AN ASSESSMENT MODEL OF AIRCRAFT STRUCTURAL SAFETY BASED ON ROUGH SET THEORY

Yuting He, Wenjun Shu, Ronghong Cui, Jinqiang Du
Department of Aircraft and Aero-engine Engineering, Engineering College, Air Force Engineering University, 710038, Xi'an, P.R.China

Keywords: *structural safety, assessment, conditional probability, uncertainty, rough set theory*

Abstract

The aim of the whole activities in the aircraft structure design and the most important issue in the service of aircraft structure is to ensure their safety for long-time operation. People used to employ the structural reliability to express the structural safety, having made a great progress in keeping the structure safe. However, the structural reliability is not the same as the structural safety. In this paper, an analytical model of the aircraft structural safety based on conditional probability is firstly built. Then, an indexes system from the static strength, fatigue strength, damage tolerance, and structural health monitoring (SHM) system is put forward. Finally, considering many uncertainties induced by the absence and decentralization of safety information, a rough set theory based model is established to assess the structural safety of aircraft.

It is shown from the case study that the model can make the assessment more objective and feasible because it can take more accounts of the uncertainties in the structural safety analysis.

1 Introduction

Safety is the number one goal in aircraft structure design. For the most time, aircraft structure has a good record, with crashes due to structural failure being extremely rare according to the reported accidents [1, 2]. Nevertheless, they occur, and at a rate that requires a continual consideration on the measures of achieving structural safety.

The design philosophies and specifications for aircraft structure came from the experience of aircraft usage. They have evolved over the years from the static strength criteria at the primary stage to the durability/damage tolerance criteria recently. Now the reliability criteria attract much attention of the aircraft structure designers and have been used in the design of aircraft structure [3]. Besides, the SHM system has been designed into the aircraft and increases the safety level of aircraft structure greatly [4].

The evolutions of the design philosophy and specification in aircraft structure have necessitated a change in the nature of aircraft structural safety assessment. People used to employ the structural reliability to express the safety of structure [5], which only takes into account the safety from the aspects of static strength, fatigue strength and durability/damage tolerance. The influence of SHM system on the safety of aircraft structure has not been considered yet. The introduction of SHM system into the aircraft structure has been proved improving much of the aircraft structural safety level. So the influence of the SHM should be taken as an important factor in the assessment of aircraft structural safety.

This paper tries to explore the nature of aircraft structural safety and put forward a comprehensive assessment model for aircraft structural safety. Firstly, an analytical model of aircraft structural safety based on conditional probability is built. Then the indexes system of aircraft structural safety is put forward from static strength, fatigue strength, damage tolerance, and SHM system. Finally, due to much uncertainty in the assessment, the rough set theory is employed to deal with the uncertainty and a rough set theory based assessment model is established and applied to a case study of aircraft structural safety assessment.

2 Safety of Aircraft Structure

2.1 The Nature of Structural Safety

Both safety and reliability are the inherent characteristics of aircraft structure. They are two closely related concepts and either can be expressed by probabilistic method. People used to think that the more reliable, the safer. Yet the reliability is not the same as the safety, and they are very different in nature. The theme of reliability theory is failure and the core technology is failure analysis, while the topic of safety theory is accident and the core technology is hazard analysis. We need to understand clearly what we mean when we say that a structure is ‘safe’.

To understand what safety is and what safety strives to do, it is necessary to employ the concepts of hazard, safety and system safety [6].

Hazard. Any real or potential condition that can cause injury, illness, or death to personnel, damage to or loss of a system, equipment or property, or damage to the environment.

Safety. Freedom from the conditions that can cause death, injury, occupational illness, or damage to or loss of equipment or property, or damage to the environment.

System safety. The application of engineering and management principles, criteria, and techniques to optimize all aspects of safety within the constraints of operational effectiveness, time and cost throughout all phases of the system life cycle.

