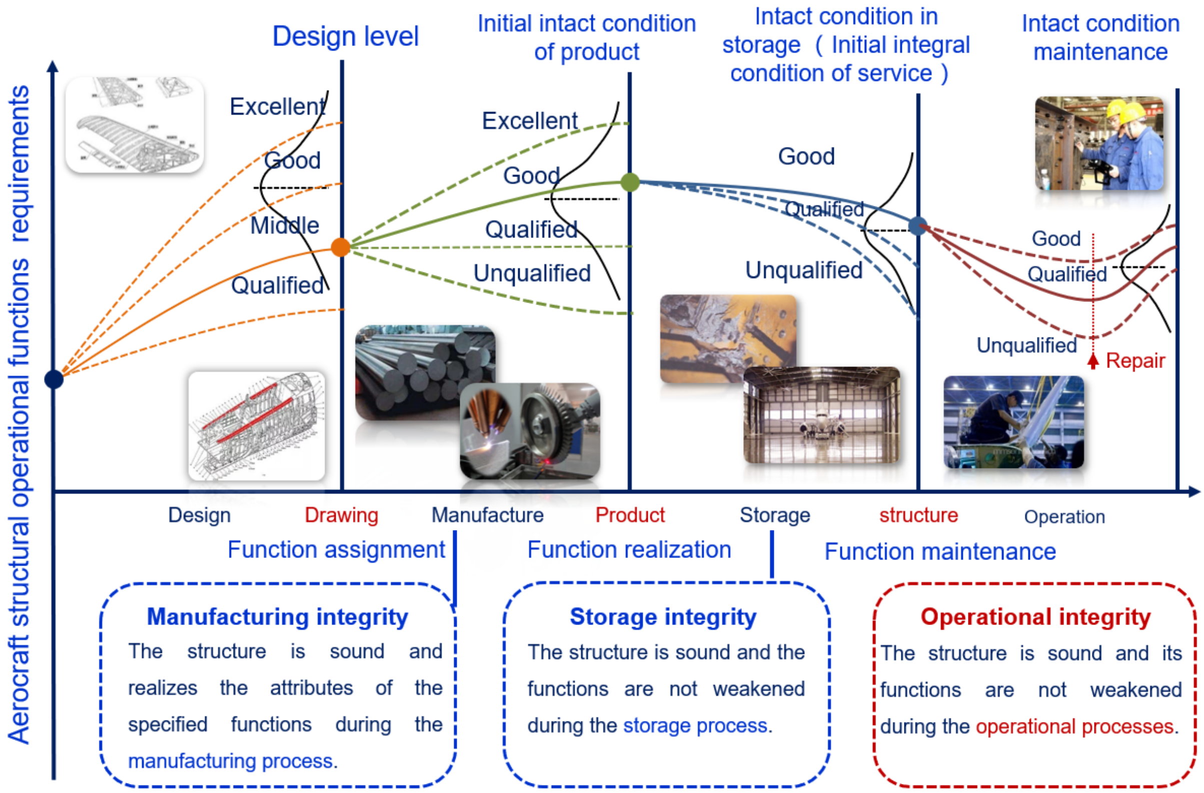
Essentially, Integrity means undivided or unbroken completeness or totality with nothing wanting. Structural integrity goes back as far as recorded history. Structural integrity is not just a case of good design, it needs to be maintained for the whole life of a structure. This requires inspection and maintenance at periodic intervals. The concept of aircraft structural integrity was first proposed by the United States Air Force in 1954[1], and gradually developed and improved with a series of accidents in the United States Air Force, and the corresponding standard, the Aircraft Structural Integrity Program (ASIP), has More than ten supplements and revisions. The latest ASIP in the United States is MIL-STD-1530D [2] released in 2016. In contrast, the latest ASIP in China is GJB775. A – 2012 [3]. In 2021, The Welding Institute stated that structural integrity is an engineering field that helps ensure that either a structure or structural component is fit for purpose under normal operational conditions and is safe even should conditions exceed that of the original design [4]. It can be seen that the connotation of structural integrity has been developed continuously.

In reference [5], from the perspective of performing and completing the functions and missions for military aircraft structures, as the development of traditional aircraft structural integrity (ASI), the author presented the concept of battle integrity for military aircraft structures. In fact, the battle integrity for military aircraft structures means the operational integrity of aircraft structures during the military processes. So, the concept of operational integrity can be further applied to all aircraft structures and other equipment structures in their operational processes, including civil or military aircraft structures and other equipment structures. Then, structural operational integrity concerns the overall quality of the structure in its whole operational process and can be used to characterize the general quality characteristic of the structure more comprehensively [6]. Correspondingly aerocraft structural operational integrity can be determined during design and manufacture, maintained during the service periods, and is the inherent attribute of the aerocraft structure which is manifested in the entire life cycle. As a more comprehensive general quality characteristic of aerocraft structure, it can be controlled from manufacturing processes to operational processes as well as the control of other aerocraft structural general quality characteristics, such as reliability, safety, maintainability [7], and so on. So, in this paper, aerocraft structural operational integrity (ASOI) is introduced briefly, including the concept, categorization, and characterization. Meanwhile, something about aerocraft structural operational integrity control (ASOIC) is described, such as the concept of aerocraft structural operational integrity control, the connotation of aerocraft structural operational integrity control, the basic modes of aerocraft structural operational integrity control, and the strategies of aerocraft structural operational integrity control, etc.

