Research on Mission-based Evaluation Model for Effectiveness of Flight Test Aircraft

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Abstract—**Large civil aircraft represents modern cutting-edge industrial technology. Especially, the flight tests are vital to ensure safety before put commercial aircraft into the aviation market. Moreover, conducting flight tests is a complex system engineering that requires multiple factors and tests to be considered. The scientific and quantitative evaluation of the performance of testing aircraft and its capability of completing flight task would contribute to the safety and effectiveness of conducting the test flights. This paper proposes a feasible WSEIAC model to quantitatively evaluate the mission capability of flight test aircraft. The method can analyze the test aircraft composition and its task characteristics, which builds the mission effectiveness model.**

***Keywords*: Civil aircraft, Flight test, WSEIAC model, Mission-based effectiveness evaluation**

I. INTRODUCTION

As a large-scale aerial vehicle, big civil aircraft concentrates on many advanced industrial technologies such as aerodynamics, structural mechanics, propulsion technology, control theory, electronic engineering, materials science, etc. It is a cutting-edge industrial product, regarded as the jewel in the crown of modern industry. The goal pursued by civil aircraft is safety, economy, comfort and environmental protection. Among them, safety is the primary goal of civil aircraft. In the aviation market, it is priority to obtain an international general aircraft type certificate (TC) through rigorous flight tests, which proves qualified civil aircraft products that meet market needs [1].

The design, manufacture and flight test research of civil aircraft are three pillars of its development, in which flight test gets through all the process of the aviation research and airplane model development project. The technical level (development level) of flight test has a vital effect on the scientific research of aviation technology and the development of aviation industry.

The flight tests of large civil aircraft include maiden flight & ferry flight, research & development test, certification test and operation test. Flight test engineering is an ultra-complex large systems engineering. In engineering practice, as a usual flight test subject, the testing aircraft can be regarded as the large and complex aviation equipment that undertakes the flight test tasks. The ability to effectively complete their missions can be evaluated with effectiveness by scientific method.

The characteristics of modern civil aircraft are as follows.

a) The flight test of commercial aircraft is an ultra-complex large systems engineering.

b) The flight test engineering is complicated.

c) The flight test mission has high-level risk.

d) The flight test requires a massive cost of manpower, material resources and time.

II. MISSION EFFECTIVENESS EVALUATION THEORY OF AERONAUTIC EQUIPMENT

The test aircraft platform is a significant component of flight test systems engineering as the subject that performs the flight test mission in the process of modern commercial aircraft flight test. The platform is a subsystem which plays a part in flight test mission with other subsystems.

Referencing the concept of modern MAC (Military Aviation Complex), the civil test aircraft undertaking the flight test tasks can be regarded as CFTAC (Civil Flight Test Aviation Complex). CFTAC consist of test aircraft (including airframe, power plant, flight control system, etc.), airborne test equipment system, ground support system (including aerodrome), aircrew, etc. The CFTAC is a large integrated system, to accomplish certain flight test missions. Based on the concept of CFTAC, the evaluation of flight test engineering can be translated into the evaluation of CFTAC.

About CFTAC, the ability to complete the flight test mission is referred to as the effectiveness of the flight test. The effectiveness evaluation is an important task in the process of the design and modification of the test commercial aircraft. The theory of flight test effectiveness evaluation is a significant theoretical basis for the design, modification of the test commercial aircraft platform, meanwhile, it's also applicable to the make flight test project and choosing the aircraft platform parameter [2].

The effectiveness evaluation of aviation equipment system is commonly defined by WSEIAC (Weapon System Effectiveness Industry Advisory Committee), "System effectiveness is a measurement what meets the need of a group of mission particular degree, and it is a function of system availability, dependability, and capability." [3, 4] According to the definition, the system effectiveness is a comprehensive reflection of systems availability, dependability and capability. For most systems, the system effectiveness means the probability of mission success aiming at the specific system, which also applies to test

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aircraft platform and CFTAC.

According to the definition above, the mission performance of the test aircraft contains three elements, the task conditions, the flight test mission and the probability of completing the mission. [5]

At present, the methods for evaluating the effectiveness of aviation equipment mainly include WSEIAC model, logarithmic model, expert scoring model, etc.

