COMPREHENSIVE DESIGN AND EVALUATION OF AIRCRAFT STRUCTURAL SYSTEM EFFECTIVENESS

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Abstract

The concept of Aircraft Structural System (ASS) effectiveness is presented, as well as the definition of comprehensive evaluation of ASS effectiveness, and the model of ASS effectiveness is selected and the influence elements and the relationship are analyzed. Then the connotation and basic methods of the design and evaluation of ASS effectiveness is introduced.

1 Concept of ASS Effectiveness

Generally speaking, the stage of aircraft design can be divided into two phases, namely, Overall Design and Structural Design. The former consists of conceptual design and preliminary design. The latter is mostly the detailed design[1,2].

The basic configuration of structure should be determined at the overall design phase so that structural design phase can be finished successfully. However, it is not certain that a safe structure is a good one. Actually, the final purpose of structural design is to get a structure with the highest effectiveness. How to find out the best one from various design schemes of ASS and how to evaluate a designed ASS? Strength, weight or service life of the ASS is traditionally used to evaluate its capability. But, these parameters could not reflect the systems' characteristics comprehensively. Here, concept of ASS effectiveness is presented, as well as the comprehensive design and evaluation methods of ASS.

Aircraft structural system effectiveness is defined as the measurement of the degree for the ASS to achieve its scheduled requirements[3]. It is the function of ASS availability, dependability and inherent capability. The ASS effectiveness may be expressed as

$$E=A\times D\times C \qquad (1)$$

Here, E is ASS effectiveness; A is ASS availability vector; D is ASS dependability matrix; and C is ASS inherent capability matrix, which stands for the probability matrix of system characteristics under the existing mission and status.

2 Design of ASS Effectiveness

The contents of design of ASS effectiveness consist of design for availability, dependability and inherent capability. The relationship between its relative elements is shown in Fig.1[3].

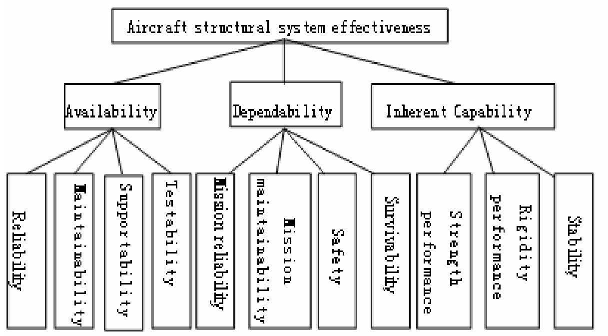

Fig.1 The Relationship of Relative Elements of Aircraft Structure Effectiveness

2.1 Design for Availability

The availability of ASS is the integrated description of its reliability, maintainability, supportability and testability.

2.1.1 Design for Reliability

The reliability of aircraft structure is the ability to complete the prescribed function for a specified period of time under the operational conditions and environments specified by the tactical and technical requirements or operational technical requirements[4,5]. The design for reliability of the aircraft structure is to take some appropriate technical measures in the aircraft structure's design process so as to improve the structure's reliability as high as possible. The detailed design is the key to ensure the structural reliability[4].

2.1.2 Design for Maintainability

The maintainability of aircraft structure is the ability to preserve or resume its prescribed function when maintaining with the required procedure and methods under the specified conditions and time[6]. Accessibility and the convenience for assembling and disassembling should be mainly considered during the design for maintainability of aircraft structures[5].

2.1.3 Design for Supportability

Supportability is the ability of the structural system that the design characteristics and the scheduled support resource can satisfy the operational requirements during both peacetime and wartime. Supportability is an inherent attribute of equipment system, which includes the meaning of the following both sides: the design characteristics of equipment system and the plenitude and adaptive degree of the support resource[7].

The aircraft structures are the flat of the aircraft weapon system. The consideration of the aircraft's supportability during its design phase will directly influence the aircraft's final supportability. During the aircraft structure's design phase, the consideration of the aircraft's supportability mainly includes the following aspects:

(1) Establish a reasonable project of maintenance and support to program the resource for maintenance and support.