2. BRIEF INTRODUCTION OF AEROCRAFT STRUCTURAL OPERATIONAL INTEGRITY

2.1 The concept of aerocraft structural operational integrity

In fact, from the view of life cycle time, the structural operational functions should be assigned in design processes, realized in manufacturing processes, and maintained in storage processes and operational processes. If we want to keep the structural integrity to meet the specified requirement, the structural manufacturing processes, structural storage processes, and structural operational processes should be focused on. Correspondingly, structural integrity can be categorized into structural manufacturing integrity, structural storage integrity, and structural operational integrity, just shown in Figure 1.



Manufacturing integrity
The structure is sound and realizes the attributes of the specified functions during the manufacturing process.

Storage integrity
The structure is sound and the functions are not weakened during the storage process.

Operational integrity
The structure is sound and its functions are not weakened during the operational processes.

Figure 1: Structural integrity classification during the life cycle time

Usually, at the end of the design process, we can get the structural design drawings. After the manufacturing, we can get the structures. After the storage processes (long or short time), the structures will be expected as being in sound conditions. when the structures are delivered to customers and operated in operational processes, they could be expected as being apolitical in order to function and perform effectively. And, the design drawings will reflect the design level of the designers. After the structure is manufactured, it will show the level of the initial integral condition of the structure itself. After the storage period, the structure will tell the level of integral condition in storage (or the level of initial integral condition of the structure in service). Then, in operational processes, the level of required integral condition of the structure should be maintained through some reasonable and necessary maintenance work. That is to say, in order to keep the operational functions of the structure in its operational processes, structural integrity should be maintained. Along the life cycle time, structural manufacturing integrity refers to the attribute that the structure is sound and realizes the specified functions in manufacturing processes, structural storage integrity refers to the attribute that the structure is sound and unimpaired in storage processes, and structural operational integrity refers to the inherent attribute that the structure is sound and unimpaired in operational processes [6]. So, aerocraft structural operational integrity can be defined as the inherent attribute which exists when a structure is sound and unimpaired in its whole operational processes. For example, how to improve the manufacturing quality of aerocraft structures in manufacturing processes, such as avoiding inclusions and voids of structural materials, getting rid of structural component surface scratches, and so on, belongs to the concern of aerocraft structural manufacturing integrity, how to prevent the degradation of aerocraft structures in storage period, such as preventing the environmental corrosions, stemming the harmful permanent deformations and so on, belongs to the concern of aerocraft structural storage integrity, and how to keep aerocraft structures sound and unimpaired in operational processes, such as preventing aerocraft structural fatigue failures, blocking the environmental corrosive failures and so on, belongs to the concern of aerocraft structural operational integrity.

This paper mainly concerns about aerocraft structural operational integrity and its control theory. Also, the basic characteristics of aerocraft structural operational integrity can be summarized as objectivity, relativity, randomness, comprehensiveness, and controllability. Objectivity means that ASOI is an objective aerocraft structural inherent attribute, which can be measured by some means. Relativity means that ASOI is for the exact task and operating environment it undertakes, and it makes no sense to leave the corresponding task and operating environment. Randomness means that ASOI also has random characteristics due to the quality of the aerocraft structure itself, the randomness of the task, and the operating environment. So, the methods of probability and statistics can often be used to describe the ASOI. Comprehensiveness means that ASOI has comprehensive characteristics because it expresses the effects of structural durability, supportability, safety, performance, survivability, and recoverability in aerocraft structural operational processes comprehensively. Controllability means that ASOI, a general quality characteristic of aerocraft structure, can be controlled by certain measures, which will be discussed in the next.

2.2 The categorization of aerocraft structural operational integrity

Essentially, aerocraft structural operational integrity refers to an inherent attribute of aerocraft structure, as a more comprehensive general quality characteristic of aerocraft structure, which includes static attributes and dynamic attributes of aerocraft structure, showing the special status and ability of aerocraft structure separately. Therefore, aerocraft structural operational integrity can be categorized into aerocraft structural static operational integrity (ASSOI) and aerocraft structural dynamic operational integrity (ASDOI) [6]. Aerocraft structural static operational integrity can be defined as a status of an aerocraft structure keeping sound and unimpaired when it performs and completes the specified missions (or the specified functions) under the specified service conditions, such as parking conditions, operational conditions, maintenance support conditions, and so on. Aerocraft structural dynamic operational integrity can be defined as the ability which exists when an aerocraft structure is sound and unimpaired while providing the desired levels of aerocraft structural durability, supportability, safety, performance, survivability, and recoverability [8-14] during service period or in operational processes. It can be seen that aerocraft structural static operational integrity concerns the aerocraft structural status of being sound and unimpaired at the exact moment, while aerocraft structural dynamic operational integrity concerns the ability of aerocraft structure to keep sound and unimpaired during one exact service period.