The WSEIAC model mathematically defines and analyzes the mission performance of aeronautical equipment that performs missions. Currently, it has become a common theory for evaluating the effectiveness of weapons and other complex equipment/systems in terms of mission performance. It has good operability and acceptability of evaluation accuracy [6].

Based on the WSEIAC model, it can be considered that the mission performance of the test aircraft can also be expressed by a function of the mission availability, mission dependability, and capability to complete the mission of the test aircraft under the conditions of the flight test configuration. The factors and variables of the extreme complexity of flight tests and the many uncertainties during the flight test mission, need to be analyzed and corrected to meet the objective test flight practice.

III. COMPREHENSIVE EFFECTIVENESS EVALUATION MODEL ANALYSIS OF TEST AIRCRAFT

According to the above definition and theory of equipment effectiveness, effectiveness evaluation has many random factors, uncertain factors and unmeasured fuzzy factors, which are generally used as comprehensive indicators. According to its definition, performance is a comprehensive reflection of system availability, credibility and capabilities. In general, the effectiveness of the test aircraft and its systems refers to the probability that the platform/system will perform a specific task [7].

Typically, civil aircraft platforms contain many aircraft systems that can be divided into subsystems by hierarchy, for example, mechanical systems, power plant systems, environmental control block, avionics system block, electrical system block, and the like. The entire mechanical system further includes subsystems such as hydraulic system, landing gear system, and braking system. The power system includes subsystems of the propulsion system, fuel system, inerting system, fire protection system, and APU system. The turbofan engine system further includes a fan subsystem, compressor subsystem, turbine subsystem, and nozzle subsystem. The overall goal of the flight test of civil aircraft is achieved through the joint role of CFTAC.

The main objectives of the civil aircraft flight test include [8]:

a) Through research and development test flight, determine aircraft design parameters, identify and solve design and manufacturing problems and defects, determine the final design configuration of the aircraft, and confirm that the aircraft products meet the expected design requirements;

b) Passing the certification test flight, confirming that the civil aircraft type design meets the airworthiness standards, special conditions and equivalent safety requirements stipulated in the certification basis of an aircraft type, and provides the basis for the Type Certificate, input batch production and delivery for a civil aircraft;

c) Through the appraised flight test of operation and maintenance, it is confirmed that the design and manufacture of a civil aircraft type meet the requirements of operational airworthiness regulations such as CCAR91 and CCAR121 and the first batch of customer operation requirements, and the demonstration aircraft has good operation ability and adaptability under the expected use conditions.

In order to meet the test flight objectives above, it is necessary to quantitatively evaluate the capability of the test aircraft and its system to complete the test flight task. This paper attempts to use the ADC model for evaluation.

The model expresses the equipment system effectiveness can be expressed as the product of the availability vector matrix, the confidence vector matrix, and the capability matrix, $E = A \cdot D \cdot C$.

A. *Task system availability analysis*

The "availability" of the test aircraft mission system can be put into performance measure anytime while the test aircraft and its systems are under specified conditions. That is the probability that the aircraft and its system are in a usable state at different evaluation levels from the moment of entering the flight test mission.

The test aircraft and its system enter the activation phase from the moment of starting the flight test mission. In the whole process of the flight test mission, the fuzzy probability of the state of an aircraft system is corresponding, with $a_i, i = 1, 2, \cdots, 5$, and the availability vector is the row vector A :

$$A = \left[a_1, a_2, \cdots, a_n\right] \qquad (1)$$

Each element represents the probability that the aircraft equipment/systems requiring evaluation will be in different states at the start of the specified task. The test aircraft and its systems can only correspond to one state from the start-up phase to the end phase, then

$$\sum_{i=1}^{n} a_i = 1 \qquad (2)$$

In the actual work of flight test, the test aircraft and its systems can be a multivariate vector, which is in the condition of modeling and solving. It is generally believed that the test aircraft and its systems have only two states in the mission process, named as the effective mission state and the fault maintenance state. Thus, the availability vector can be simplified as:

$$\bar{A} = \left[a_1, a_2\right] \qquad (3)$$

In this formula, a_1 indicates the probability of the effective state of the task system; a_2 indicates the probability that the system is in a fault state.

