Airworthiness Compliance Verification Method Based on Simulation of Complex System

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Abstract

A study is conducted on a new airworthiness compliance verification method based on pilot-aircraft-environment complex system simulation. Verification scenarios are established by “block diagram” method based on airworthiness criteria. A pilot-aircraft-environment complex model is set up and a virtual flight testing method based on connection of MATLAB/Simulink and Flightgear is proposed. Special researches are conducted on the modeling of pilot manipulation stochastic parameters and manipulation in critical situation. Unfavorable flight factors of certain scenario are analyzed, and reliability modeling of important system is researched. A distribution function of small probability event and the theory on risk probability measurement are studied. Nonlinear function is used to depict the relationship between the cumulative probability and the extremum of the critical parameter. A synthetic evaluation model is set up, modified genetic algorithm (MGA) is applied to ascertaining the distribution parameter in the model, and a more reasonable result is obtained. A clause about vehicle control functions (VCFs) verification in MIL-HDBK-516B is selected as an example to validate the practicability of the method.

Keywords: aircraft; airworthiness; certification; pilot model; flight simulation; flight safety

1. Introduction

Airworthiness compliance verification is an essential part for a new aircraft to obtain its airworthiness certificate (AC). Methods of airworthiness compliance verification involve compliance statement, explanatory documents, analysis/calculation, safety assessment, laboratory tests, aircraft ground test, flight testing, aircraft inspection and equipment eligibility inspection. However, to verify the safety performance of the whole aircraft affected by unfavorable factors, the above ten methods are not enough. Those traditional methods, such as laboratory test, aircraft ground test and flight testing have their weaknesses such as high cost, long time for preparation and execution, and difficulties in checking all flight conditions in aircraft operational domain, especially in complex and critical situations [1-2].

The verification method based on complex system simulation has its unique advantages. A) This new airworthiness verification method could be applied to the phase of aircraft design, so that the design process can be optimized, the cost reduced, and schedule shortened. B) Conducting “virtual flight-testing” prior to detailed design can reduce the cost greatly with the total amount of test and certification (T&C) flight hours being reduced. C) A safer and more accurate flight envelope is formed by conducting safety assessment in complex and critical conditions, thus enhancing aircraft airworthiness and safety level [3-4].

Airworthiness verification always refers to risk probability assessment. The occurrence probability of flight accident is very small. Therefore, small risk evaluation method using limited amount of samples obtained from “pilot-aircraft-environment” complex system simulation is a significant problem to be solved [5].
2. Modeling of Complex System Based on Verification Scenario

Modeling of “pilot-aircraft-environment” system is the groundwork of system simulation. And the modeling is always based on specific scenario. So the first step of airworthiness verification is the construction of a scenario according to specific airworthiness clause. There are three components in the complex system, including pilot, aircraft and environment.

2.1. Potential hazard analysis and establishment of scenarios

Scenarios of flight testing are established according to clauses in airworthiness criteria [6]. In the U.S., Federal Aviation Regulations (FAR) are promulgated by Federal Aviation Administration (FAA). FAR series are the standards for air traffic control, qualification of production license and airworthiness certificate, etc. The U.S. has more comprehensive civil aviation airworthiness criteria, such as FAR 23, 25, 27, 33 which include specific airworthiness standards for various systems of the aircraft. China Civil Aviation Regulations (CCAR) series are formed on the basis of the U.S. civil aviation airworthiness standards. Currently, the U.S. F-22, F-35 and other advanced fighters have brought in airworthiness idea and used MIL-HDBK-516B as the basis for aircraft design.

Accident chain starts from hazard factors. Thus, potential hazard analysis of certain clauses in airworthiness criterion is the basis of the scenarios’ establishment. Hazard analysis methods include fault mode and effect analysis (FMEA), event tree analysis (ETA), fault tree analysis (FTA), hazard checklist method, engineering experience method, etc [7].

“Block diagram” is adopted in this paper to establish scenarios. The function of scenario is depicting potential accident chains in a certain airworthiness clause. Its main components include potential hazard factors effecting flight safety, effects of hazard factors on aircraft motion and safety decisive parameters.