2.3 Characterization of aerocraft structural operational integrity

Usually, aerocraft structural operational integrity (ASOI) can be characterized by means of the inherent readiness rate of aerocraft structures in the fleet with the same type of aerocraft, R_s, aerocraft structural inherent health degree of an aerocraft structure, $H_s(t)$, and aerocraft structural operational integrity degree, I_{so}. Aerocraft structural static operational integrity (ASSOI) concerns the status of aerocraft structure at the exact moment. Therefore, aerocraft structural static operational integrity can be directly reflected by the inherent readiness rate [15] of aerocraft structures, R_s, which represents the ratio of the number of structures in the sound state to the total number of structures in the fleet with the same type of aerocraft in a specified environment, such as operational environment, supporting environment, management environment and so on.

$$R_s = \frac{E_{s\text{-int}act}}{E_{s\text{-}total}} \tag{1}$$

where R_s is aerocraft structural inherent readiness rate; $E_{s-intact}$is the number of aerocraft structures in the sound state; $E_{s-total}$ is the total number of structures in the fleet with the same type of aerocraft. In fact, aerocraft structural inherent readiness rate can be categorized into aerocraft structural inherent readiness rate R_{sn} in peacetime or normal service environments and aerocraft structural inherent readiness rate R_{sb} in wartime or accidental service environments. Their values are generally different. On the other hand, it can be clearly shown that the values of aerocraft structural inherent readiness rate will usually be changed along the service time of aerocraft structures.

Meanwhile, aerocraft structural health degree [6] was used to express the health status of a structure often. Aerocraft structural inherent health degree is the level at which the structure can remain sound (or work normally) and its functions are not weakened when the structure performs the specified tasks under the specified environments, such as operational environment, supporting environment, management environment and so on, as presented in formula 2.

$$H_s(t) = 1 - L_a(t)/L_c(t) \tag{2}$$

where t is the point in time; $H_s(t)$ is aerocraft structural inherent health degree, which is a function of the point in time;$L_a(t)$ is the real crack length of aerocraft structure when the structure is in work. $L_c(t)$ is the critical crack length of the structure when the structure is in failure due to fracture. Aerocraft structural inherent health degree covers from 0 to 1, which reflects the healthy level of an aerocraft structure at a moment. Then, aerocraft structural health status can be determined according to the value of aerocraft structural inherent health degree and classified into healthy status, sub-healthy status, and unhealthy status.

Usually, it is unnecessary to repair aerocraft structure when it is in healthy status; it is necessary to make a plan to repair the structure when it is in sub-healthy status; and it is equally necessary to repair the structure at once when it is in unhealthy status.

Basically, the status of a structure being sound and unimpaired means the state of a structure is in health. Thereby, aerocraft structural static operational integrity can also be characterized by means of aerocraft structural inherent health degree, $H_s(t)$ When an aerocraft structure is in healthy status and sub-healthy status, it can work normally, and the structure can be thought of being in a sound state. When an aerocraft structure is in unhealthy status, it can't work normally and must be repaired at once, and the structure can be thought as being in a soundless state. Furthermore, the inherent readiness rate of aerocraft structures, $H_s(t)$, can be calculated based on the number of aerocraft structures in a sound state and the total number of structures in the fleet with the same type of aerocraft. And this also clearly shows that the inherent readiness rate of aerocraft structures, $H_s(t)$, and aerocraft structural inherent health degree, $H_s(t)$, can be employed to express aerocraft structural static operational integrity. It should be pointed out that the inherent readiness rate of aerocraft structures, $H_s(t)$, concerns the structures in the fleet with the same type of aerocraft, while aerocraft structural inherent health degree, $H_s(t)$, concerns the structure in one exact aerocraft.

On the other hand, aerocraft structural dynamic operational integrity (ASDOI) concerns the ability of aerocraft structure to keep sound and unimpaired during one exact service period. Aerocraft structural operational integrity degree, I_{so}, can be given, and then aerocraft structural dynamic operational integrity can be measured. Aerocraft structural operational integrity degree [6] is the probability that aerocraft structure can remain sound (or work normally) and unimpaired (or functions are not weakened) when the structure performs and completes the specified missions (or the specified functions) within the specified time under the specified conditions, which can be represented by formula (3). After analyzing aerocraft main operational processes and mission chain, and finding the master affecting elements, according to the definition of aerocraft structural dynamic operational integrity, the aerocraft structural ability to keep sound and unimpaired is determined by aerocraft structural durability, supportability, safety, performance, survivability, and recoverability, etc.

