32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

On Aircraft Operational Integrity

Yuting He

Air Force Engineering University; Xi'an 710038, China; email: heyut666@126.com

Abstract

As a type of complex equipment, the general quality characteristics of aircraft, such as reliability, safety and maintainability, reflect a certain aspect of quality characteristics. From the perspective of performing and completing the functions and missions for aircraft, the concept of aircraft operational integrity (AOI) is proposed, which is used to describe the comprehensive quality characteristics of the aircraft during service. Aircraft operational integrity is defined as the attribute with which the aircraft can be kept sound (or work normally) and its functions are not weakened under the required levels of durability, supportability, safety, performance, survivability and recoverability during service. Operational integrity, operational suitability and operational effectiveness constitute three basic attributes of the aircraft, which respectively reflect the degree of "integrity", "suitability" and "effectiveness" of aircraft in its operational processes. Furthermore, the connotation, characterization, composition and distribution of aircraft operational integrity are discussed. The concepts and measurement methods of durability, livability and recoverability of aircraft are also presented. Last but not the least the load-bearing capability-acting load interference model is proposed to analyze the failure probability and livability degree of aircraft due to the weak performance as well as the measuring models of aircraft supportability, safety and survivability introduced.

Key words: aircraft, operational integrity, durability, performance, survivability, recoverability

1. Introduction

As a type of complex equipment, usually, the general quality characteristics of the aircraft during service include reliability, maintainability, supportability, safety, and testability [1]. However, they all reflect the characteristics of the aircraft from a certain aspect, and the relationship among them is not well explained. In fact, users' quality requirements for aircraft or other products are to be meeting the performance requirement, performance-stable and service-durable during the service processes. In reference [2], the author gave the concept of operational integrity for military aircraft. In fact, the concept of operational integrity can be further applied to all aircraft. Therefore, the aircraft's operational integrity parameters can be used to characterize its comprehensive quality characteristics. The comprehensive quality characteristics of aircraft, often determined during design and manufacture, maintained during the service period are the inherent attributes of the aircraft which are manifested in the entire life cycle. Like other equipment operational integrity[3], the operational integrity of the aircraft, along with its operational suitability and operational effectiveness, constitute three basic attributes of the aircraft. The operational integrity of the aircraft reflects the comprehensive quality characteristics of the aircraft during service processes; the operational suitability reflects the satisfaction level of the aircraft in the field usage; and the operational effectiveness reflects the extent to which the aircraft completes the given missions or functions during the service period. The aircraft operational integrity is the basis for aircraft operational suitability and aircraft operational effectiveness. The operational integrity is the basic requirement for aircraft while the operational suitability and operational effectiveness are the higher requirements for aircraft.

2 The basic concept of the aircraft operational integrity

2.1 Origin of the aircraft operational integrity concept

The concept of integrity was first proposed by the United States Air Force in 1954[4], 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 [5] released in 2016. In contrast, the latest ASIP in China is GJB775.A – 2012 [6].

Afterwards, the term integrity became an important concept to characterize the quality characteristics of aircraft [7]. The structural integrity of the aircraft was first proposed. Accordingly, the structural integrity of the engine [8], the integrity of avionics [9] and the mechanical equipment and subsystem integrity [10], etc., were all developed. In terms of aircraft functional system-level integrity, there are concepts of weapon system integrity [11] and propulsion system integrity [12]. As for the entire aircraft, only the ordinary/training usage conditions are taken into account. Traditional integrity refers to the state in which the aircraft can be used normally (or kept sound) and its functions are not degraded under the required levels of durability, supportability, safety and aircraft performance. In order to meet wartime requirements, on the basis of the original integrity index system, consideration should also be given to increasing indexes that affect the continuous operation ability as well as mission completion and the index that reflects the aircraft's comprehensive quality characteristics. After the concept of operational integrity of military aircraft structures was proposed in [13, 14], the author has extended it to other equipment or systems [3].

Therefore, to analyze the aircraft operational integrity, we must first analyze the aircraft's main operational processes and go to find the master elements which affect the operation of aircraft. When the military aircraft is placed on the battlefield, its combat mission chain can be simply summarized as follows: aircraft assembly → aircraft sortie generate → aircraft cruise → aircraft entry (to the battlefield) → aircraft combat → aircraft withdrawal (from the battlefield) → aircraft return. Then, the aircraft re-assembly, and enters the next combat cycle until the battle is finished, as is shown in Fig.1. The civil aircraft's operational processes are much simpler as follows: aircraft assembly → aircraft sortie generate → aircraft cruise → aircraft return. And then, the next usage cycle continues. So, military aircraft will be mainly discussed afterwards.