An example is introduced to illustrate the process of founding a flight scenario. Clause 6.2.4.2 in vehicle control functions (VCFs) in Chapter 6 of MIL-HDBK-516B is selected. The specification of this clause is “all single point failures are identified with the associated probability of failure(s) and that they demonstrate an acceptable flight safety risk” [8].

Using the “cannikin law”, the weakest link of the VCF should be found first. According to the reliability test of a fly-by-wire and the flight record of the exemplified aircraft, no. (normal overload) sensor and roll rate sensor are the organs that most likely to fail [9]. Thus, there are two potential accident chains caused by two sensors’ malfunction. Failures of sensors lead to the malfunction of elevator and aileron. The safety decisive parameters of the two possible accident chains are \( \alpha \) (angle of attack (AOA)), \( n_z \) or \( p \) (roll rate).

Flight scenario of this clause is shown in Fig. 1.

![Fig. 1 Flight scenario of Clause 6.2.4.2 in MIL-HDBK-516B.](image-url)

2.2. Stochastic pilot model

1) Stochastic modeling of pilot behavior parameters

Statistical property analysis of pilot behavior parameters show that the static gain of pilot \( K_p \), with minimal constraints, is close to meeting the lognormal distribution law. The lognormal distribution density function of random variable \( x \) is [10]

\[
f(x) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left( -\frac{1}{2\sigma^2} \left( \ln x - \ln \mu \right)^2 \right) \tag{1}\]

where \( \ln \mu = \frac{\sum_{i=1}^{N} \ln x_i}{N} \), \( N \) is the number of random variable \( x \), \( \sigma = \sqrt{\frac{\sum_{i=1}^{N} (\ln x_i)^2 - \left( \sum_{i=1}^{N} \ln x_i \right)^2}{N-1}} \).

Histogram is established according to parameter identification of the pilot manipulation. Through comparison, it can be seen that the model based on lognormal distribution law (solid line) is more accurate than the model based on normal distribution law (triangle line), as shown in Fig. 2.
form distribution. If \(0.5\) distribution. Set that random number
random numbers subject to the truncated normal dis-
obeys lognormal distribution. Mathematical
methods can be used to obtain random numbers that
be obtained through its transformation. Mathematical
logarithmic normal distribution and truncated normal
function, set

\[
F_y = \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi} \sigma} \exp \left[ -\frac{1}{2\sigma^2} (x - \mu)^2 \right] dx
\]  

(2)

If \(\hat{\mu} = \ln \mu\), \(\hat{x} = \ln x\), then

\[
F_y = \int_{-\infty}^{\hat{x}} \frac{1}{\sqrt{2\pi} \sigma} \exp \left[ -\frac{1}{2\sigma^2} (\hat{x} - \hat{\mu})^2 \right] d\hat{x}
\]  

(3)

\(Y = \{y_1, y_2, \ldots, y_n\}\) obeys the \(N(\hat{\mu}, \hat{\sigma}^2)\) distribution; order \(z_i = e^{y_i}\), then the random \(Z = \{z_1, z_2, \ldots, z_n\}\) obeys lognormal distribution.

Inverse transformation principle is used to generate
random numbers subject to the truncated normal dis-
Set that random number \(m_i\) obeys \((0,1)\) uni-
form distribution. If \(m_i < 0.5\), then \(m_i\) falls into
the range of left-censored; if \(m_i \geq 0.5\), then \(m_i\) falls into
the right-censored interval. When it is in the left truncated
interval, then

\[
m_i = \int_{m_i}^{0} \frac{1}{c_i \sigma_i \sqrt{2\pi}} \exp \left[ -\frac{1}{2\sigma_i^2} (x - \mu_i)^2 \right] dx - \int_{-\infty}^{m_i} \frac{1}{c_i \sigma_i \sqrt{2\pi}} \exp \left[ -\frac{1}{2\sigma_i^2} (x - \mu_i)^2 \right] dx - \int_{-\infty}^{0} \frac{1}{c_i \sigma_i \sqrt{2\pi}} \exp \left[ -\frac{1}{2\sigma_i^2} (x - \mu_i)^2 \right] dx = \int_{-\infty}^{m_i} \frac{1}{c_i \sigma_i \sqrt{2\pi}} \exp \left[ -\frac{1}{2\sigma_i^2} (x - \mu_i)^2 \right] dx
\]  