Thus safety can be thought of as a state, a perceived state or a quality. Absolute safety is not possible because complete freedom from all hazardous conditions is not possible. Therefore, safety is a comparative term that implies a level of risk that is both identified and accepted. System safety is an optimized level of risk that is constrained by cost, time, and operational effectiveness (performance). System safety requires that the safety should be considered as an indispensable design parameter and designed into the system and the system program should be carried out from the initial design phase to the following test, operation, maintenance, and retire treatment in order to ensure the system safety throughout the life cycle.

The complete structure of aircraft, also named “the airframe” is a safety critical complex system including the fuselage, wing, empennage, landing gear, control systems and surfaces, engine section, nacelle, air induction, weapon mount, engine mounts, structural operating mechanisms, and other components as described in the contract specification [7]. Its failure usually causes huge loss of lives and property. For aircraft structure, the safety can be defined as the capability of the aircraft structure to be free from catastrophic failure in the defined period of time under the defined operational conditions and environment.

It’s not the fact that an unreliable structure is unsafe either. The main concern of the reliability is failure but not all the failures can result in accident. For example, when a certain part of the aircraft structure fails, if people have adequate time to detect and finally solve it, this failure can not lead to a catastrophic consequence and just bring some barriers to carrying out the prescribed mission in the stated time [8]. But if the failure will lead to a fatal consequence, the failure becomes the hazard, and then the reliability is the safety. Accordingly, the safety of the structure can be increased by improving the structural reliability.

2.2 An Analytical Model for Structural Safety Based on Conditional Probability

According to the descriptions above, it can be seen that the structural safety is not the same as the structural reliability and that they have a close relationship. Here, we define S to denote the structural safety, R to denote the structural reliability, and P to denote the probability of the occurrence of the accident when the structure carry out the stated missions in the prescribed conditions during the whole life cycle time.

On one hand, the structure is always considered to be safe when they are reliable. On the other hand, when the structure fail, the accident may happen or not lying on whether the failure can be detected and solved in time by the SHM system.

So, P, the probability of the occurrence of the accident, can be expressed as follows:

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

Here, R is the structural reliability and $P_{A/F}$ is the probability of the occurrence of the accident when structure fails.

So, the structural safety S can be expressed by

$$S=1-P=1-(1-R)*P_{A/F} \tag{2}$$

When we define $P_{\bar{A}/F}$ ($P_{\bar{A}/F}=1-P_{A/F}$) as the probability of the condition that the accident would not take place after the structure fail, the Eq.(2) can be transformed to

$$S=R+(1-R)\cdot P_{\bar{A}/F} \tag{3}$$

The Eq.(3) indicates that the safety of structure is not only related with structural reliability but also the measures employed to prevent the occurrence of the accident when the structure fail. So the safety of aircraft structure can not be evaluated only by the reliability of structure.

3 The Evolution of Design Philosophy of Aircraft Structure

The design philosophy of aircraft structure is derived from the practice of aircraft usage. By summing up the practice experience of aircraft, the higher and newer technique requirement is put forward on the aircraft structure design. Generally, the evolution process of design philosophy of aircraft structure can be divided into the following stages [9].

3.1 Design for Static Strength

In the 1930s or earlier, the design of aircraft structure just followed the static strength criteria. The static strength criteria is the most fundamental one in the design of aircraft structure, and continue to be implemented in modern aircraft design. The static strength criteria require that the permanent deformation should not take place in the structure of aircraft under the maneuvering load and that the structure will not fail in full scale under the design load. The design criteria is

$$P_u \geqslant P_d \tag{4}$$

$$P_d=f\cdot P_e \tag{5}$$

$$[\sigma]\geq\sigma_d \tag{6}$$

where P_u is the limit load, P_d is the design load, P_e is maneuvering load (the estimated maximum of the load during the whole life cycle), f is the factor of safety (usually with 1.5), $[\sigma]$ is the limit stress of the component, and σ_d is the stress induced by the design load.