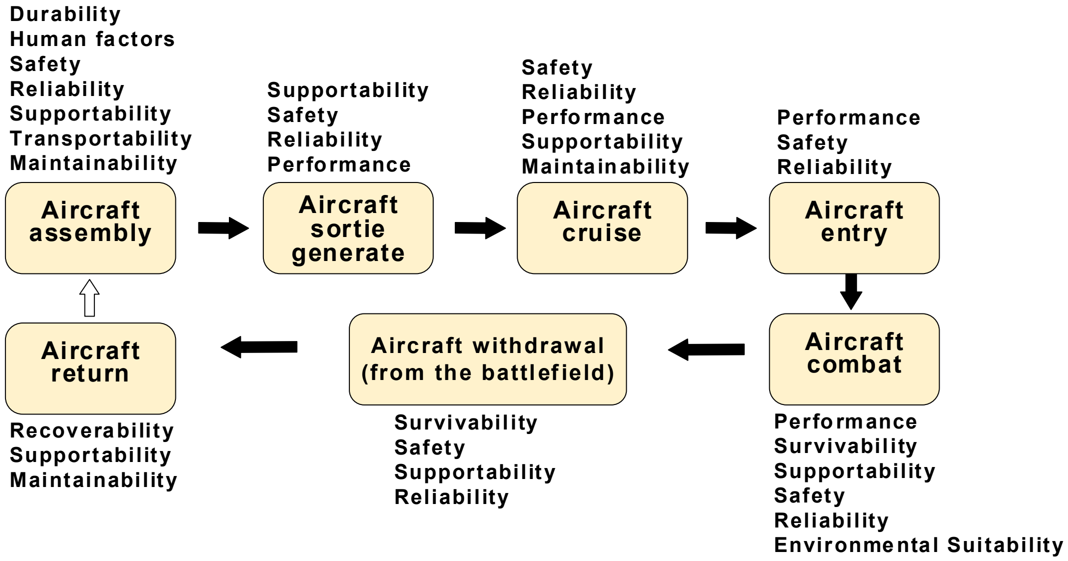

Figure 1 – Requirements for aircraft characteristics at main stages during operational processes

In order to keep the aircraft sound and the functions not weakened throughout the operational processes, various requirements are imposed on the basic characteristics of the aircraft at each operational stage. If some of the most critical and core requirements are not met, it will directly affect the integrity of the aircraft or its functions. For example, at the aircraft assembly stage, we must first have enough available aircraft, which puts forward direct requirements on the durability of the aircraft. If the aircraft has poor durability, it will not be available for a long time service, and it will be impossible to assemble enough aircraft. In the aircraft sortie generate phase, the first thing is to ensure the supportability of the aircraft. Only when the supportability is good enough, can the aircraft be dispatched and prepared quickly and in an orderly way. Otherwise, although there are many aircraft standby, they are not effective enough to get ready for taking off, and of course, they will not be able to effectively enter the battlefield finally. At the cruise stage of the aircraft, the primary requirement is its safety. Because it is impossible to stop for maintenance during aircraft flight, some failures will directly lead to accidents such as crashes. So safety has become the most important requirement during cruise. If the aircraft fails to meet safety requirements, it means that the aircraft will have a high probability to fail in the process of cruise. Consequently the combat mission will be terminated. When an aircraft successfully enters the combat airspace to prepare for the combat, the main requirement is its mission performance. If its mission performance reaches the required state, the aircraft can begin effective attack and enter the combat processes. If the aircraft's mission performance does not meet the requirements, it means that the aircraft cannot start an effective attack and cannot enter a predetermined combat process. In the combat phase of an aircraft, the aircraft combat performance and survivability of the aircraft are most important. If the combat performance cannot be exerted, it cannot attack and defense effectively. Poor survivability means that it will be destroyed by the enemy in this phase. When the aircraft is withdrawn from the battlefield, the reliability, safety, and survivability of the aircraft become very important, among which poor survivability means that the damaged aircraft cannot return directly. If the aircraft is not damaged after it returns, it can directly enter the assembly state and perform the next combat task. If the aircraft is damaged and cannot return, it is necessary to make an emergent landing. There are also requirements for crashworthiness, which are part of safety and also the requirements of the aircraft performance. If the aircraft is damaged, usually it must be repaired and recovered. At this time the aircraft recoverability is very critical. With high recoverability, the damaged aircraft can be quickly repaired and recovered, then put back into operation again; if the recoverability is poor, the damaged aircraft cannot be recovered quickly, it will affect the execution of the next task. Even worse it will lead to no aircraft available after several operational cycles, which will directly affect the victory of the battle.

Generally speaking, the reliability and economical efficiency of an aircraft are reflected in its durability and maintainability; testability are reflected in supportability. And the aircraft must be kept sound or its functions are not weakened during the operational processes. From the above analyses, it can be seen that the durability, supportability, safety, performance, survivability and recoverability of the aircraft must be maintained at satisfactory levels during the operational processes since they are the master elements affecting the aircraft operational integrity during the operational processes.

So, the aircraft operational integrity (AOI) can be described as follows. It is the attribute which exists in aircraft during the operational process, with which the aircraft can be kept sound (or work normally) and its functions are not degraded under the required levels of durability, supportability, safety, performance, survivability and recoverability. The operational integrity of aircraft can also be described as the inherent attribute with which the aircraft remains sound or does not degrade when the aircraft performs and completes the specified missions (or the specified functions) within the specified time and under the specified service conditions (including storage conditions, operational conditions and maintenance support conditions).

The aircraft operational integrity is based on the perspective of the aircraft completing the operational missions, and comprehensively reflects the quality characteristics of the aircraft during the entire operational period. For military aircraft, the operational process includes the process of preparing for combat (training), the process of performing combat mission, and the process of continuously completing the combat missions (that is, the process of repeatedly performing the combat mission until the completion of the combat missions). The process from aircraft structural integrity to aircraft operational integrity is shown in Fig.2.