$$I_{so} = P\{\tau > t_0\} = f(U_s, A_s, S_s, C_s, S_{su}, R_{sc}) \tag{3}$$

where, t_0 is the specified time; τ indicates the time during which aerocraft structure can be sound and unimpaired; U_s is aerocraft structural durability degree; $D_s = 1 - U_s$, which is aerocraft structural damage degree, a quantitative measure of the durability damage of aerocraft structure when it reaches the specified time t; A_s is aerocraft structural availability degree, which is used to measure aerocraft structural supportability; S_s is aerocraft structural safety degree, which is used to measure aerocraft structural safety and represents the probability without accidents when aerocraft structure completes the specified missions under the specified conditions throughout the specified time cycle; C_s is aerocraft structural livability degree, $F_s = 1 - C_s$, the failure rate of aerocraft structures, which is the probability of aerocraft structural failure when the ability of aerocraft structure to bear the loads is equal to or less than the loads carried by the structure; S_{su} is aerocraft structural survivability degree, which refers to the probability of aerocraft structure being able to keep working with the damage due to various weapons, unexpected accidents and non-calculated loads; R_{sc} is aerocraft structural recoverability degree, which means the probability where aerocraft structure suffering from accidental damage or unconventional damage can be recovered to the state with ability of completing the specified missions by means of effective repairs according to the specified procedures and methods within the specified time and under the specified conditions.

For the sake of simplicity, aerocraft structural durability degree, availability degree, safety degree, livability degree, survivability degree, and recoverability degree can be thought of as independent parameters. If the influence of each parameter on aerocraft structural dynamic operational integrity is simply expressed in a linear relationship, the model of aerocraft structural operational integrity degree can be expressed as follows:

$$I_{so} = U_s \cdot A_s \cdot S_s \cdot C_s \cdot S_{su} \cdot R_{sc} \tag{4}$$

According to the above models, the "cask effect" for aerocraft structural dynamic operational integrity is very clear. As long as one of the parameters above is very small, aerocraft structural dynamic operational integrity will be greatly affected. Therefore, under certain limited resources (such as funds, design level, supportability, etc.), the durability degree, availability degree, safety degree, livability degree, survivability degree, and recoverability degree of aerocraft structure can be coordinated with each other through reasonable resources control, so as to achieve the highest aerocraft structural dynamic operational integrity.

3. THE BASIC CONCEPT OF AEROCRAFT STRUCTURAL OPERATIONAL INTEGRITY CONTROL(ASOIC)

Aerocraft structural operational integrity (ASOI) shows the general quality characteristic [16,17] of aerocraft structure in service or operational processes more comprehensively, and it can be determined by structural durability, supportability, safety, performance, survivability, and recoverability, and there are many factors affecting the above properties. Aerocraft structural operational integrity depends on three major elements, namely design, manufacturing, and service/usage. Among them, the design and manufacturing technologies are the innate factors that determine the aerocraft structural operational integrity, and have a decisive influence on aerocraft structural operational integrity. The scientificity of aerocraft usage and the fineness of maintenance during the service period is the acquired factors affecting the actual aerocraft structural operational integrity, and it determines the speed at which aerocraft structural operational integrity declines. The above three elements, whether it is the design, manufacturing, or service/usage of aerocraft structures, can ensure aerocraft structural operational integrity through active control and meet the service/operation requirements of aerocraft structures.

Before aerocraft structure is put into service, the employment of advanced design techniques can lay a good foundation for aerocraft structural operational integrity, so that it has "excellent genes". The employment of advanced manufacturing and processing techniques can improve the quality of aerocraft structures, forging its "strong physique". For aerocraft structures that have been delivered, the basic quality can be considered to be certain, but aerocraft service environments, flight loads, and supporting conditions have decisive effects on aerocraft structural operational integrity, which can be maximized through a series of control measures.

Therefore, aerocraft structural operational integrity control(ASOIC) can be defined as follows, it is a series of activities carried out in the process of aerocraft structural design, manufacture, and service/operation to achieve the established aerocraft structural operational integrity objectives, including expected aerocraft structural durability, supportability, safety, performance, survivability and recoverability, such as aerocraft structural design, structural manufacturing process optimization, structural modification, structural life determination/extension, individual structural life monitoring (tracking), structural repair, structural reinforcement, structural replacement, structural service/operation plan adjustment, structural maintenance measures, and plan adjustment, etc. Its essence is the adjustment and control process of aerocraft structural operational integrity.

4. THE CONNOTATION OF ASOIC

Based on the ESVRE concept [18], it can be developed that the connotation of aerocraft structural operational integrity control can be expressed by means of the control activity-wheel of aerocraft structural operational integrity, which is shown in Figure 2.

Figure 2: Aerocraft structural operational integrity control (ASOIC) activity-wheel

Aerocraft structural operational integrity control activity-wheel consists of six parts of activities: design/establishment, manufacture/achievement, evaluation/validation, monitoring/sustaining, recovery/increasement, and inspection/exploitation of aerocraft structural operational integrity. Thereby, the connotation of aerocraft structural operational integrity control is shown in details in Table 1.