3.2 Static and Dynamic Aeroelasticity Design

As the increasing demand of the flight velocity and tactics and technique performance of aircraft, thin aerofoil with small resistance coefficient was used widely, this led to obvious aeroelasticity problems. So the structure should have enough stiffness besides the static strength requirement. The design criteria is

$$V_{max} \leqslant V_d \tag{7}$$

$$V_d=V_{cr}=\max(f_fV_f,\ f_sV_s,\ f_aV_a) \tag{8}$$

Here, V_{max} is the maximum flight velocity, V_d is design aeroelasticity velocity, V_{cr} is the critical aeroelasticity velocity, V_f, V_s, V_a are the flutter velocity, wing divergence velocity, aileron failure velocity respectively, and f_f, f_s, f_a are the corresponding safety factors.

3.3 Design for Fatigue Safe Life

Many unexpected accidents, especially the mid-air disassembly of comet aircrafts in 1954, had proved that the safety of aircraft could not be ensured just by static strength criteria and aeroelasticity criteria. The fatigue went into the eyes of structure designers. Since the 1950s, the anti-fatigue design had become an important criterion. The earliest was safe life design philosophy, which was based on the assumption that the structure had no initial flaw. By the safe life criteria, the visible crack is not allowed and the structure should be announced failure if the visible crack exists. The safe life criteria is

$$N_e \leqslant N_{sa} = N_{ex}/n_f \qquad (9)$$

where N_e is the value of service life, N_{sa} is the safe life, N_{ex} is the experimental life, and n_f is the decentralization coefficient (usually with 4).

3.4 Durability/Damage Tolerance Design

A lot of fracture accidents between the late 1960s and the early 1970s indicated that the safe life design could not ensure the safety of the structure. The researchers found that the safe life criteria didn't account for the initial flaw existing in the structure indeed. There came the damage tolerance design philosophy.

The damage tolerance design guideline is provided in JSSG-2006 and should be applied to the principal structural elements and mission-essential structure. Damage tolerance designs are categorized into two general concepts:

a. fail-safe concepts where unstable crack propagation is locally contained through the use of multiple load paths or crack arrest structure in multiple-load-path structure, and

b. slow crack growth concepts where flaws or defects are not allowed to attain the size required for unstable, rapid propagation in single-load-path structure.

Either design concept should assume the presence of undetected flaws or damage, and should have a described residual strength-level both during and at the end, of a prescribed period of unrepaired service usage. The initial damage size assumptions, damage growth limits, residual strength requirements, and the minimum periods of unrepaired service usage depend on the type of structure and the appropriate inspectability level.

With the continuing increase of the cost during the acquisition phase and the whole ownership of an aircraft, it seemed like the aircraft was unaffordable. So the durability concept was put forward. Durability is the ability of the aircraft structure to resist cracking (including stress corrosion and hydrogen-induced cracking), corrosion, thermal degradation, delamination, wear, and the effects of foreign object damage for a prescribed period of time.

In the durability/damage tolerance design philosophy, the durability should be carried out to ensure the economy while the damage tolerance should be implemented to ensure the safety of structure.

3.5 Design for Reliability

Reliability criteria are newly put forward design criteria in recent years. The main tasks of reliability design are to determine the failure models and rules, study the effect of the various internal and external factors on the reliability of structure.

The structural reliability design replaced the deterministic design variables by the stochastic ones. After the structure is design by the static strength criteria, dynamic strength criteria and damage tolerance/durability criteria, the reliability theory is then employed to analyze and evaluate the reliability of aircraft structure, including failure detection analysis, failure probability estimation, and so on. The criteria for reliability design is

$$R_{si} \geq R_{si}^{*} \qquad (10)$$

where R_s is the reliability of the structure system and i is the static strength, dynamic strength, damage tolerance, life et al correspondingly. The superscript * represents the related reliability index.

3.6 SHM System

There still exist several deficiencies though the design philosophy has experienced such evolutions above. The catastrophic accidents due to the structural failures took place at the rate that requires a continual consideration on the measures of achieving structural safety. With the increasing requirement on the aircraft safety, the structure designers have devoted more attentions to mitigating the risk of catastrophic structural failure.