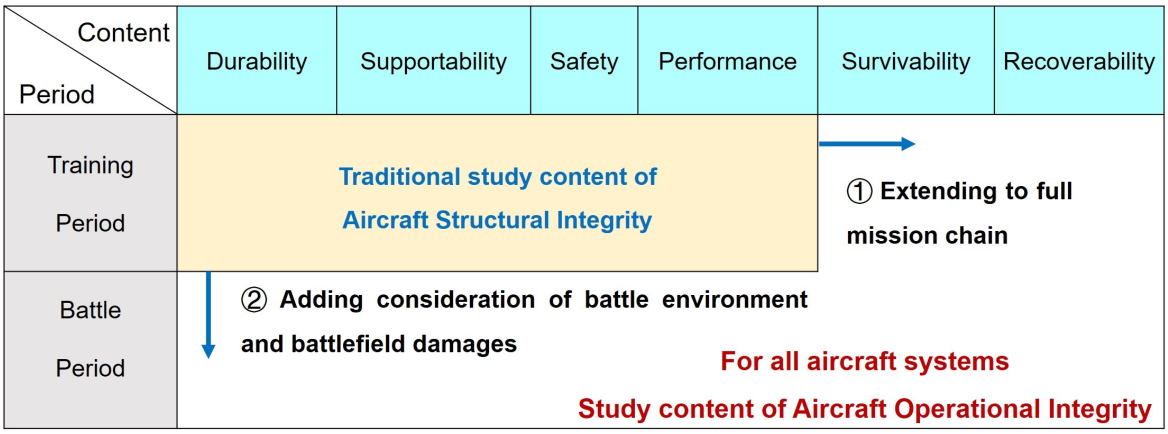

Figure 2 – The formation of Aircraft Operational Integrity

If the aircraft operational integrity is poor, that is, its comprehensive quality characteristics are poor, which is specifically manifested in the poor durability, supportability, safety, performance, survivability, and recoverability, etc., it will directly lead to the aircraft not being effectively used to complete combat missions. Since civil aircraft do not conduct training missions, the combat mission will usually be replaced with transport missions.

2.2 The relationship between aircraft operational integrity and traditional general quality characteristics

The general quality characteristics of the aircraft refer to reliability, safety, maintainability, testability, and supportability. They are gradually developed and improved around the problem of aircraft failures [15], which are reflected from different aspects. The main purpose is to ensure that the aircraft can meet the usual reserve and use requirements during the service period, to ensure stable working conditions and technical performance, and to reduce life cycle costs [16-17]. Indeed, the environmental adaptability belongs to the aircraft operational suitability. In general, the six indexes of aircraft operational integrity are mostly the same as the general quality characteristics of the aircraft. However, comparing both of them, the general quality characteristics of the aircraft reflect a series of measurements of the general quality level of the aircraft, each of which indicates the quality characteristic of a certain aspect of the aircraft. Strictly speaking, environmental adaptability is part of the operational suitability, and it’s higher than quality requirements. The application characteristics of aircraft operational integrity are more distinctive. It takes the aircraft's capability to complete operational missions as a traction, adds the survivability and recoverability indexes of the aircraft as new parameters, and reflects the comprehensive quality characteristics of whether the aircraft can be successfully used to complete required missions. The aircraft operational integrity is a measurement of the available state of an aircraft, where durability concerns reliability and economy. Therefore, it can be seen that the aircraft operational integrity comprehensively reflects the quality characteristics requirements of the aircraft, the stable performance and durable service. The aircraft operational integrity is not only related to the general quality characteristics of an aircraft, but also has their own distinct characteristics, which cannot be replaced by each other.

There have been many studies on the supportability, safety, and performance involved in the aircraft operational integrity.

Survivability refers to the aircraft's capability to avoid and withstand hostile environments without permanently degrading its ability to perform specified missions. The military aircraft sensitivity and vulnerability are the two main factors that determine the survivability of it [18]. The survivability of a civil aircraft can be used to characterize its capability to avoid and withstand accidental threats such as bird strikes, hail or lightning strikes during flight, without permanently degrading its ability to perform specified transportation tasks.

The aircraft durability is considered as a quality characteristic of aircraft [7], which refers to the capability of an aircraft to resist failures and damage caused by environment, load and accidental damage during service, and which reflects the durability of the aircraft. Generally, the durability life can be used to represent the durability of an aircraft, that is, the service lifespan of an aircraft refers to the service limitation period when it is uneconomical to repair or there is a major damage to the aircraft that endangers the safety when in use. In practical application, the durability life of a type of aircraft usually requires high reliability to ensure the safety and reliable operation of the aircraft in operational process; or, within the specified service conditions and durability life cycle of the aircraft, its reliability level also indicates its durability degree. It can also be said that the aircraft durability is a comprehensive reflection of the reliability and economy of the aircraft.

Aircraft recoverability [2] refers to the capability of the aircraft to recover to the required functional state to complete the specified tasks when repairing the unconventional damage (including accidental damages, battle damages, etc.) according to the specified procedures and methods under the specified conditions within the specified time. The aircraft recoverability concerns the repair of unconventional damage such as accidental damages and battle damages. In wartime, the recoverability at the field level is equivalent to battle damage repairability [19-20]. The degree of aircraft recoverability is reflected in two aspects. One is whether the aircraft can be easily recovered in the event of a damage, especially the unconventional damage, which is reflected in the supporting equipment, recovery technology, manpower, and time required for recovery; the other is whether the aircraft can be repaired economically in case of the same damage, which is reflected in the spare parts, consumables and cost needed in the recovery process. When the cost and time required for the repair exceeds a certain value, the aircraft recovery is not cost-effective. So the aircraft is considered unrecoverable at this time. The recoverability and maintainability of the aircraft are inherent characteristics of the aircraft that are given through the design processes and they have many common requirements: such as accessibility, interchangeability, and error proofing design, etc. However, there are obvious differences between recoverability and maintainability. Maintainability concerns the natural failures of the aircraft during normal service period, including failures due to reliability and quality of the aircraft, and human errors. The focus is on "maintain and repair", so generally there is expected standard maintenance or troubleshooting schemes. Recoverability, however, concerns unexpected damages, including accidental damages (such as bird strikes, lightning strikes, ground aircraft collisions, etc.) and battle damage (such as weapon damage and secondary damage, etc.). With its emphasis on "repair and recover", recoverability emphasizes repair measures for unforeseen damages. In addition, compared with maintainability design, recoverability design should pay more attention to the employment of modular design ideas, which is more conducive to the capability of easily and quickly recovering damaged parts of an aircraft.