(2) Try hard to reduce the workload of the preventive maintenance, especially the maintenance at the air fields, in order to reduce the maintenance down-time and amount of the maintenance staffs.

(3) Make it easy to carry on the maintaining to get rid of failure, and try to adopt general-purpose and simple tools and equipments (including the test equipments inside the aircraft). For example, key structural components should be reachable and open, and the maintenance equipments should be products off the shelf as more as possible.

(4) Under the battle damage conditions, the maintenance work should be finished by using the usual maintenance tools as more as possible, even the special maintenance kits and equipments also should be convenient for using, carrying and transporting.

(5) Maintenance fittings ration and its supply project should be standardized, and the varieties and quantity should be reduced.

(6) Fixed facilities and corresponding maintenance equipments suiting different level of maintenance should be considered and try to make full use of the existing equipments.

(7) Concise and applicable technical documents that are consistent with the technical state of the equipments should be worked out so that maintenance requirements can be unified. And it will be easy for the maintenance staffs to operate.

(8) Training of maintenance staffs should be easy to be carried out. Maintenance staffs don't need very high cultural level and can be easily replaced and added.

2.1.4 Design for Testability

An ASS with favorable testability will has high self-checking ability and be convenient to be checked and maintained and convenient for maintaining and diagnosing by exterior test set. The testability of an ASS can be improved by enhancing the inherent testability design, compatibility design and Body Inside Test(BIT) design [8].

2.2 Design for Dependability

The dependability of aircraft structure is the ability to be used and complete the prescribed function at any time in the prescribed mission profile with the availability prescribed at the beginning of mission. It describes the state that the aircraft structural system in mission duration, in other word, it reflects whether or not the aircraft structures could work continuously.

In the mission duration, because of the effectiveness of enemy equipments, part of effectiveness of an aircraft can not be brought into play. Or part of equipments or facilities can not work because of aircrafts are beaten or destroyed, and the accomplishment of the combat mission could be influenced. Thus, considering the actual combat conditions, mission reliability and survivability of aircrafts are the main contents of the design for aircraft structure dependability.

2.2.1 Design for Mission Reliability

Not considering the actual combat conditions, the aircraft structural reliability could be showed as:

$$D=R_m+(1-R_m)M_t \qquad (2)$$

Here, R_m is mission reliability, M_t is mission maintainability.

Mission reliability of an aircraft structure is the ability to complete the prescribed function in the prescribed mission profile. It reflects the ability of ASS to accomplish mission in the mission duration. Mission maintainability of aircraft structures is the ability to preserve or resume the prescribed state in fixed mission profile through maintaining. It emphasizes the ability to keep effectively and resume rapidly function at operating location and in certain time limit in its mission duration. Here, aircraft structural dependability is the function of mission reliability and mission maintainability. As to fighting aircraft, it can’t be repaired during the flight, so M_t equals zero, and aircraft structural dependability is the mission reliability.

2.2.2 Design for Survivability

Aircraft structural survivability is the survivability under the combat conditions of aircraft structures[9]. Aircraft structural survivability is the synthesis of susceptibility and vulnerability and it always is expressed by the survivability(or damage probability)under particular environments. Survivability may be expressed indirectly by single shot hit probability, the survivability probability of one versus one, the survivability probability of single attack.

The purpose of design for aircraft structure survivability is to reduce the susceptibility and vulnerability of aircraft structures by technical measures.

2.3 Design for Inherent Capability

The purpose of design for aircraft structural inherent capability is to make aircraft structures meet the strength performance, rigidity performance and requirements for stability by using of technical methods. In this field, there have been a lot of ripe methods, means and theories which have been developed by aircraft structural engineers[10,11], and here we skip them.

3 Evaluation of ASS Effectiveness

The inherent effectiveness of aircraft structure system has been determined after the completion of design[12]. To evaluate and compare different aircraft structural systems or balance the structural design scheme at the initial phase of development of aircrafts, certain quantitative methods must be adopted to measure quantitatively ASS effectiveness, and this kind of scale of measurement is the index of ASS effectiveness.