The probability that the test aircraft and its systems are in an active state is expressed as:

$$a_1 = \frac{MTBF}{MTBF + MTTR} = \frac{\frac{1}{\lambda}}{\frac{1}{\lambda} + \frac{1}{\mu}} \qquad (4)$$

The probability that the above system is in a fault state is expressed as:

$$a_2 = \frac{MTTR}{MTBF + MTTR} = \frac{\frac{1}{\mu}}{\frac{1}{\lambda} + \frac{1}{\mu}} \tag{5}$$

In the above formula, MTBF means Mean Time Between Failure, and MTTR means Mean Time To Repair.

Based on the concept of CFTAC, during analyzing the test aircraft and its system availability vector, the time of system failure and maintenance should be fully considered, as well as the factors that cause the whole component failure and the entire system unavailable should be taken into account. The time required for maintenance must be sufficient. Indirect factors such as maintenance preparation, personnel deployment, and spare parts transportation must be taken into consideration. Factors involved in flight test outside the aircraft platform should also be fully considered, however, the time required is calculated to facilitate the simplification of the model when integrated assessment modeling.

B. *Task system dependability analysis*

The “dependability” of the test aircraft mission system is an indicator used to measure an aircraft system to complete a particular test flight mission. It is a probability representation used to describe the certain state of the initial moment of the test aircraft and its systems from the start of the mission, the certain state in the process until the mission is completed (end). Meantime, the number of state transitions varies depending on the task.

In the ADC model, availability is a measure of the test machine and its system in a state that satisfies the flight test task (configuration is in place, the aircraft is in a suitable flight test state), and dependability is a measure of the task execution state. Both in same the test aircraft system is expressed in different stages of the task.

In the civil aircraft test mission, there are many high-risk subjects, such as the Rejected Take-Off (RTO) Test, which is one of the most demanding tests for aircraft to obtain airworthiness certification [9-11]. The test aircraft may have the most severe conditions in the mission, such as the brakes might be completely worn, the aircraft might reach the maximum takeoff weight, or the thrust reverse device might be prohibited. In the RTO test, most of the kinetic energy of the aircraft will be converted into heat by the brakes, which may cause the fusible plug to melt and the entire tire to leak. In this way, the test aircraft and its system during the test flight mission, its overall and part of the state are all important to complete the test flight mission. This is especially obvious in high-risk test flights.

At the beginning of the flight test mission, the described test aircraft and its systems are following the task preparation state and have n states which can be changed to other states. The dependability matrix D is represented by the $n \times n$ -order state matrix as follows:

$$D = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{nn} \end{bmatrix} \tag{6}$$

In this formula, $d_{ij}, i = 1, 2, \cdots n; j = 1, 2, \cdots, n$ represents the probability that the test aircraft and its systems will shift from the i state at the initial time of the task to the j state during the task. The time to perform the entire test flight task is recorded as ΔT . d_{ij} is closely related to the dependability of the test aircraft and its systems, the flight test environment, the failure rate, human factors, mission characteristics, flight test plan layout, aircraft maintenance and other factors. For calculation and application, the problem and model are generally simplified. It is given statistically.

In the n states, the state of the initial phase of the task is set to 1, and the state of the task completion (end) is n , $n \in (1, n)$. It is known that 1 indicates the best state with successively decrementing, and the n state of n is the worst.

With

$$\sum_{j=1}^{n} d_{ij} = 1, i = 1, 2, \cdots, n; j = 1, 2, \cdots, n \tag{7}$$

In a single flight test mission, usually, the test aircraft takes off from the base, performs the test flight mission, and ends the mission back to the base without repairing opportunity during this process. The matrix D is indicating the task state can only be unilaterally transferred $1 \to n$. However, the analysis and evaluation of the task performance of the test aircraft systems are in a relatively long-term scope, which is the process of allowing the test aircraft to have multiple sorties. In the whole test flight process time, ΔT , the state changes from poor to good, then D is a completed square matrix.