(4)

where \(D_{\text{min}}\) is the minimum value of \(x\), \(c_i\) a positive
constant, \(\sigma_i\) the variance of \(x\), \(m_0\) the cumulative
probability \(m_0 = \mathbb{P}(X \leq D_{\text{min}})\).

According to the distribution of \(N(\mu, \sigma^2)\), the
maximum of random numbers \(x_i\) is calculated with the
cumulative probability \(c_i m_i + m_0\). Similarly, process
\(m_i\) which falls into the right-censored interval, and
\(X = \{x_1, x_2, \ldots, x_n\}\) obeys the truncated normal
distribution.

The simulated pilot behavior parameters gained
through the above-mentioned mathematical methods
have eight groups, as shown in Table 1. In the table, \(\tau\)
is the time delay, \(T_1\) is the lead compensation time
constant, \(T_2\) is time delay of transmission and processing
of central information, \(T_N\) is the neuromuscular
delay time.

<table>
<thead>
<tr>
<th>Simulation results</th>
<th>(K_E)</th>
<th>(\tau)</th>
<th>(T_1)</th>
<th>(T_2)</th>
<th>(T_N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>2.020</td>
<td>0.105</td>
<td>0.213</td>
<td>0.274</td>
<td>0.094</td>
</tr>
<tr>
<td>2nd</td>
<td>1.627</td>
<td>0.204</td>
<td>0.093</td>
<td>0.331</td>
<td>0.312</td>
</tr>
<tr>
<td>3rd</td>
<td>2.267</td>
<td>0.076</td>
<td>0.226</td>
<td>0.163</td>
<td>0.168</td>
</tr>
<tr>
<td>4th</td>
<td>1.239</td>
<td>0.264</td>
<td>0.112</td>
<td>0.236</td>
<td>0.041</td>
</tr>
<tr>
<td>5th</td>
<td>2.117</td>
<td>0.210</td>
<td>0.312</td>
<td>0.121</td>
<td>0.177</td>
</tr>
<tr>
<td>6th</td>
<td>1.319</td>
<td>0.335</td>
<td>0.505</td>
<td>0.093</td>
<td>0.085</td>
</tr>
<tr>
<td>7th</td>
<td>5.587</td>
<td>0.108</td>
<td>0.204</td>
<td>0.618</td>
<td>0.055</td>
</tr>
<tr>
<td>8th</td>
<td>1.205</td>
<td>0.172</td>
<td>0.143</td>
<td>0.259</td>
<td>0.108</td>
</tr>
<tr>
<td>Mean value</td>
<td>2.173</td>
<td>0.184</td>
<td>0.226</td>
<td>0.262</td>
<td>0.130</td>
</tr>
<tr>
<td>Variance</td>
<td>2.075</td>
<td>0.008</td>
<td>0.018</td>
<td>0.024</td>
<td>0.008</td>
</tr>
</tbody>
</table>

The calculated mean and variance are close to the
identification of the true results. Taking the
first simulation for example, the results of pilot
model simulation match the real practice, which is
shown in Fig. 3. In the figure, \(T\) is the simulation
time.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{Output signal of pilot behavior stochastic model.}
\end{figure}

2) Pilot manipulation model in critical stochastic model
The research is focused on pilot manipulation mod-
eling after a severe failure of certain key system. Pilot
feels drastic change of acceleration caused by the fail-
ure, and has the response to counteract this change by
manipulation. The pilot’s control strategy can be un-
derstood as eliminating the sudden change of flight
status, reducing adverse consequences as caused by non-human factors.

The established pilot model is shown in Fig. 4. In the figure, \( Y(f_0, x_0, v_0, t) \) is the function, \( f_0 \) is rod force, \( x_0 \) is rod displacement, \( v_0 \) is speed of pilot manipulate the rod, \( t \) is time of pilot manipulate the rod.