3 Basic connotation of aircraft operational integrity

3.1 Essential status of aircraft operational integrity

The operational integrity, operational suitability, and operational effectiveness of the aircraft are three basic attributes of any aircraft. The aircraft operational integrity is the attribute with which the aircraft can be used normally (or kept sound) and its function is not degraded under the required durability, supportability, safety, performance, survivability and recoverability levels during the operational processes. The aircraft operational integrity reflects the comprehensive quality characteristics of the aircraft during its operational period, that is, whether the aircraft is integral and capable to be operated to complete the missions. The GJB451A-2005 "Reliability and Maintainability Supportability Terms" defines operational suitability as: "the degree of satisfaction of the aircraft system on the battlefield. It is related to reliability, maintainability, supportability, safety, compatibility, and interoperability factors, including transportability, environmental adaptability, documentation, personnel, and training. " The core of it is to reflect the extent to which the aircraft is satisfactorily put into use in the field, that is, whether the aircraft is suitable for use in the field. The aircraft operational effectiveness is the overall extent to which the representative personnel complete a mission with the aircraft in a planned or expected aircraft operation environment (such as natural environment, electromagnetic environment, battlefield threat, etc.). Factors considered include organization, principles, tactics, and threats (Including interference, initial nuclear weapon effects, and threats of nuclear, biological, and chemical contamination). The core of it is to reflect the extent to which the aircraft completes its mission, that is, whether the aircraft is effective to complete the missions.

The relationship among three basic attributes of the aircraft is shown in Fig.3.

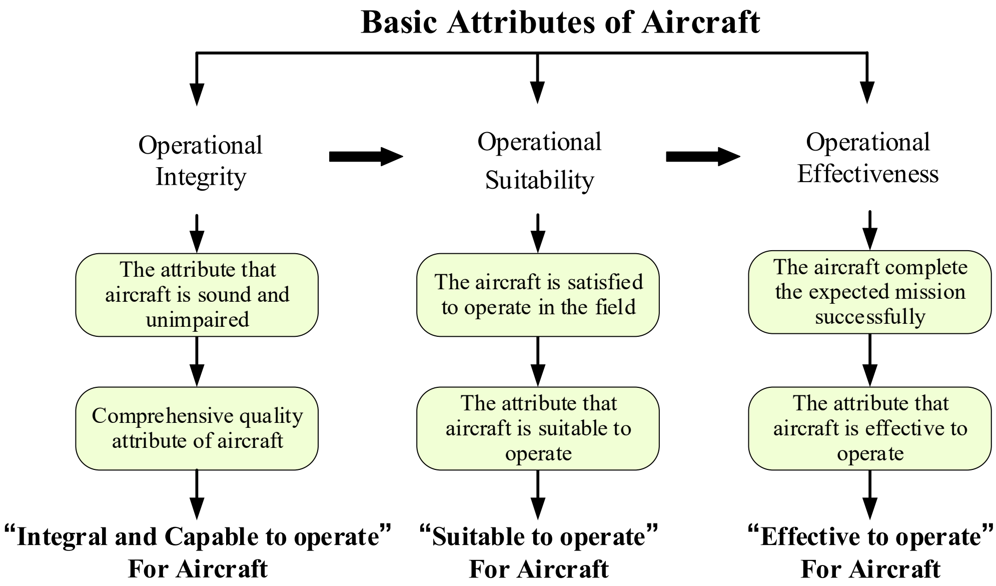

Figure 3 – Three basic attributes of aircraft

From the above, it can be seen that the aircraft operational integrity is the basis for the operational suitability and effectiveness of the aircraft, and also the comprehensive quality characteristics of the aircraft. It reflects the basic problem of whether the aircraft can be used in the operational process. It is the basic attribute endowed in its design and solidified in the manufacturing processes. The aircraft development test and evaluation, the aircraft live fire test and evaluation, and aircraft operational test and evaluation are used to jointly carry out test verification and evaluation systems.

3.2 Research category of aircraft operational integrity

The aircraft operational integrity is a state attribute which characterizes that the aircraft remains sound and its functions are not weakened during the entire operational processes. From the above analyses, it can be seen that the durability, supportability, safety, performance, survivability and recoverability of the aircraft must be maintained at satisfactory levels during the operational processes. Therefore, to study the aircraft operational integrity is to study its durability, supportability, safety, performance, survivability, and recoverability as an organic interconnected whole.

3.3 Basic characteristics of aircraft operational integrity

The basic characteristics of aircraft operational integrity can be summarized as objectivity, relativity, stochasticity and controllability.

Objectivity means that the aircraft operational integrity is an objective attribute, which can be measured by some means. Relativity refers to that the aircraft operational integrity corresponds to the exact training and combat tasks the aircraft undertakes as well as its environments. Without the corresponding tasks and environments, it is meaningless. Stochasticity concerns the randomness of the operational integrity due to the randomness of the quality of the aircraft itself, the tasks undertaken and the working environments. Therefore, the methods of statistics can also be used to describe the aircraft operational integrity. Controllability means that the aircraft operational integrity can be controlled, maintained and increased through certain measures.

3.4 The influence of various parameters on aircraft operational integrity

The aircraft operational integrity is the basis of ensuring the aircraft fleet scale, normal operation, safe use, completion of combat missions and survival on the battlefields in the whole operational processes of the mission implementation and preparation, which directly affects the operational effectiveness of the aircraft. According to the definition of the aircraft operational integrity, the poor aircraft operational integrity can be reflected in one or several aspects of poor durability, poor supportability, poor safety, poor performance, poor survivability and poor recoverability, as is shown in Fig.4.