SHM is a new and alternative way of Non-Destructive-Inspection (NDI) in order to ensure the safety of aircraft structure [10]. It is the continuous, autonomous in-service monitoring of the physical condition of a structure by means of embedded or attached sensors with a minimum manual intervention, to monitor the structural integrity of the aircraft. The basic is the application of permanent fixed sensors on the structure. SHM includes all monitoring aspects related to damages, loads, conditions, etc. on aircraft level, which have a direct influence on the structure. The sources are resulting from fatigue, corrosion, impacts, excessive loads, unforeseen conditions, etc.

SHM is a new concept whose time has now come, as the required technology is available to take the first steps. While the maintenance cost reduction, increased aircraft availability and weight saving reached by SHM were considered, the safety benefits should also be taken into account. The below will make research work on the influence of SHM on the safety of aircraft structure.

4 Indexes of the Aircraft Structural Safety

From the above, we can know that the safety of aircraft structure has a close relationship with the static strength, fatigue strength, damage tolerance and SHM system. An indexes system (shown in Fig.1) for comprehensive assessment of the aircraft structural safety is established from these four aspects, and fifteen bottom indexes are gained.

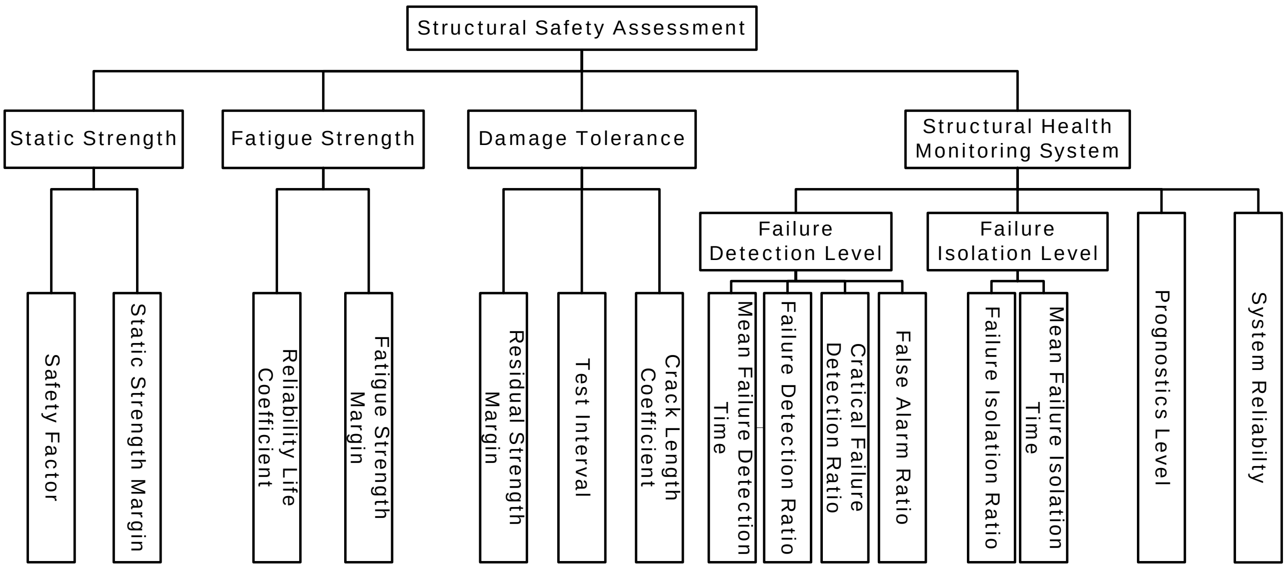

Fig. 1. Sketch of Indexes System of Structural Safety Assessment

4.1 Indexes of Static Strength

The safety factor and static strength margin are chosen in the static strength.

4.1.1 Safety Factor (SF)

The safety factors are different among the various kinds of structures.

For the generic important structures, the safety factors are usually 1.5.

For the safety critical structures, the factors are 1.5~2 considering the changeful operational environment and the uncertainty in the load calculations.

In fact, the safety factor can be calculated by

$$SF = P_d / P_e \tag{11}$$

Here, P_d is the design load, P_e is maneuvering load (the estimated maximum of the load during the whole life cycle).