System analysis, research and quantitative evaluation of ASS effectiveness and its comprehensive cost-effectiveness characteristics are considered as the comprehensive evaluation of ASS effectiveness. It consists of the evaluation of availability, dependability, capability and comprehensive cost-effectiveness characteristics of ASS.

3.1 Evaluation of Availability

The purpose of evaluation of availability is to make the aircraft structure systems achieve its anticipated optimization aim by confirming the requirements of availability index and the responding indexes such as reliability and maintainability.

Based on the different moment at which aircraft structures work, the availability of aircraft structures can be expressed by instantaneous availability, mean availability or stationary availability.

The content of evaluation of availability of ASS is shown in Fig.2.

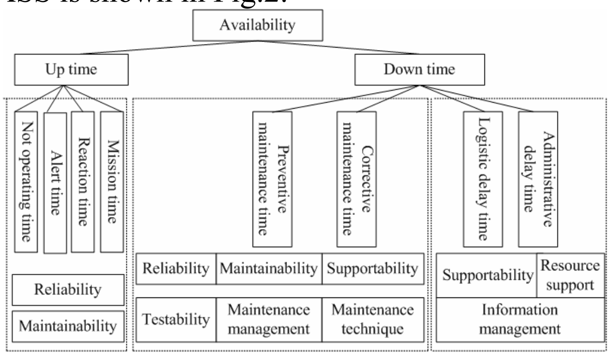

Fig.2 The Relative Elements and Time Component of Availability

3.1.1 Instantaneous Availability

The instantaneous availability is the probability that the structural system is operable in certain time t after it has began to work, expressed as $A(t)$. If it only has two kinds of states,

$$X(t)=\begin{cases}0 & \text{in up time}\\ 1 & \text{in down time}\end{cases} \tag{3}$$

thus,

$$A(t)=P\{X(t)=0\} \tag{4}$$

3.1.2 Mean Availability

The mean availability is the average of instantaneous availability of ASS in the period of time [0,t], and can be expressed as $\overline{A}(t)$,

$$\overline{A}(t)=\frac{1}{t}\int_0^t A(t)dt \tag{5}$$

3.1.3 Stationary Availability

When the structural system has to work for a long time in succession, the stationary availability could be getting. It can be expressed as A, $0 \le A \le 1$.

$$A=\lim_{t\to\infty} A(t) \tag{6}$$

This value expresses the proportion of time in which the aircraft structure is in up time during a long period of operation. So, the stationary availability A could be showed as,

$$A=U/(U+D) \tag{7}$$

Here, U is the up time, D is the down time.

Generally, the stationary availability A consists of three parts: inherent availability, achieved availability and operational availability.

Only considering the actual operating time and corrective maintaining time, the inherent availability is the stationary availability, expressed as A_i. It reflects the inherent attribute of aircraft structural reliability and maintainability.

$$A_i = MTBF/(MTBF+MTTR) \tag{8}$$

Here, MTBF is the mean-time-between-failures, and MTTR is the mean-time-to-repair.

To ensure the aircraft structure to be operable, maintenance activities should consist of corrective maintenance and preventive maintenance. If the down time of aircraft structure is defined as the sum of preventive maintenance time and corrective maintenance time, the stationary availability A is the achieved availability, expressed as A_a. It is the maximum of the ASS availability, and preventive maintenance time, logistic delay time and administrative delay time are not considered in it.

$$A_a = \overline{T}_{bm}/(\overline{T}_{bm}+\overline{M}) \tag{9}$$

Here, $\overline{T}_{bm}$ is the mean-time-between-maintenance, $\overline{M}$ is the mean-maintenence-time [6].

The operational availability is the measurement of availability based on the up time and down time of aircraft structure system, expressed as A_o. Preventive maintenance time, corrective maintenance time, logistic delay time and administrative delay time are entirely considered in down time of aircraft structures, and it has described the operable state of ASS under actual operational environmental conditions.

$$A_o = \overline{T}_{bm} / \left(\overline{T}_{bm} + \overline{D}\right) \quad (10)$$

Here, $\overline{D}$ is the mean down time including maintenance time and delay time. Generally speaking, $A_o \le A_a \le A_i$.