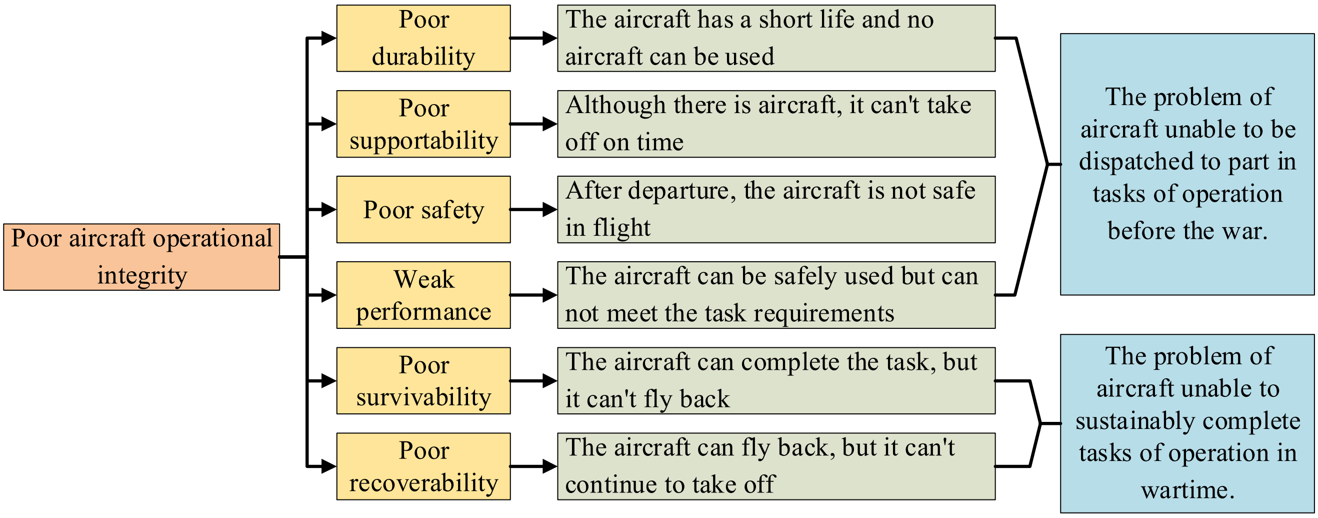

Figure 4 – The embodiment of poor aircraft operational integrity

Poor aircraft durability results in a short service life of the aircraft and may lead to no aircraft available. Poor aircraft supportability makes the aircraft difficult to maintain, even if the aircraft does not operate on time. Poor aircraft safety causes the aircraft to be prone to accidents even after taking off; poor aircraft performance causes that, even though the aircraft can safely reach combat airspace, it cannot meet mission requirements due to aircraft performance limitations; poor survivability of aircraft leads to low survival of aircraft under the threat of enemy fires even though they can complete the tasks, so it is difficult for aircraft to evacuate and return smoothly; the poor aircraft recoverability will result in the damaged aircraft unable to be repaired and recovered in time even if it can return, and the aircraft cannot enter the re-assembly state to continue to perform the next task. Of course, the actual situation is much more complicated and serious than these descriptions, because some index elements work continuously at several stages of aircraft operational process.

It can be seen that, in the aircraft operational integrity, the deficiency of index factors in any aspect will lead to the overall low level of the aircraft operational integrity. That is to say, the aircraft operational integrity index system conforms to the "cask effect", which must be considered comprehensively and coordinately in the whole life cycle of the aircraft.

4 Characterization of aircraft operational integrity

4.1 Characterization of aircraft operational integrity

In order to effectively represent the aircraft operational integrity, the aircraft operational integrity degree, I_o, can be given so that the aircraft operational integrity can be measured. The aircraft operational integrity degree is the probability that the aircraft can remain sound (or normally work) and functions are not weakened when the aircraft performs the specified tasks within the specified time under the specified conditions, which can be represented by formula (1). According to the definition of aircraft operational integrity, the aircraft status with normal work and functions without weakening is determined by the durability, supportability, safety, performance, survivability and recoverability. Therefore, the aircraft operational integrity degree I_o is comprehensively characterized by durability degree U, availability degree A, safety degree S, livability degree C, survivability degree S_u and recoverability degree R_c, which can be expressed as follows.

$$I_o = P\{\tau > t_0\} = f(U, A, S, C, S_u, R_c) \tag{1}$$

In the formula t_0 is the specified time, and τ indicates the time during which the aircraft can work normally and its functions are not weakened. U is the aircraft durability degree. D = 1-U is the damage degree. It is a quantitative measure of the durability damage of the aircraft when it reaches the specified time t. A is the availability degree, which is the ratio of the number of aircraft that can be dispatched normally to the total number of aircraft at a certain level of support (personnel and spare parts). S is the safety degree representing the probability without accidents when the aircraft completes the specified task under the specified conditions throughout the life cycle. C is the livability degree. F = 1-C is the failure rate of the aircraft which is the probability of aircraft failure when the capacity of the aircraft to withstand the load is less than the load carried by the aircraft. S_u is the survivability degree which refers to the probability of the aircraft able to keep working under the damage due to various weapons and non-calculated loads. R_c is the recoverability degree which means the probability that the aircraft suffering from accidental damage or unconventional damage can be recovered to the state capable of completing the specified missions by means of repairs according to the specified procedures and methods under the specified conditions within the specified time. These characteristic parameters of aircraft are determined by those sub-systems of the aircraft.

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

$$I_0 = U \cdot A \cdot S \cdot C \cdot S_u \cdot R_c \tag{2}$$

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

Of course, in practice, the aircraft operational integrity can also be directly reflected by the readiness rate of the aircraft, R which represents the ratio of the number of aircraft in sound state to the total number of the aircraft in the fleet under a given service environment during the specified service period.

$$R = \frac{E_{\text{intact}}}{E_{\text{total}}} \tag{3}$$

In the above formula R is the aircraft readiness rate; E_{intact} is the number of aircraft in sound state, and E_{total} is the total number of aircraft in the fleet. In fact, the aircraft readiness rate can be divided into the aircraft readiness rate R_p in peacetime and the aircraft readiness rate R_w in wartime. Their values are generally different.