4.1.2 Static Strength Margin (SSM)

The static strength margin is derived from the strength tests, which is usually considered as a parameter to validate the safety of aircraft structure design.

The static strength margin can be expressed by

$$SSM = P_{uT} - P_{uD} \tag{12}$$

Here, P_{uT} is the load when the structure fail in the strength test, and P_{uD} is the limit design load.

4.2 Indexes of Fatigue Strength

From the fatigue strength, the Reliability Life Coefficient and Fatigue Strength Margin are selected.

4.2.1 Reliability Life Coefficient (RLC)

The RLC can be expressed by

$$RLC = N_r / N_o \tag{13}$$

where N_r is the reliability life theoretically, and N_o is the expected reliability life.

4.2.1 Fatigue Strength Margin (FSM)

The fatigue strength margin is usually used to indicate the real safety margin in terms of reliability life in the strength test. The *FSM* can be expressed by

$$FSM = N_{ex} - N_o \tag{14}$$

Here, N_{ex} is the reliability life obtained by strength test, N_o is the expected reliability life.

4.3 Indexes of Damage Tolerance

Damage tolerance is the attribute of a structure that permits it to retain its required residual strength for a period of unrepaired usage after the structure has sustained prescribed levels of fatigue, corrosion, and accidental or discrete source damage. The crack length coefficient, test interval and residual strength margin are selected from the damage tolerance aspects.

4.3.1 Crack Length Coefficient (CLC)

The crack length coefficient can indicate the safety status of the structure containing the crack or having the initial flaw. The *CLC* can be expressed by

$$CLC = L / L_a \tag{15}$$

Here, L is the length of crack, and L_a is the allowable.

4.3.2 Test Interval (TI)

The test interval can indicate the inspectability of a structure. A too long test interval can not detect the damage in time while a too short one is expensive. So an appropriate inspect plan is very important for increasing the safety of structure in an economic way.

4.3.3 Residual Strength Margin (RSM)

The residual strength margin can indicate the safety margin of the structure containing the fatigue damage. The *RSM* can be expressed by

$$RSM = L_U / L_{DT} \tag{16}$$

Here, L_U is the ultimate load of the damaged structure and L_{DT} is the damage tolerance load, usually 1.25 times of the limit load.

4.4 Indexes of Structural Health Monitoring System Performance

The performance of structural health monitoring system can be evaluated by failure detection level, failure isolation level, prognostic level and system reliability.

4.4.1 Failure Detection Level

The failure detection level can be evaluated by the following indexes.

(1) Mean Failure Detection Time (M*FDT*)

The mean failure detection time is the mean time required in the detection process from the start to giving the failure indication. It is usually expressed by

$$MFDT = \frac{\sum t_{Di}}{N_D} \tag{17}$$

where t_{Di} is the time required in the detection of the ith failure and N_D is the number of the detected failures.

(2) Failure Detection Ratio (*FDR*)

The failure detection ratio is the ratio of the failures detected accurately to the total failures. The *FDR* can be obtained by

$$FDR = \frac{N_D}{N_T} \times 100\% \tag{18}$$

where N_D is the number of the failures detected correctly, and N_T is the number of the total failures.

(3) Critical Failure Detection Ratio (*CFDR*)

The critical failure detection ratio is the ratio of critical failures detected by SHM system to the total critical failures. The *CFDR* can be obtained by

$$CFDR = \frac{N_{CD}}{N_{CT}} \times 100\% \qquad (19)$$

Here, N_{CD} is the number of critical failures detected accurately, and N_{CT} is the number of total critical failures.

(4) False Alarm Ratio (*FAR*)

The false alarm ratio gives the fraction of forecast failures that were observed to be non failures. The *FAR* can be expressed by

$$FAR = \frac{N_{FA}}{N} = \frac{N_{FA}}{N_F + N_{FA}} \times 100\% \qquad (20)$$

Here, N_{FA} is the number of false alarms, N_F is the number of true alarms, and N is the total alarms.

4.4.2 Failure Isolation Level

The failure isolation level can be evaluated by the following indexes.