3.2 Evaluation of Dependability

The dependability is the probability measurement of the aircraft structural dependability and in common is expressed as 'D'. 'D' is the matrix of conditional probability of ASS in some mission duration, and it describes the probability of state transfer in mission duration. The dependability matrix is a phalanx.

$$D = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ d_{n1} & d_{n2} & \cdots & d_{nn} \end{bmatrix} \quad (11)$$

In the matrix, d_{ij} is transfer probability from initial state i to state j after prospective part of mission duration. If the output of aircraft structural system is not continuous in mission duration but it produces outputs only in certain time points, d_{ij} is defined as transfer probability from initial state i to output state j. If some basic parameters of the aircraft structural reliability and maintainability have been obtained, such as MTBF and MTTR, its dependability usually can be confirmed directly, and the computation method is similar to the computation method of common systems[4]. The obtained dependability is a kind of measurement of the "comparative static" dependability of aircraft structures and description of the ability to operate continuously under common operational conditions without any artificial enemy threatening conditions.

Here the dependability is mostly decided by the reliability, maintainability, supportability and testability, and so on. And the dependability is easy to be confirmed generally considering the parameters such as MTBF, MTTR, MCSP (Mission Complete Successfully Probability), and MTBCF (Mission Time Between Critical Failure) .

Considering the actual environmental conditions, the aircraft structural survivability becomes the main content of the dependability. The aircraft structural survivability mostly includes susceptibility and vulnerability[9]. The former represents the ASS's ability of avoiding exposure and being hit by enemy, and the latter represents the ability not to be damaged after being hit.

The susceptibility of ASS usually can be scaled by hit probability P_H. It is the product of detected probability P_d and hit probability after being detected $P_{H/d}$.

$$P_H = P_d \cdot P_{H/d} \quad (12)$$

The vulnerability of ASS can be expressed by conditional damage probability after being hit one time $P_{K/H}$, so the damage probability of aircraft structure can be expressed as:

$$P_K = P_H \cdot P_{K/H} = P_d \cdot P_{H/d} \cdot P_{K/H} \quad (13)$$

The survivability of ASS after being hit one time can be expressed by the probability of survival P_s, so

$$P_s = 1 - P_K \quad (14)$$

The probability of survival of ASS after being hit n times can be expressed as $\overline{P_s}^{(n)}$, so

$$\overline{P_s}^{(n)} = P_s^{(1)} \cdot P_s^{(2)} \cdots P_s^{(i)} \cdots P_s^{(n)} \quad (15)$$

Here, $P_s^{(i)} (i = 1,2,\cdots,n)$ is the probability of survival of ASS after being hit about i times.

3.2.1 Evaluation of ASS Dependability under Common Operational Conditions

Not considering the battle environments, the dependability of the ASS may be represented as follows:

$$D = R_M + (1 - R_M)M_t \qquad (16)$$

Here, R_M is the mission reliability, and M_t is mission maintainability.

An aircraft can not be repaired in its flight process. Therefore, dependability of ASS is just the mission reliability. In fact, we are only concern about the reliability during its mission duration.

$$R(t + \Delta t / t) = R(t + \Delta t)/R(t) \qquad (17)$$

Mission failure rate is opposite to mission reliability. It is the conditional probability of failure during the period of time $[t, t + \Delta t]$ which might influence the accomplishment of combat mission of ASS. When failure rate obeys the exponential distribution, the experiential failure rate ($\lambda^*(t)$) could be calculated by statistical data.

$$\lambda^*(t) = \left(1/\overline{N_s}(t)\right)\left(\Delta N_f(t)/\Delta t\right) \qquad (18)$$

Here, $\overline{N_s}(t)$ is the average survival number, and $\Delta N_f(t)$ is the number of failures during the period of Δt.

$$\overline{N_s}(t) = [N_s(t - \Delta t) + N_s(t)]/2 \qquad (19)$$

3.2.2 Evaluation of ASS Dependability Under Battle Environmental Conditions

Under the battle environments, the content of the evaluation of ASS dependability is mainly the evaluation of survivability, which mainly involves the evaluation of susceptibility and vulnerability of aircraft structure.