Table 1: The connotation of aerocraft structural operational integrity control

Part Ⅰ Design/ Establishment	**Part Ⅱ** Manufacture/ Achievement	**Part Ⅲ** Evaluation/ Validation	**Part Ⅳ** Monitoring/ Sustaining	**Part Ⅴ** Recovery/ Increasement	**Part Ⅵ** Inspection/ Exploitation
Durability design Supportability design Safety design Performance design Survivability design Recoverability design ASOI design	Structure manufacture/achievement Durability manufacture/achievement Supportability manufacture/achievement Safety manufacture/achievement Performance manufacture/achievement Survivability manufacture/achievement Recoverability manufacture/achievement ASOI manufacture/achievement	Durability evaluation/validation Supportability evaluation/validation Safety evaluation/validation Performance evaluation/validation Survivability evaluation/validation Recoverability evaluation/validation ASOI evaluation/validation	Structural health monitoring Condition based maintenance Predictive maintenance	Durability recovery /increasement Supportability recovery /increasement Safety recovery /increasement Performance recovery /increasement Survivability recovery /increasement Recoverability recovery /iNcreasement ASOI recovery /increasement	Tear-down inspection Residual performance test Extend Out-of-Service Date Data collection of structures

Design/Establishment (Activity partI)

The work to gather initial ASOI evidence can be classed as an Establishing ASOI activity. Of course, the establishment of ASOI is usually by means of ASOI design. ASOI design means the optimization design of structural durability, supportability, safety, performance, survivability, and recoverability, etc. Design activity also includes material selections, design technology employment, analyses of technology selection, analyses of software selection, and so on. ASOI is basically determined by aerocraft structural design.

Manufacture/Achievement(Activity partII)

After manufacturing processes, aerocraft structures can be gained, and aerocraft structural operational integrity can be achieved at the same time. As the manufacturing processes of aerocraft structures are determined, the more comprehensive general quality characteristic of aerocraft structure, aerocraft structural operational integrity (ASOI), will usually be kept as certainty. Usually, as the employment of advanced manufacturing technologies increases, much more higher values of aerocraft structural operational integrity will be obtained.

Evaluation/Validation(Activity partIII)

The actions to verify the ASOI are Validating activities. The validating activities usually consist of evaluation and test of ASOI. For the ASOI evaluation, structural durability, supportability, safety, performance, survivability, and recoverability should be evaluated first, then the ASOI could be evaluated by means of some special models, i.e., some models discussed before. To understand whether the ASOI meets the requirements, structural tests are necessary. If the structural durability, supportability, safety, performance, survivability, and recoverability all meet the designed requirements, that means the ASOI meets its requirements. Meanwhile, “cask effect” of these parameters should be paid more attention. Similarly, the aerocraft structural test and evaluation can be classified into three types [19,20]: Development test and evaluation （DT&E）、Live fire test and evaluation (LFT&E), and Operational test and evaluation (OT&E）. And their relationship with aerocraft structural operational integrity (ASOI), aerocraft structural operational suitability (ASOS), and aerocraft structural operational effectiveness (ASOE) is shown in Figure 3.

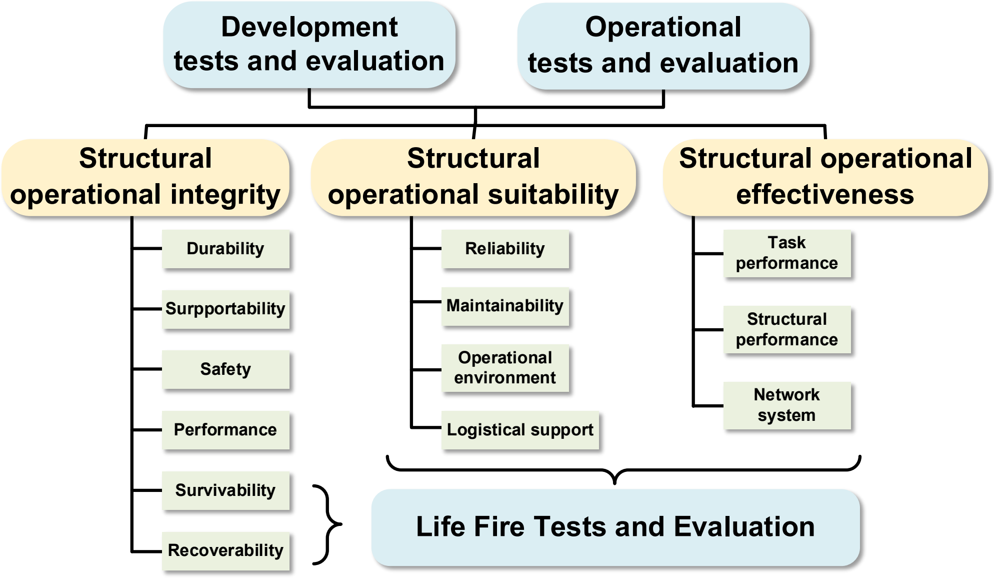


Figure 3: Test and evaluation of ASOI, ASOS, and ASOE

Monitoring/Sustaining(Activity partIV)

The actions to maintain ASOI through a lifetime are sustaining activities. To maintain the ASOI, individual ASOI monitoring or individual structural monitoring is necessary. Especially aerocraft structural health monitoring (ASHM) is useful to keep ASOI. Then adequate maintenance, i.e., condition-based maintenance (CBM), on-condition maintenance or case-dependent maintenance, and predictive maintenance, is useful to sustain the ASOI values.