Assuming that the initial pilot handling characteristic involved in closed-loop control is \( Y(t) \), the effective time is \( \Delta T \), the time that unit \( \dot{C} \) converts to unit \( \ddot{C} \) is \( \frac{pt}{173} \), the time that unit \( \ddot{C} \) converts to unit \( \dot{C} \) is \( \frac{pt}{174} \), where \( t_p \) is the delay time of pilot manipulation, and according to the conversions between units at different time instants, the model’s input-output relationship can be described as

\[
P_{\text{out}}(t) = \begin{cases} 0 & t < t_p \\ Y(t) X_n(t) & t_p < t \leq t_p + \Delta T \\ G(t) X_n(t) + h(t) & \text{Safe}, t > t_p + \Delta T \\ 0 & \text{Accident}, t \geq t_p + \Delta T 
\end{cases}
\]  

where \( P_{\text{out}} \) is the final output of pilot, \( X_n(t) \) the input offset signal, \( G(t) \) the pilot quasilinear function when the changes of flight parameters are stable, \( h(t) \) pilot noise function.

The most important parameter of the model is the delay time of pilot manipulation \( t_p \). In this paper, the probability distribution method is used to establish the mathematical model of \( t_p \).

Pilot average response delay time \( t_b \) calculated by simulation is 1.209. Formula \( \ln t_b = \ln \frac{t_b}{\sqrt{k^2 + 1}} \) is applied \([10]\) to gaining the mathematical expectation of the delay time: \( t_b = -0.043 \). A constant to describe the differences of pilot manipulation in tilt channel is \( k = 0.5 \), and the variance of latency is calculated to be \( D = 2 \ln \sqrt{k^2 + 1} = 0.2231 \). The pilot manipulation delay time subjects to lognormal distribution \( T_p \) obeys \( \text{LN}(-0.0438, -0.2231) \).

The simulation result of pilot delay time stochastic model using Monte Carlo method is shown in Fig. 5.

2.3. Aircraft model and external environment modeling

Flight risk is always related to scenario in critical state. Due to coupling and non-linear characteristics of parameter changes, the non-linear six-degree-of-freedom mathematical model of aircraft flight dynamics is adopted. These equations are a set of high-rank non-linear coupling differential coefficient equations, from which dynamic characteristics of an aircraft is obtained. Generally, appropriate equation simplification can be made according to specific problem. In the study of rolling characteristics, changes of velocity can be neglected, so equations can be changed into five-degree-of-freedom differential coefficient equations.

Aircraft fly-by-wire control system is usually constructed on the basis of Simulink. For a specific aircraft, the model of airframe and control system is fixed.

The key point of environment research is adverse operational situation, involving some events and phenomena in atmospheric environment or in air corridor, which could threaten flight safety. Such events and phenomena include adverse weather condition (wind shear, turbulence, heavy rain, icing, thunderstorm, atmosphere discharge), flying birds and possible objects that may cause collision, wake vortex left by aircraft, wet runway, etc. The corresponding simulation model can be set up according to specific situation \([11]\), and the related impact on aircraft movement is involved in the equations.

3. Potential Risk Analysis and Reliability Modeling of Scenarios

3.1. Analysis of potential risk

The risks of flight testing come mainly from the following aspects: risks from new products, new systems and new component parts, risks from critical flying conditions, risks from technologies in new explored areas, and risks caused by human factors and adverse environment.

Changes that take place from hazard to accident is an evolution process of the system status. The transition process from safe to unsafe state can be depicted as an accident chain (see Fig. 6).
Risk analysis methods include FMEA, ETA, FTA, hazard checklists law, and engineering experience method, etc [7]. Based on the theory of accident chain and the ideas of FMEA, mathematical models of representative failure mode are established as follows.

3.2. Failure mode modeling and effects analysis

The performance type of the failure is called failure mode, which describes the basic characteristics of product failure. Research of failure model involves three aspects, failure mode, failure impact on flight safety, and failure probability. The failure mode concept provides clues and evidence for fault identification and comprehensive failure analysis. Typical failure modes are shown in Table 2.