It can be seen that the aircraft readiness rate represents the intuitive results of the aircraft operational integrity, but it can not reflect the direct relationship between it and other general quality characteristic parameters of the aircraft. Aircraft operational integrity degree, I_o, can also be used to represent aircraft operational integrity, and it can also reflect the relationship between it and aircraft durability degree U, availability degree A, safety degree S, livability degree C, survivability degree S_u, recoverability degree R_c, so as to realize the design and control of aircraft operational integrity.

4. 2 Characterization of aircraft durability

The aircraft durability reflects the durable extent of aircraft. It refers to the ability of aircraft to resist failure caused by service environments, regular loads or accidental damages. The aircraft durability doesn't only reflect the aircraft reliability, but also reflects the economical efficiency of aircraft.

The damage degree D of the aircraft can be used to measure the severity of the damage in the durability life of an aircraft. It is a quantitative measurement of the damage generated when the aircraft reaches the specified durable service time t. So the calculation method is as follows:

$$D=\frac{\bar{L}(t)}{N} \tag{4}$$

In the above formula $\bar{L}(t)$ refers to the number of aircraft that cannot be kept sound (or work normally) or whose functions are weakened when the specified durable service time t is reached, and N refers to the total number of aircraft of a certain model. It should be noted that aircraft can be repaired economically during the period of the specified durable service time t of the aircraft.

Therefore, the aircraft durability degree U can be used to measure the durability of the aircraft:

$$U=1-\frac{\bar{L}(t)}{N} \tag{5}$$

In practice, the durable service life time N_d is often used to express the aircraft durability, and number of flight hours, taking off-landings, equivalent repeated cycles or service years employed often[21].

4.3 Characterization of aircraft supportability

The aircraft availability degree is often used to measure the aircraft supportability. Here, only the inherent availability degree is used to characterize the aircraft supportability for a brief analysis [22-23].

The inherent availability degree A_i is the ratio of the actual work time to the total time of aircraft. If the probability density function of fault is $b(t)$ and the maintenance time density function is $m(t)$, then the fault interval time T_u and maintenance time T_m are respectively:

$$T_u=\int_0^{\infty} tb(t)\mathrm{d}t \tag{6}$$

$$T_m=\int_0^{\infty} tm(t)\mathrm{d}t \tag{7}$$

then the inherent availability degree is

$$A_i=\frac{T_u}{T_u+T_m} \tag{8}$$

Therefore, the aircraft availability degree is

$$A=A_i \tag{9}$$

4.4 Characterization of aircraft safety

Aircraft safety degree is used to measure the aircraft safety. When the aircraft completes the specified tasks under the specified conditions in the whole life cycle, the probability P of accidents can be expressed as follows[24].

$$P = R \cdot 0 + (1-R) \cdot P_{A/F} \tag{10}$$

R is the aircraft reliability. $P_{A/F}$ is the probability of accidents when the aircraft fails.
Therefore, the aircraft safety degree *S* can be expressed as follows.

$$S = 1 - P = 1 - (1-R) \cdot P_{A/F} \tag{11}$$

If $P_{\overline{A}/F} = 1 - P_{A/F}$ is defined as the probability without accidents. When the aircraft fails, the above formula can be converted into

$$S = R + (1-R) \cdot P_{\overline{A}/F} \tag{12}$$

4.5 Characterization of aircraft performance

The livability degree can be used to measure the aircraft performance. Any aircraft has the performance needed to achieve based on design. That is, the aircraft should be able to bear the load of the design. However, in the actual service and operational processes, for the aircraft that has been produced and delivered for service, its ability to bear the load is a random variable, and the actual load carried by the aircraft in the operational process is also a random variable. It is inevitable that even in the regular service processes, there will be aircraft failures and damages due to that the ability to bear the load is less than the actual acting load. Therefore, the aircraft load-bearing capability—acting load interference model can be used to describe the livability degree under normal usage. The schematic relationship is shown in the Fig.5.

If the one-dimensional probability density function of the acting load amplitude l_a and load-bearing capability amplitude L_a of the aircraft is $f(l_a)$ and $g(L_a)$ respectively, the probability of L_a less than l_a corresponding to any acting load amplitude l_a is

$$G(l_a) = P\left(L_a < l_a\right) = \int_0^{l_a} g(L_a)\mathrm{d}L_a \tag{13}$$

Since the acting load amplitude is always non negative, the lower limit of integration is zero. The distribution function $G(l_a)$ is shown as the shaded area in Fig.5. The probability of acting load amplitude l_a as a random variable is $f(l_a)\mathrm{d}l_a$. Since $G(l_a)$ is a monotone function of l_a and also a random variable, the probability of $G(l_a)$ occurrence is also $f(l_a)\mathrm{d}l_a$. The product of the two is the differential $\mathrm{d}F$ of aircraft failure probability F:

$$\mathrm{d}F = G(l_a) f(l_a)\mathrm{d}l_a \tag{14}$$

By integrating the above formula, the aircraft failure probability F is obtained

$$F = \int_0^{(l_a)_{\max}} G(l_a) f(l_a)\mathrm{d}l_a \tag{15}$$

Then, take equation (13) into the above equation to get

$$F = \int_0^{(l_a)_{\max}} \left[\int_0^{l_a} g(L_a)\mathrm{d}L_a\right] f(l_a)\mathrm{d}l_a \tag{16}$$