Taking the RTO test flight as an example, it would be necessary to consider the test aircraft’s maintenance and repair capabilities and its state transference when conducting a damaged test flight mission. The r (good) is used to indicate the influence of favorable factors; while the k (bad) is used to indicate the influence of adverse factors. The system status level and the number of affected times are shown below [12].

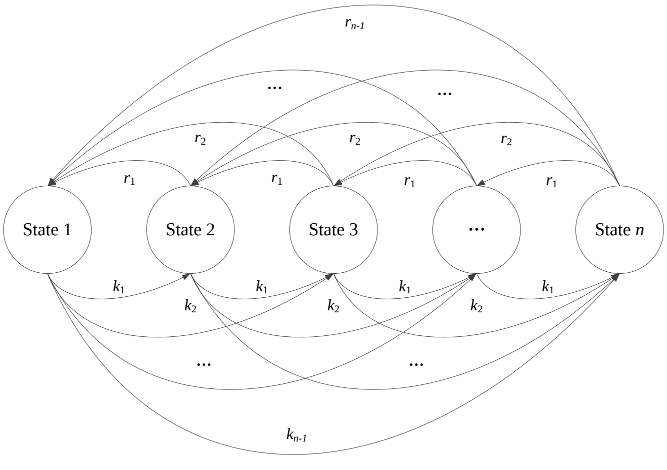

Fig.1. Schematic diagram of the relationship between the system status level and the number of affected actions

The test aircraft is affected by the configuration and the environment during the test flight. The favorable events and adverse events occur randomly during the test flight time ΔT . The number of occurrences of the event is $\xi = r$, $\xi = k$, which obey Poisson Distribution, then $\xi \sim P(\lambda)$.

With

$$\begin{cases} P(\xi = r) = \dfrac{\lambda_g^r}{r!} \mathrm{e}^{-\lambda_g} \\ P(\xi = k) = \dfrac{\lambda_b^k}{k!} \mathrm{e}^{-\lambda_b} \end{cases} \tag{8}$$

In the formula, λ_g means the average number of favorable events in time ΔT . λ_b means the average number of adverse events in the time ΔT .

From the above formula, the probability $P_g(r)$ of r .occurrence favorable events and the probability $P_b(k)$ of k occurrence adverse events in the occurrence of $1 \sim n-1$ events are respectively calculated.

$$\begin{cases} P_g(r) = \begin{bmatrix} P_g(1) \\ P_g(2) \\ \vdots \\ P_g(\geq n-1) \end{bmatrix} \\ P_b(r) = \begin{bmatrix} P_b(1) \\ P_b(2) \\ \vdots \\ P_b(\geq n-1) \end{bmatrix} \end{cases} \tag{9}$$

According to the Markov Process stochastic process model, the positive state (by worse-to-good) transition matrix G and the reverse state (by good-to-worse) transition matrix B can be obtained.

With

$$G = \begin{bmatrix} g_{11} & g_{12} & \cdots & g_{1n} \\ g_{21} & g_{22} & \cdots & g_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ g_{i1} & g_{i2} & \cdots & g_{in} \\ \vdots & \vdots & \vdots & \vdots \\ g_{n1} & g_{n2} & \cdots & g_{nn} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & \cdots & 0 \\ P_g(1) & 1-P_g(1) & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ P_g(i-1) & P_g(i-2) & \cdots & 1-\sum_{j=1}^{n-i} P_g(j) & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ P_g(n-1) & P_g(n-2) & P_g(n-3) & P_g(n-4) & \cdots & 1-\sum_{j=1}^{n-1} P_g(j) \end{bmatrix}$$

$$B = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ b_{i1} & b_{i2} & \cdots & b_{in} \\ \vdots & \vdots & \vdots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{bmatrix}$$

$$= \begin{bmatrix} 1-\sum_{i=1}^{n-1} P_b(i) & P_b(1) & P_b(2) & P_b(3) & \cdots & P_b(n-1) \\ 0 & 1-\sum_{i=1}^{n-2} P_b(i) & P_b(1) & P_b(2) & \cdots & P_b(n-2) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 1-\sum_{i=1}^{n-i} P_b(j) & \cdots & P_b(n-j) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 1 \end{bmatrix} \tag{10}$$