### Table 2 Typical failure modes

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Failure mode</th>
<th>Serial number</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Structural failure (broken)</td>
<td>10</td>
<td>External leak</td>
</tr>
<tr>
<td>2</td>
<td>Tied knot, or stuck on</td>
<td>11</td>
<td>Beyond tolerance (maximum)</td>
</tr>
<tr>
<td>3</td>
<td>Vibration</td>
<td>12</td>
<td>Beyond tolerance (minimum)</td>
</tr>
<tr>
<td>4</td>
<td>Failure to keep the normal position</td>
<td>13</td>
<td>Run accident</td>
</tr>
<tr>
<td>5</td>
<td>Failure to open</td>
<td>14</td>
<td>Intermittent work</td>
</tr>
<tr>
<td>6</td>
<td>Failure to close</td>
<td>15</td>
<td>Shift work</td>
</tr>
<tr>
<td>7</td>
<td>Open error</td>
<td>16</td>
<td>Error indication</td>
</tr>
<tr>
<td>8</td>
<td>Close error</td>
<td>17</td>
<td>Poor circulation</td>
</tr>
<tr>
<td>9</td>
<td>Internal leak</td>
<td>18</td>
<td>Incorrect action</td>
</tr>
</tbody>
</table>

Modeling of system’s weak links is an important foundation for flight safety quantitative assessment. In this paper, research is conducted on the modeling of aircraft failures in key systems, and fly-by-wire system is taken as an example.

Fly-by-wire system failures occur generally in two aspects, including sensor failure and actuator failure. The mathematical models of sensor failure modes are established as follows:

- 1) Sensor stuck model
  - The failure model of No. i sensor is
    \[ y_{\text{out}}(t) = a_i \]  
    where \( a_i \) is a constant, \( i = 1, 2, \ldots, m \).

- 2) Failure model of sensor constant gain changes
  - The failure model of No. i sensor is
    \[ y_{\text{out}}(t) = \beta_i y_{\text{in}}(t) \]  
    where \( \beta_i \) is the constant changes in the proportion of the gain coefficient, \( i = 1, 2, \ldots, m \).

3) Constant bias sensor failure fault model
   - The failure model of No. i sensor is
     \[ y_{\text{out}}(t) = y_{\text{in}}(t) + \Delta_i \]  
     where \( \Delta_i \) is a constant, \( i = 1, 2, \ldots, m \).

4) General sensor fault model
   - The failure behavior of the above three sensors could result in control function errors, so for the control system type, a sensor fault is usually expressed as
     \[ \begin{align*}
     x(t) &= A x(t) + B u(t) \\
     y(t) &= C x(t) + Q f_i(t)
     \end{align*} \]
     where \( A \) is the state matrix, \( B \) the input matrix, \( C \) the output matrix, \( Q \in \mathbb{R}^{m \times e} \) the sensor fault distribution matrix, and \( f_i(t) \in \mathbb{R}^e \) the function of the failure impact on the system output.

4. Risk Probability Assessment Model

4.1. Basic model

- \( S \) is the cumulative probability series, and \( x \in S \), \( R \) is the random variable set of extremum sample, and \( y \in R \). On the double negative logarithm scaling axis (DNLSA), the coordinate of \( x \) is \( x = -\ln(-\ln x) \) [12].

   It can be supposed that \( x' \in S' \), and \( S' \) is the set of cumulated probability series on the DNLSA.

   According to the scatter plot, the mapping \( g(S' \rightarrow R) \) can be ascertained. By statistical analysis on a number of data groups, it can be found that the scatter diagrams are likely to be linear distribution adopting DNLGA. So the mapping can be solved by linear regression as expressed in [13]

   \[ g(t) = ax^t + b \]
   where \( a \) and \( b \) are the coefficients of the equation. So the nonlinear function is

   \[ f'(x) = a(-\ln(-\ln x)) + b \]

   The occurrence probability is

   \[ P = 1 - f'^{-1}(y_i) \]

4.2. Nonlinear regress model

In fact, extremum samples are restricted by boundary, and this fact is not considered in the basic model. Thus, a calculation model containing adjusting parameter is set up in this paper by nonlinear regress.