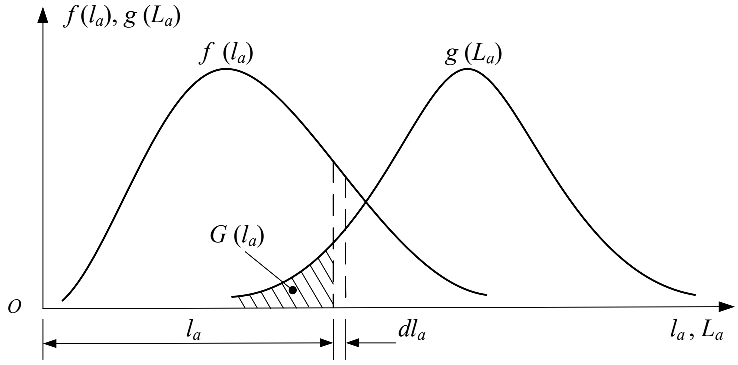

Figure 5 – Load-bearing capability—acting load interference model of aircraft

Therefore, the livability degree of aircraft is

$$C=1-F \tag{17}$$

4.6 Characterization of aircraft survivability

The sensitivity and vulnerability are two main elements that determine the survivability of aircraft [17]. The sensitivity is generally expressed by means of the hit probability P_H by the threatened mechanisms. Vulnerability is a conditional probability $P_{K/H}$, which is the damage probability when an aircraft is hit by one or more mechanisms. It is also equal to the ratio of killed aircraft to the number of hit aircraft.

$$P_{K/H}=M_{Killed}/M_{Hit} \tag{18}$$

In the above formula, M_{Killed} is the number of lost aircraft and M_{Hit} is the number of hit aircraft.

Therefore, after the aircraft takes part in a battle, its damage probability is:

$$P_D = P_H \cdot P_{K/H} \tag{19}$$

Thus, the aircraft survivability degree is

$$S_u = 1 - P_D \tag{20}$$

4.7 Characterization of aircraft recoverability

The aircraft recoverability can be measured by the recoverability degree [2], which is a probability index and mainly reflected in the recovery time, recorded as $R_c(t)$. The meaning of aircraft recoverability degree $R_c(t)$ is the probability that the aircraft suffering from accidental and unconventional damages can be restored to the state with capacity of completing the specified tasks in accordance with the specified procedures and methods within the specified time under the specified conditions. It can also be expressed by the proportion of the number of aircraft recovered to the state with capacity of completing the specified tasks. That is, aircraft recoverability degree $R_c(t)$ can be expressed by the following formula.

$$R_c(t) = P(T \le t) = \frac{q_t - q_{n,t}}{q_t} \tag{21}$$

T is the recovery time under the specified conditions, procedures and methods; *t* is the specified time; q_t and $q_{n,t}$ refer to the total number of aircraft suffering from accidental and unconventional damages within the specified time t and the number of aircraft unable to be recovered to the state with specified capabilities.

Recoverability can also be expressed by the Mean Time to Recovery, *MTTRC*, which is the average time taken by a required group of persons with the required technical levels to repair the aircraft with a certain level of accidental and unconventional damage to restore specified functions based on specified procedures and resources (equipment, tools, spare parts, manpower, logistics, etc.). It can be expressed as follows.

$$MTTRC{=}E(Y)=\int_0^\infty tm(t)dt \tag{22}$$

Y is the recovery time and *m(t)* is the recovery density function, which is the probability of completing the repair work in time $\Delta(t)$.

Aircraft recoverability also can be characterized by the accidental damage recovery cost *MRCC* (Mean Recovery Cost). *MRCC* is actually the mean amount of resources expended by personnel with specified technical levels to repair the same model aircraft with a certain extent of accidental damages to the status with specified functions by means of the prescribed procedures and methods. And the Mean Working Time to Recovery, *MWTTRC*, can also be used to measure the aircraft recoverability. The *MRCC* and *MWTTRC* factors can be used to compare the recoverability of similar models of aircraft.

5 Composition and distribution of aircraft operational integrity

5.1 Composition of aircraft operational integrity

The aircraft is composed of various component systems, briefly known as functional systems and missional systems, as is shown in Fig.6. Usually there are some functional systems in aircraft such as structural system, fuel system, environmental control system, flight control system, power system, propulsion system, etc. as well as some mission systems such as communication system, detection system, fire control system, early warning system, etc. These systems have their own operational integrity characteristics, and they eventually constitute the aircraft operational integrity. In fact, the aircraft is also a large system.

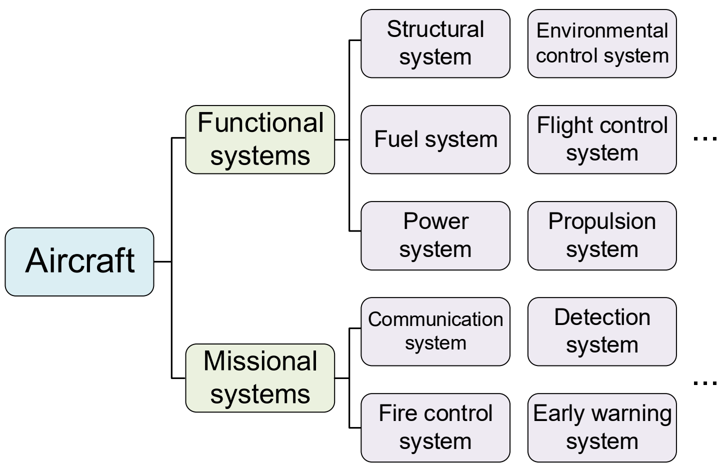

Figure 6 – Composition of aircraft

The system operational integrity (SOI) can be similarly defined: as the attribute with which the system can be kept sound (or work normally) and the functions are not weakened, under the required durability, supportability, safety, capability, survivability and recoverability levels during the operational processes of the system. The system operational integrity can also be expressed as the inherent attribute with which the system is in good condition or does not degrade in functions when performing the specified tasks (or completing the specified functions) under the specified service conditions (including storage conditions, operational use conditions and maintenance support conditions) within the specified time. The system operational integrity can be characterized by the system operational integrity degree I_{os}, which is the function of durability degree U_s, availability degree A_s, safety degree S_s, livability degree C_s, survivability degree S_{us} and recoverability degree R_{cs}.

$$I_{os} = P\{\tau > t_0\} = f(U_s, A_s, S_s, C_s, S_{us}, R_{cs}) \quad (23)$$

If the operational integrity degrees of systems of the aircraft can be expressed as I_{os1}、I_{os2}、I_{os3}、I_{os4} ……I_{osn}, the aircraft operational integrity degree should be the function of them and can be expressed as:

$$I_o=f(I_{os1}, I_{os2}, I_{os3}, I_{os4}, \ldots\ldots I_{osn}) \quad (24)$$

5.2 Distribution of aircraft operational integrity

The aircraft operational integrity is composed of the operational integrity of each system that makes up the aircraft. Therefore, if the requirements of aircraft operational integrity are put forward, the operational integrity index of each system must be obtained through the distribution method of operational integrity. Because the operational integrity is a probability index, it can be dealt with by probability theory, such as series model method, parallel model method, hybrid model method and so on[25].