Recovery/Increasement(Activity partV)

In service, aerocraft structural damage can be caused by any of the threats, i.e., overload, fatigue, fretting, wear, accidental or unexpected damage, environmental damage, procedural (design, manufacturing, maintenance, or supply) error, or a combination of them. The above damage will affect ASOI seriously and the recovering activities are necessary, which may range from simple component exchange to a full design organization repair. If the ASOI can’t be recovered, the accepted structural performance will be lowered or it will lead to the retirement of the aerocraft structure. Sometimes, for some special purposes, as the maintenance methods improve, ASOI will be increased by means of increasing structural durability, supportability, safety, performance, survivability, and recoverability, or some of them optimally.

Inspection/Exploitation(Activity partVI)

If it’s necessary sometimes, some additional activities are needed to safely exploit the inherent capabilities of aerocraft structures, to extend the Out-of-Service Date (OSD). Or after aerocraft structure retirement, some activities are also needed to exploit the residual performance of the retired structures. For example, the careful or tear-down inspections are useful to understand the actual damage of structure after a long-time service. Some structural parts can be put into special tests to discover the residual performance of aerocraft structures. And these data are very helpful for the ASOI design of new aerocraft structures.

5. THE BASIC MODES OF ASOIC

Generally, there are three main modes of ASOIC: Open-loop control, Coordinated control, and Balanced control.

5.1 Open-loop control

During the service of the aerocraft, due to various factors, the aerocraft structural operational integrity will inevitably decline. According to the characteristics of aerocraft structural operational integrity, a series of structural durability, supportability, safety, performance, survivability, and recoverability growth measures, i.e. ① improving aerocraft structural reliability; ② introducing aerocraft structural damage monitoring technology; ③ improving aerocraft structural maintenance level; ④ increasing the number of aerocraft structural inspections; ⑤ increasing the depth of aerocraft structural repair; ⑥ strengthening aerocraft structural safety construction; ⑦ employing modular design method of aerocraft structures and so on, can be adopted during the design, manufacturing, and service of aerocraft structures to increase the durability, supportability, safety, performance, survivability, and recoverability of aerocraft structures, so as to achieve the sustainment or growth of aerocraft structural operational integrity, as shown in Figure 4.

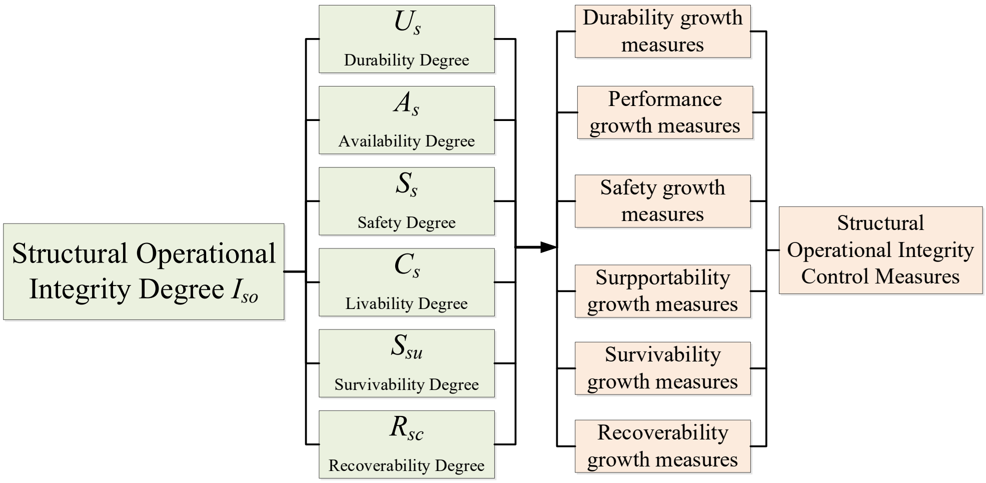


Figure 4: Effect of various control measures on aerocraft structural operational integrity

5.2 Coordinated control

From the above-mentioned control ways, it can be seen that safety growth measures not only cause safety growth but also have an impact on durability. Similarly, growth measures for durability, safety, and structural performance will have more or less positive or negative effects on the growth of the other properties.

To achieve the growth of aerocraft structural operational integrity, we must aim at maximizing aerocraft structural operational integrity and coordinating the growth of durability, supportability, safety, performance, survivability, and recoverability.

For a variety of growth measures, they can be combined to form a variety of aerocraft structural operational integrity control schemes. Each scheme has different effects on each parameter of aerocraft structural operational integrity, which has different effects on aerocraft structural operational integrity. To maximize aerocraft structural operational integrity, the optimization of aerocraft structural operational integrity control scheme can be completed, as shown in Figure 5.