(1) Mean Failure Isolation Time (*MFIT*)

The mean failure isolation time is the mean time required in isolating failures. The *MFIT* can be expressed by

$$MFIT = \frac{\sum t_{Ii}}{N_I} \qquad (21)$$

Here, t_{Ii} is the time required in the isolation of the *i*th failure and N_I is the number of isolated failures.

(2) Failure Isolation Ratio (*FIR*)

The failure isolation ratio can be considered as a measure of the ability to isolate a detected failure. The *FIR* can be obtained by

$$FIR = \frac{N_L}{N_D} \times 100\% \qquad (22)$$

Here, N_L is the number of failures isolated to L LRUs and N_D is the number of failures detected accurately.

4.4.3 Prognostic Level (ΔT_{prog})

The prognostic level is the ability to forecast a future failure. The prognostic level can be measured by ΔT_{prog}, which can be expressed by

$$\Delta T_{prog} = T_{true} - T_{forecast} \qquad (23)$$

Where T_{true} is the time when the failure really happens and $T_{forecast}$ is the forecasted.

4.4.4 System Reliability ($MTBF_S$)

The reliability can indicate the dependability of a SHM system. It is usually measured by *MTBF* (Mean Time between Failures).

5 Rough Set Theory Based Safety Assessment Model for the Aircraft Structure

The assessment of aircraft structural safety is a comprehensive process which should consider the above fifteen bottom indexes and the relationship among them. So there arises the problem how to get the weight coefficient for each index objectively.

Recently, there are such popular methods as one-by-one comparing method, KLEE method, expert evaluation method et al to obtain the weight coefficient. However, these methods are essentially of some subjective.

This paper employs the conception of information entropy to determine the significance of each index, and then, the significance of each index is shifted to rough weight. Based on this, a rough set based model for comprehensive assessment of aircraft structural safety is set up.

5.1 Setting up Two-Dimensional Information Table

According to the classical rough set theory, the object in a universe of discourse can be depicted by a 2-D information table $S = < U, C, V, f >$. Each row is corresponding to an object, and each column is corresponding to the values of an attribute of the objects. Here, U is a universe of discourse, a finite nonempty object set, and C is a finite nonempty attribute set. V_c is the value range of attribute c, that is $V = \cup V_c$. f is the information function.

This paper tries to describe the indexes of aircraft structural safety by a 2-D information table. The universe $U = \{u_1, u_2, \cdots, u_n\}$ is the set of typical aircraft structures. Taking the fifteen evaluation indexes as the attributes of aircraft structures, we can get the attribute set $C=\{c_1,c_2,\cdots,c_{15}\}$. Take the values of fifteen indexes of an aircraft structure as a piece of information of object u_j, $u_j=\{c_{1j},c_{2j},\cdots,c_{15j}\}$. So the attribute value of object u_j can be expressed by $c_i(u_j)=c_{ij}$, where $i=1,2,\cdots,15$ and $j=1,2,\cdots,n$. In order to predigest the computing process, an equidistance algorithm is adopted to characterize the attributes.

Tab. 1. Information Table of Aircraft Structural Safety

U	C			
	c_1	c_2	$\cdots$	c_{15}
u_1	c_{11}	c_{21}	$\cdots$	c_{151}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
u_n	c_{1n}	c_{2n}	$\cdots$	c_{15n}

5.2 Obtaining the Weight Coefficient of Each Index

The information entropy is employed to indicate the importance of an attribute. U is a universe and $X_1,X_2,\cdots,X_n$ are divisions of U, which obey the probability distributions rule as

$$X=\begin{Bmatrix} X_1,X_2,\cdots,X_n \\ p_1,p_2,\cdots,p_n \end{Bmatrix} \tag{24}$$

Defining $H(X)=-\sum_{i=1}^{n} p_i \log p_i$ as the information entropy of X, then the importance of each index can be obtained by

$$S_c(c_i)=\left|H(C)-H(C-\{c_i\})\right| \tag{25}$$

So the weight coefficient of each index can be obtained by

$$\omega_i=\frac{S_c(c_i)}{\sum_{i=1}^{j} S_c(c_i)}(i=1,2,\cdots,15) \tag{26}$$

5.2 Establishing Comprehensive Assessment Model

When the value of each index and the corresponding weight coefficient are gotten, an comprehensive assessment model for aircraft structural safety can be expressed by

$$S=\sum_{i=1}^{15}(\omega_i \bullet \chi_i) \tag{27}$$

where χ_i is the value of structural safety index, and ω_i is the corresponding weight coefficient.