6 Summary

（1）The basic concept of aircraft operational integrity was put forward. It represents the comprehensive quality characteristics of aircraft, and reflects the basic attribute of whether the aircraft can be sound(or work normally) and the functions are not weakened in the operational processes.

（2）The basic connotation of aircraft operational integrity was expounded and the characterization method of aircraft operational integrity was proposed. For the purpose of simplification, it can also be characterized as $I_o = U \times A \times S \times C \times S_u \times R_c$. At the same time, it is pointed out that the aircraft operational integrity can also be intuitively reflected by the readiness rate R of the aircraft.

（3）The aircraft load-bearing capability—acting load interference model is proposed to describe the failure probability of the aircraft due to the weak performance.

（4）It is pointed out that the aircraft operational integrity is composed of the operational integrity of each component system, and the basic distribution method from the operational integrity index of aircraft to the operational integrity index of each component system is given briefly.

As the comprehensive quality characteristics of aircraft, aircraft operational integrity is the basis of aircraft operational suitability and aircraft operational effectiveness. This paper attempts to describe and characterize the comprehensive quality characteristics of aircraft scientifically and provide theoretical basis for the comprehensive quality control of aircraft. 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 representation of aircraft operational integrity can also be applied to other products.

Copyright Statement

References：

[1] Gan Maozhi，Wu Zhenzhen. Maintainability design and verification. Beijing: National Defense Industry Press,

1995.

[2] He Yuting. Aircraft recoverability and its design methods. Journal of Air Force Engineering University (Natural Science Edition), Vol. 20, No. 6, pp 1-8,2019.

[3] He Yuting. A study of equipment operational integrity. Journal of Air Force Engineering University (Natural Science Edition), Vol. 21, No. 1, pp 1-8,2020.

[4] Jiao Zhiqiang, Shu Chenghui. The development of the design concept of aircraft structural integrity and the evolution of its standards. Aeronautic Standardization & Quality, No. 1, pp 21-24,2010.

[5] USA Department of Defense. Aircraft structural integrity program (ASIP). Department of defense standard MIL-STD-1530D(USFA), 2016.

[6] The General Armaments Department of PLA. Structural integrity program of military aircraft. The People's Republic of China military standard, GJB775.A–2012, 2012.

[7] Wang Liqun. Aircraft Equipment Integrity. ACTA Aeronautica ET Astronautica SINICA, Vol. 9, No. 10, pp 433-439, 1988.

[8] USA Department of Defense. Engine structural integrity program (ENSIP). Department of defense standard MIL-STD-1783(USFA), 1984.

[9] USA Department of Defense. Avionic integrity program (AVIP). Department of defense standard MIL-STD-1796A(USFA), 2011.

[10] USA Department of Defense. Mechanical equipment and subsystems integrity program. Department of defense standard MIL-STD-1798C(USFA), 2013.

[11] USA Department of Defense. Weapon system integrity program. Department of defense standard MIL- HDBK-515 (USFA), 2013.

[12] USA Department of Defense. Propulsion system integrity program. Department of defense standard MIL-STD-3024(USFA), 2008.

[13] He Yuting, Zhang Teng, Ma Binlin, et al. Structural integrity control technology based on structural damage monitoring. 36th Conference and 30th Symposium of the International Committee on Aeronautical Fatigue and Structural Integrity, Poland, 2019.

[14] He Yuting, Zhang Teng, Ma Binlin. Basic connotation and evaluation of military aircraft structural operational integrity. Journal of Air Force Engineering University (Natural Science Edition), Vol. 20, No. 5, pp 1-7, 2019.

[15] The General Armaments Department of PLA. Quality management system requirements. The People's Republic of China military standard, GJB 9001C-2017, 2017.

[16] Zhang Haijun. Review on quality characteristic of equipment. Dual Use Technologies & Products, Vol. 09, No. 2, pp 252-253, 2015.

[17] The General Armaments Department of PLA. Terminology of reliability and maintainability. The People's Republic of China military standard, GJB451.A–2005, 2005.

[18] Li Shulin, CHANG Fei, HE Yu-ting. Survivability analysis and evaluation of military aircraft in operational use. National Defense Industry Press, 2016.

[19] Zhang Jianhua. Aircraft battle injury emergency repair engineering. Aviation Industry Press, 2001.

[20] Yao Wuwen. Criteria and methods for safety flight assessment of battle injured aircraft. National Defense Industry Press, 2016.

[21] He Yuting, Zhang Teng, Cui Ronghong, et al. Theory and technology of aircraft structural life control. National Defense Industry Press, 2017.

[22] Zhang Hengxi, Liu Xiaodong, Duan Baojun, et al. Cost-effectiveness analysis of modern aircraft. Aviation Industry

Press, 2001.

[23] Ma Shaoming, Zhang Guodong. Comprehensive support project. National Defense Industry Press, 1995.

[24] He Yuting. Safety engineering of aircraft. National Defense Industry Press, 2014.

[25] Forcina Antonio; Silvestri Luca; Di Bona Gianpaolo, et al. Reliability allocation methods: A systematic literature review. Quality and Reliability Engineering International, Vol. 36, No. 6, pp 2085-2107, 2020.