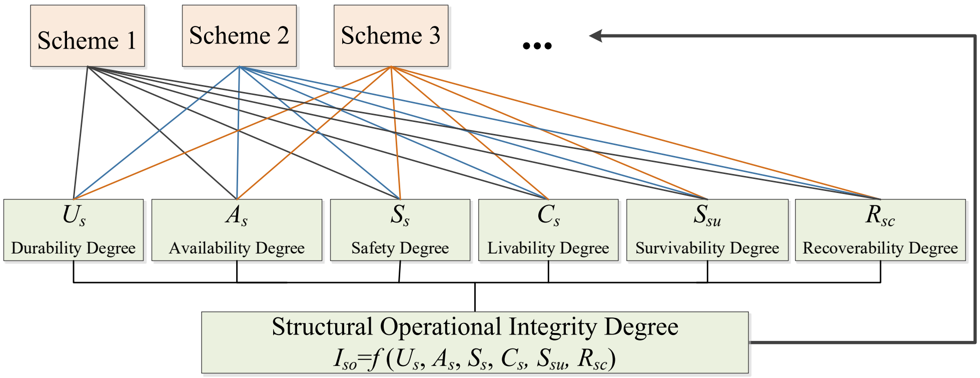


Figure 5: Diagram of the impact of control schemes on aerocraft structural operational integrity

5.3 Balanced control

According to the concept of aerocraft structural operational integrity, aerocraft structural operational integrity can be improved by limiting the usage, improving task conditions, and reducing the requirements for the ability to accomplish tasks. However, it should be noted that when aerocraft structural operational integrity control is implemented with the goal of maximizing aerocraft structural operational integrity, it cannot be at the expense of aerocraft structural performance, aerocraft structural operational effectiveness and aerocraft structural economical effectiveness [21]. For example, increasing the safety and strengthening aerocraft structural protective system can improve aerocraft structural operational integrity, but also increase the structural weight, which reduces aerocraft structural efficiency, thereby it is not recommended. Therefore, under the premise that aerocraft structural efficiency and economical effectiveness are not greatly reduced, the balanced control of aerocraft structural operational integrity should be implemented with the goal of maximizing aerocraft structural operational integrity.

It can be seen that optimizing aerocraft structural operational integrity is always with compromising structural performance, operational effectiveness, and economical effectiveness. The relationship model between aerocraft structural operational integrity degree and aerocraft structural operational integrity control schemes (i.e., durability, supportability, safety, performance, survivability, and recoverability growth measures) should be established. Then the optimization of aerocraft structural operational integrity control schemes can be achieved to maximize aerocraft structural integrity degree under a comprehensive consideration of aerocraft structural performance, operational effectiveness, and economical effectiveness.

6. THE BASIC STRATEGY OF ASOIC

The basic strategy to control aerocraft structural operational integrity is to establish and apply aerocraft structural operational integrity program (ASOIP) to all aerocraft structures. ASOIP can be obtained by means of expanding the traditional aircraft structural integrity program (ASIP) [22]. The five, interrelated ASOIP tasks and their corresponding detailed requirements are summarized in Table 2.

Table 2: ASOIP tasks and corresponding detailed requirements

Task Ⅰ Design Information	**Task Ⅱ** Design Analysis and Development Tests	**Task Ⅲ** Full Scale Testing	**Task Ⅳ** Force Management Data Package	**Task Ⅴ** Force Management
ASOIP Master Plan Structural Design Criteria Damage Tolerance & Durability Control Process Selection of Materials, Processes＆ Joining Methods Design Service Goal and Design Usage Mass Properties Survivability Design Data Reparability Design Data ASOI Design	Material＆Joint Allowables Load Analysis Design Service Loads Spectra Design Chemical/Thermal Environment Spectra Stress Analysis Damage Tolerance Analysis Durability Analysis Aeroacoustics Analysis Vibration Analysis Flutter Analysis Nuclear Weapons Effects Analysis Non-Nuclear Weapons Effects Analysis Design Development Tests Mass Properties Analysis Survivability Analysis Repairability Analysis ASOI Analysis	Static Tests Durability Tests Damage Tolerance Tests Flight＆Ground Operations Tests Aero-acoustic Tests Flight Vibration Tests Flutter Tests Aero-acoustic Analysis Interpretation＆Evaluation of Test Results Weight＆Balance Testing Life Fire Tests （Operational Effectiveness, Survivability, Suitability, Recoverability） Evolution of ASOI	Final Analyses Strength Summary Force Structural Maintenance Plan Loads/Environment Spectra Survey Individual Aircraft Tracking Program Fire Protection Critical Part Shading Battle Damage Evaluation Battle Damage Repair First-aid Repair Plan ASOI Control Plan	Loads/Environment Spectra Survey Individual Aircraft Tracking Data Individual Aircraft Maintenance Times Structural Maintenance Records Weight and Balance Records Fire Protection Critical Part Shading First-aid Repair and Evaluation ASOI monitoring Training

Design information (Task I)

The design information task encompasses those efforts required to apply the existing theoretical, experimental, application research, and operational experience to specific criteria for materials and process selection, which includes design, production, sustainment, anti-battlefield damage, recovery, and retirement/disposal. The objective of this task is to ensure appropriate criteria and planned operational characteristics are applied to aerocraft design to meet specific structural operational, performance, and sustainment requirements throughout aerocraft life cycle time, so as to prepare aerocraft structural operational integrity design.