Since the forward state transition matrix and the reverse state transition matrix exist in the same task time ΔT , the two process chains can better describe the state transition law of the test aircraft and its system during the flight test mission. Thus, the matrix D can be obtained.

$$D = \frac{[B+F]}{2}$$

$$= \frac{1}{2} \cdot \begin{bmatrix} 2-\sum_{i=1}^{n-1} P_b(i) & P_b(1) & P_b(2) & P_b(3) & \cdots & P_b(n-1) \\ P_g(1) & 2-P_g(1)-\sum_{i=1}^{n-2} P_b(i) & P_b(1) & P_b(2) & \cdots & P_b(n-2) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ P_g(i-1) & P_g(i-2) & 0 & 2-\sum_{j=1}^{n-i} P_g(j)-\sum_{i=1}^{n-i} P_b(j) & \cdots & P_b(n-j) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ P_g(n-1) & P_g(n-1) & P_g(n-1) & P_g(n-4) & \cdots & 2-\sum_{j=1}^{n-1} P_g(j) \end{bmatrix} \tag{11}$$

C. Task system capability analysis

The capability of a civil flight aircraft to perform a test flight mission is a probabilistic representation of its ability and effectiveness to perform different specified flight test mission requirements under various specified flight test conditions. The main factors affecting the validity of the capability include, but are not limited to, the design performance of the flight platform, the onboard system, the redundancy and coupling of the major components, the fault tolerance of the control system, and the error correction performance.

For the type-test aircraft, there are different test flight mission requirements, and different airborne systems are configured according to various task types to test different flight test systems and objects.

If a test flight task has m requirements for the test aircraft and its systems, the $n \times m$ test flight capability matrix can be constructed according to the n states in the test flight process.

$$C = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1m} \\ c_{21} & c_{22} & \cdots & c_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{nm} \end{bmatrix} \tag{12}$$

In this formula, $c_{jk}, j = 1,2,\cdots n; k = 1,2,\cdots ,m$, it denotes the probability that the test aircraft and its systems satisfy the k^{th} requirement in the j state. If only one requirement is considered, i.e. $m = 1$, then

$$C = \begin{bmatrix} c_1 & c_2 & \cdots & c_n \end{bmatrix}^T \tag{13}$$

In the formula, $c_j, j = 1,2,\cdots n$ is the probability that the test aircraft and its systems complete the flight test mission in the j state. c_{jk} or c_j is obtained by analyzing the technical performance/indicators of the test aircraft and its system, whose coefficients can be solved by the AHP (The Analytic Hierarchy Process) method commonly used in multicriteria decision making.

D. Integration analysis of ADC model

The complete task performance matrix E of the comprehensive reflection test aircraft and its systems, which are represented by the three matrix products A, D and C in each test flight environment and flight test conditions, can be expressed as $E = A \cdot D \cdot C$.

Then the matrix A, D, C comprehensive single probability indicator is expressed as:

$$P_E = P_A P_D P_C \tag{14}$$

In the above formula, P_E means the probabilities of the test aircraft and its systems completing the flight test mission; P_A is the probability of the test aircraft and its systems available; P_D refers the probability of the test aircraft and its systems operating normally; P_C indicates the probability that the test aircraft and its system will function and perform.

The C event occurs on the condition that the A and D events occur; while the D event occurs on the condition that the A event occurs. Thus, the relationship between the test aircraft and its systems to complete a test flight task can be expressed as:

$$P(E) = P(A)P(D \mid A)P(C \mid AD) \tag{18}$$

IV. CONCLUSION

According to the technical and mission characteristics of the civil type test aircraft, the comprehensive effectiveness of the test aircraft and its systems, aiming at the flight test mission, is an ability to evaluate the mission complete capability based on the analysis of the mission implementation process. Therefore, the comprehensive effectiveness evaluation is not a numerical comparison of simple technical and performance indicators. By applying the improved WSEIAC effectiveness model, a quantitative analysis model of the test flight performance of the test aircraft and its systems could be established, which provides a scientific basis for the test aircraft to perform the test flight planning decision.

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