6 Case Study

In this section, a case study is given to validate the model.

The values of structural safety indexes of six aircraft have been shown in Tab.2. Because of the different kinds of data, the index data should be standardized. The S function is applied to the standardization according to the reference [11].

For the item which is better to be bigger, the standardization equation is

$$\overline{A_i}=\frac{1}{1+e^{-[\frac{6}{A_{i\max}-A_{i\min}}(A_i-\frac{A_{i\max}+A_{i\min}}{2})]}} \tag{28}$$

While for the item which is better to be smaller, the standardization equation is

$$\overline{A_i}=\frac{1}{1+e^{[\frac{6}{A_{i\max}-A_{i\min}}(A_i-\frac{A_{i\max}+A_{i\min}}{2})]}} \tag{29}$$

Here, A_i is the initial value of each index, $\overline{A_i}$ is the standardized, $A_{i\max}$ is the maximum of A_i and $A_{i\min}$ is the minimum.

Tab.3 shows the standardized values of structural safety indexes calculated by the Eq.(28) and Eq.(29).

Then, characterize the data in Tab.3 by applying the equidistance algorithm. The values of each index are graded to 3(very satisfied), 2(middling), and 1 (not at all satisfied). Then, we can get a 2-D information table (Tab.4)

According to the Eq.(25) and Eq.(26), the weight coefficients can be calculated. They are 0.084, 0.074, 0.077, 0.063, 0.067, 0.078, 0.060, 0.059, 0.057, 0.079, 0.058, 0.067, 0.056, 0.067, and 0.054. Then the structural safety of each aircraft can be computed by the Eq.(27) and the results are shown in Tab.5. We can see that the order of the aircraft structural safety is C>F>A>E>D>B. The result is in accordance with the fact, and proves the feasibility of this model.

Tab.2. Structural Safety Indexes Values of 6 Types of Airplanes

	SF	*SSM*	*RLC*	*FSM*	*CLC*	*TI*	*RSM*	*MFDT*	*FDR*	*CFDR*	*FAR*	*MFIT*	*FIR*	ΔT_{prog}	$MTBF_S$
A	1.5	100	2.5	110	0.7	0.25	60	15	0.85	0.7	0.1	10	0.8	10	400
B	2	55	1.5	85	0.6	0.1	50	5	0.7	0.65	0.2	15	0.7	15	358
C	4	85	2	60	0.3	0.3	45	10	0.9	0.70	0.15	5	0.85	5	269
D	2.5	67	1.2	128	0.8	0.15	65	20	0.95	0.85	0.2	15	0.65	10	425
E	1.6	60	4	50	0.4	0.2	75	15	0.65	0.9	0.25	10	0.75	5	265
F	1	105	2.4	124	0.2	0.3	70	10	0.85	0.75	0.3	5	0.8	15	156

Tab. 3. Standardization Values of Aircraft Structural Safety Evaluation Indexes

	SF	*SSM*	*RLC*	*FSM*	*CLC*	*TI*	*RSM*	*MFDT*	*FDR*	*CFDR*	*FAR*	*MFIT*	*FIR*	ΔT_{prog}	$MTBF_S$
A	0.119	0.917	0.447	0.834	0.119	0.182	0.500	0.269	0.731	0.142	0.953	0.500	0.818	0.500	0.920
B	0.269	0.047	0.087	0.424	0.269	0.953	0.119	0.953	0.119	0.047	0.500	0.047	0.182	0.047	0.818
C	0.953	0.646	0.217	0.097	0.881	0.047	0.047	0.731	0.881	0.142	0.818	0.953	0.953	0.953	0.382
D	0.500	0.174	0.047	0.953	0.047	0.818	0.731	0.047	0.953	0.858	0.500	0.047	0.047	0.500	0.953
E	0.142	0.083	0.953	0.047	0.731	0.500	0.953	0.269	0.047	0.953	0.182	0.500	0.500	0.953	0.362
F	0.047	0.953	0.395	0.937	0.953	0.047	0.881	0.731	0.731	0.354	0.047	0.953	0.818	0.047	0.047