Design analyses & development testing (Task II)

The objectives of the design analyses and development testing task are as follows:

(1) Determining the environments in which the aerocraft structures must operate (load, thermal, chemical, abrasive, vibratory, aeroacoustics, high-speed impact, fire, heating, etc.);

(2) Performing preliminary and final analyses and tests based on these environments;

(3) Designing aerocraft structures to meet the strength, rigidity, durability, damage tolerance, force protection, fast-repair, and other specified requirements, so as to meet aerocraft structural operational integrity requirements.

Full-scale testing (Task III)

The objective of this task is to assist in the determination of aerocraft structural adequacy of the design through a series of ground and flight tests, including the live fire tests. Test plans, procedures, and schedules shall be approved by the procuring agency. Test results shall be used to validate or correct analysis methods and results, and to demonstrate requirements are achieved. Mostly, the aerocraft structural operational integrity should be demonstrated to meet the requirements.

Certification & force management development (Task IV)

Initial aerocraft structural certification is based on the results of Tasks I through III by means of design analyses correlated to ground and flight testing, including live fire tests. To maintain aerocraft structural certification, an appropriate force management strategy including battlefield damage evaluation and repair tactics, and aerocraft structural operational integrity control plan shall be developed in preparation for force management execution that occurs during sustainment under Task V.

Force management execution (Task V)

Task V describes the execution of the force management strategies described in Task IV. Task V encompasses all tasks necessary to maintain aerocraft structural operational integrity and to perform structural certification updates.

The main purposes of applying ASOIP are as follows:

(1) Determining the requirement of aerocraft structural operational integrity corresponding to aerocraft structural operational suitability and aerocraft structural operational effectiveness;

(2) Controlling aerocraft structural operational integrity by means of establishment, evaluation, certification, sustainment, regeneration, and development, etc;

(3) Evaluating the individual aerocraft structural operational integrity sustainingly with obtained service data;

(4) Supporting the determination of logical support and force management plans for aerocraft (i.e., maintenance, inspection, supply, equipment exchange, system development, and substantializing of prospective aerocraft structures, etc.);

(5) Providing a foundation for the design, evaluation, and substantializing of future aerocraft structures.

7. SUMMARY

(1) The basic concept of aerocraft structural operational integrity is expounded and it is the inherent attribute that exists when an aerocraft structure is sound and unimpaired in service or operational processes. Aerocraft structural operational integrity represents the general quality characteristic of aerocraft structures more comprehensively. While the categorization of aerocraft structural operational integrity and basic characterization methods of aerocraft structural operational integrity are also introduced briefly.

(2) The basic concept of aerocraft structural operational integrity control (ASOIC) is introduced. It contains a series of activities carried out in the process of aerocraft structural design, manufacturing, and service/operation to achieve the established aerocraft structural operational integrity objectives, including expected aerocraft structural durability, supportability, safety, performance, survivability and recoverability. Usually, these activities include aerocraft structural design, structural manufacturing process optimization, structural modification, structural life determination/extension, individual structural life monitoring (tracking), structural repair, structural reinforcement, structural replacement, structural service/operation plan adjustment, structural maintenance measures, structural maintenance plan adjustment, and aerocraft structural operational integrity monitoring, etc. Its essence is the adjustment and control process of aerocraft structural operational integrity.

(3) Consequently, the connotation of aerocraft structural operational integrity control (ASOIC) is analyzed, which can be expressed by the control activity-wheel formed by design/establishment, manufacture/achievement, evaluation/validation, monitoring/sustaining, recovery/increasement and inspection/exploitation activities of aerocraft structural operational integrity.

(4) The basic modes of aerocraft structural operational integrity control (ASOIC) are shown here, which include open-loop control, coordinated control, and balanced control of aerocraft structural operational integrity.

(5) Aerocraft structural operational integrity control strategy (ASOICS) was discussed briefly, which is to establish and apply an aerocraft structural operational integrity program (ASOIP) to all aerocraft structures.

As a general quality characteristic of aerocraft structure, aerocraft structural operational integrity can be controlled in structural life cycle time. This paper attempts to provide a theoretical basis for aerocraft structural operational integrity control (ASOIC). However, the research work is still preliminary, and there is still a lot of work needed to be done. It should be noted that the basic concept and modes of aerocraft structural operational integrity control can also be applied to other equipment and product structures, as well as aerocraft structural operational integrity control strategy (ASOICS).

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