The function \( y = \frac{c}{\ln x} \) is selected as the match curve. It can be transformed to \( \ln x = -b/y^c \).

The assessment model \( F(Y) = e^{\frac{b}{Y}} \) is set up. It can be deduced that \( Y = \ln Y \), \( X = -\ln(-\ln x) \), \( k = 1/c \), \( b' = k \ln b \). Hence, the linear function is obtained

\[ Y = kX + b' \]
The nonlinear regress model is

\[ F(Y) = \begin{cases} \frac{1}{b} e^{\frac{b}{1-L}} & Y \leq L \\ 1 & Y > L \end{cases} \]  

(14)

where \( L \) is the boundary value of random extreme samples.

The model can be considered a linear model after logarithm transformation of the cumulative probability and double negative logarithm function transformation of random extremum.

### 4.3. Synthesis assessment model

The scattered points on transformed coordinates are linear fitting in the nonlinear model, but larger error may be produced. It can be more precise applying cubic polynomial. The synthesis assessment model is set up.

\[
\begin{align*}
Y' &= \ln(L - y) \\
X &= -\ln(-\ln x) \\
Y' &= C_4 X^3 + C_3 X^2 + C_2 X + C_1
\end{align*}
\]

(15)

The parameters \( C_4, C_3, C_2, C_1 \) of the polynomial can be obtained by least-square method. And the objective function is the error in the transformed coordinates. It will be more reliable that the target function is the error in the original coordinates. The objective function can be expressed as

\[
E = \sqrt{\sum_{n=1}^{N} (Y'_n - f(F(Y'_n)))^2}
\]

(16)

The objective function is complex and nonlinear. The adjusting parameter for distribution can be optimized by modified genetic algorithm (MGA) \[14\]. Genetic algorithm (GA) can search for the optimal solution by random mode and has a better ability as a whole. But the algorithm is weak in local searching, and easy to become premature. Simulated annealing has a stronger capability in local searching. To avoid the disadvantage of GA, a mixed algorithm applying simulated annealing (SA) to GA is adopted, and the flow chart is shown in Fig. 7.

**Fig. 7** Flow chart of MGA.

The mode of coding is binary-valued. The fitness is acquired from the transformation of the objective function and adjusted by fitness linear scaling for population diversity. Operation of GA is the adaptive genetic algorithm (AGA) proposed by Srinivas, which can adaptively choose the probability of cross-over and mutation. In order to avoid getting the local optimal solution in early evolution, the elitist selection is adopted \[15\].

### 4.4. Calculation case

In certain aircraft flight status, the safety critical parameter is lift coefficient \( C_L \). Twenty extreme samples are obtained by flight data recorder (FDR) and shown in Table 3. The limit value of \( C_L \) is \( x_{\text{li}} = 1.25 \), and the parameters cannot reach the boundary value 1.4 \[9\].

Figure 8 depicts the whole process of GA, and Fig. 9 describes the searching process of SA for one time. It can be found that the calculation on the synthesis assessment model converges by using MGA. The fractional error is in the range of \( 8 \), and the detailed calculation results are shown in Table 4. The curve of the approximating function for the optimal solution is shown in Figs. 10-11. Risk probability is 0.0402.

**Table 3** Samples of extremum of critical parameter \( C_L \)

<table>
<thead>
<tr>
<th>Data 1 group</th>
<th>0.688</th>
<th>0.722</th>
<th>0.822</th>
<th>0.902</th>
<th>0.698</th>
<th>0.657</th>
<th>0.753</th>
<th>1.095</th>
<th>0.634</th>
<th>0.648</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data 2 group</td>
<td>0.932</td>
<td>0.720</td>
<td>0.591</td>
<td>0.798</td>
<td>0.929</td>
<td>0.564</td>
<td>0.743</td>
<td>0.753</td>
<td>1.210</td>
<td>0.696</td>
</tr>
</tbody>
</table>