Tab. 4. Evaluation Information Table of Structural Safety of 6 Types of Airplanes

U	C														
	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_{13}	c_{14}	c_{15}
u_1	1	3	2	2	1	1	2	1	2	1	3	2	3	2	3
u_2	1	1	1	1	1	3	1	3	1	1	2	1	1	1	3
u_3	3	2	2	1	3	1	1	2	2	1	3	3	3	3	2
u_4	2	1	1	3	1	3	3	1	3	3	2	1	1	2	3
u_5	1	1	3	1	2	2	3	1	1	3	1	2	2	3	2
u_6	1	3	2	3	3	1	3	2	2	2	1	3	3	1	1

Tab. 5. Evaluation values of structural safety of 6 types of airplanes

Aircraft	A	B	C	D	E	F
SS	0.504	0.315	0.570	0.474	0.489	0.515

7 Summary

The safety of aircraft structure is not equal to the reliability. Besides the reliability, it is influenced by the measures of preventing the failures of structures simultaneously. The analytical model for the aircraft structural safety can take into account the safety benefit from the safety measures.

An indexes system is established from the static strength, fatigue strength, damage tolerance, and SHM system aspects. It can comprehensively consider the most influencing factors of the aircraft structural safety, especially the newly arisen SHM system.

The assessment of aircraft structural safety is really a multiattribute evaluation process. Because of many uncertainties induced by the absence and decentralization of safety information, a rough set based model to comprehensive assessment of aircraft structural safety is set up. The proposed model is applied to the structural safety assessment of the in-service aircraft. It was shown from the results that the model can make the assessment more objective and feasible.

Acknowledgements

The work is sponsored by the National High Technology Research and Development Program (No.2009AA04Z406) and National Natural Science Funds (No.50975284) of China.

References

[1] David G. Elms. Achieving structural safety: theoretical considerations. *Structural Safety*, Vol. 21, No. 4, pp 311-333, 1999.

[2] Amit K, Erdem A, Raphael T. Why are airplanes so safe structurally? Effect of various safety measures on structural safety of aircraft. Structures, Structural Dynamics & Merterials Confer, California, 2004

[3] Meizhen TAO. *Comprehensive design for modern aircraft structure*. Northwestern Polytechnical University Press, 2001

[4] Holger S, Henrik R. Structural health monitoring: a contribution to the intelligent aircraft structure. *ECNDT 2006*.

[5] Robert E. Discussion on 'The strategies and value of risk based structural safety analysis'. *Structural Safety*, Vol. 22, No.3, pp 281-286, 2000

[6] MIL-STD-882D. *Standard practice for system safety*. 2000

[7] MIL-HDBK-1530B. *Aircraft structural integrity program, general guidelines for*. 2002

[8] Wenjun SHU, Yuting HE, Ronghong CUI, et al. Model for aircraft safety analysis based on conditional probability. *Aviation Precision Manufacturing Technology*, Vol. 45, No. 6, pp 53-57, 2009

[9] Shengnan WANG. *Study on integrated evaluation system of general damage tolerance and its some key technique*. Northwestern Polytechnical University Ph.D. Dissertation, 2005

[10] Thomas E M, Renee M K, Antony B, et al. *Health monitoring for airframe structural characterization*. NASA/CR-2002-211428, 2002

[11] Liyuan WANG, Hengxi ZHANG, Haojun XU. Multi-index synthesize evaluation model based on rough set theory for air combat efficiency. *ACTA AERONAUTICA ET ASTRONAUTICA SINICA*, Vol. 29, No. 4, pp 880-885, 2008

Contact Author Email Address

Pro. Yuting HE, hyt666@tom.com.

Copyright Statement