Evaluation of ASS survivability mainly involves the calculation of the aircraft structure survival probability under particular environment. The damage probability of the aircraft structure is a synthesis measurement of the structural susceptibility and vulnerability under the environment.

The damage probability of single shot hit of aircraft structure P_{KSS} is calculated on the basis that the aircraft has already be found and the threat has already launched or fired. It depends on the ability of the fire control or guidance system of enemy. P_{KSS} can be obtained by

$$P_{KSS} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \rho(x, y) P_f(x, y) V(x, y) d_x d_y \qquad (20)$$

Here, $\rho(x, y)$ is distributing function of distance of missing the target. $V(x, y)$ is the damage function, it define the target damage probability induced by the threat when it exploded in the interception level. $P_f(x, y)$ is the probability of touching off the high energy bomb. These functions are described and analyzed in relevant literature in detail[9].

3.3 Evaluation of Inherent Capability

The inherent capability of ASS consists of strength, rigidity and stability. So evaluation of inherent capability includes the following aspects.

3.3.1 Evaluation of Strength

Aircraft structural strength is the ability to resist being destroyed. Traditionally, the index system for aircraft structural strength includes: static strength index, dynamic strength index, fatigue strength index, thermal strength index, damage tolerance / durability index, etc [10].

3.3.2 Evaluation of Rigidity

Besides strength, rigidity is an important index for modern aircraft structures. The design criterion for structural rigidity can be expressed as

$$\delta \le [\delta] \qquad (21)$$

Here, δ is the deformation amount of structure under design load, $[\delta]$ is the permitted deformation amount.

As to pneumatic elastic problem, the requirement rigidity is put forward, its formula is

$$fV_{man} \le V_{cr} \qquad (22)$$

Here $V_{\max}$ is the maximum flight velocity, V_{cr} is the critical flutter velocity, and f is safety factor.

3.3.3 Evaluation of Stability

Structural stability is a very complicated issue, which is related to geometry, loading, boundary conditions, and so on. For the analyses of aircraft structural stability, design criteria include statics criterion and energy criterion [11].

3.3.4 Comprehensive Characteristics Evaluation

According to behavior in the operation of aircraft structure, three indexes can be used to assess its characteristics.

(1)Aircraft structural weight coefficient

An important goal of the design work of present aircraft is to lighten its structural weight. The rate that aircraft structural weight account for its take off weight is called aircraft structural weight coefficient normally. The structural weight coefficient of the second generation of fighter is about 33%, and the third generation of fighter's is about 30%, and the fourth generation of fighter's is reduced to about 28%. The decline of the structural weight coefficient of aircrafts can improve the performance of aircrafts.

(2)Aircraft structural service life

Aircraft structural service life is usually represented by its fatigue life (flight hours or takeoff and landings), it reflects integrated characteristics of aircraft structures and is the embodiment of the integrated application of various strength designing techniques. People always don't hope the aircraft structural service life is too short. The aircraft structural service life usually is determined by the way of the combining of tests and analyses [13].

(3)Aircraft structural calendaric life

Aircraft structural calendric life is mainly influenced by the environmental condition in which it served in. The aircraft structural calendric life is related to not only service environmental conditions but also its annual flight intensity. The methods of evaluation of structural calendric life is introduced and analyzed in detail in relevant literature[13].

3.4 Evaluation of Comprehensive Cost-effectiveness Characteristics

Comprehensive cost-effectiveness characteristics of ASS may be expressed with the ratio of cost-effectiveness[14]. At the same time, the comprehensive cost-effectiveness characteristics may be evaluated through the tradeoff analysis.

$$M(M) = M(E) / M(ASLCC) \qquad (23)$$

Here, M(M) is index of effectiveness and cost; M(E) is normalized ASS effectiveness; M(ASLCC) is normalized life cycle cost of aircraft structure.

4 Conclusion

After presenting the concept of ASS effectiveness, the model of ASS effectiveness is selected and the influence elements and the relationship are analyzed. The definition of comprehensive evaluation of ASS effectiveness is presented. Then the connotation and basic methods of the design and evaluation of ASS effectiveness is introduced.

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