**Fig. 8** Process of searching for optimal solution (GA).

**Fig. 9** Process of searching for optimal solution (SA).
Table 4  Calculation results

<table>
<thead>
<tr>
<th>Arithmetic</th>
<th>Coefficient C/10^-2</th>
<th>Fractional error/10^-4</th>
<th>Probabilistic risk/10^-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-34.95</td>
<td>-14.45</td>
<td>-2.40</td>
</tr>
<tr>
<td>2</td>
<td>-35.43</td>
<td>-14.04</td>
<td>-1.54</td>
</tr>
<tr>
<td>3</td>
<td>-35.42</td>
<td>-14.12</td>
<td>-1.52</td>
</tr>
<tr>
<td>4</td>
<td>-35.19</td>
<td>-14.11</td>
<td>-1.60</td>
</tr>
<tr>
<td>MGA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-35.25</td>
<td>-13.82</td>
<td>-1.51</td>
</tr>
</tbody>
</table>

Fig. 10  Curve of the approximating function (linear).

Fig. 11  Curve of the approximating function (DNLSA).

5. Main Idea of the Method

The main idea of the airworthiness compliance verification based on the complex system simulation proposed in this paper can be illustrated in Fig. 12. The verification process can be divided into six steps:

1) Verification scenario is established according to airworthiness standards and correlative materials.
2) Pilot-aircraft-operational environment model is built based on the scenario established in Step 1.
3) Hazard analysis and reliability modeling are carried out to obtain potential hazards of the system and occurrence rate of hazards.
4) The scenario is simulated in a computer based on the work done in Step 2 and Step 3, which can also be called virtual flight testing.
5) The extreme value of determined parameters are gathered through simulation, and flight risk is calculated using EVT [13].
6) Combining the results of Step 3 and Step 5, safety verification and measures for improving flight safety are obtained, which is the goal of this method.

Fig.12  Airworthiness compliance verification process based on complex system simulation.

6. Exemplification

The failure in fly-by-wire system may cause catastrophic consequence. How to improve its safety and reliability is a key technology in its development. The reliability of fly-by-wire system is critical to flight safety. So the Clause 6.2.4.2 in VCFs in Chapter 6 of MIL-HDBK-516B is selected to be verified.

6.1. Analysis of airworthiness clause and scenario foundation

The Clause 6.2.4.2 regulates that flight risk caused by
single point failures of VCFs should be “acceptable”. The quantitative requirement of fly-by-wire system is regulated by GJB2878-97 “general specification for fly-by-wire flight control system of piloted aircraft (fixed wing)” from three aspects including catastrophic failure, loss probability of aircraft and availability of urgent/spare system. The loss probability caused by failure of flight control system is prescribed quantitatively in GJB2878-97. Flight accident risk of light aircraft and fighter is no more than $100 \times 10^{-7}$/h [16]. The assessment probability is verified according to this quantitative standard in the following part. Measures and index suggestion for aircraft design can be obtained by verification [17].

6.2. Complex modeling and simulation

Flight testing scenario of this clause is founded in Section 2.1, and is shown in Fig. 1. Modeling and simulation are based on this scenario.

Firstly, the failure model of the scenario is founded. The failure of overload sensor in fly-by-wire system can cause uncommanded deflection of elevator, and the deflection step of elevator can cause a sudden elevation or descent, which may lead to the paranormal of $n_z$ and $\alpha$. A negative elevator angle can cause nondirective elevation, and the angle of attack is selected as a crucial parameter. A positive elevator angle may cause nondirective decent, and overload is the crucial parameter.

The failure model of overload sensor is stuck model $y_{\text{load}}(t) = a_i$. It is analyzed statistically that the failure value of elevator deflection conforms to the normal distribution with maximum and minimum values [5]; the region of value is $(-8^\circ, 8^\circ)$.

The failure value of roll rate sensor conforms to uniform distribution. The mathematical expression of failure model is

$$ x_i = \begin{cases} x_n & \text{Normal} \\ x_{\min} + (x_{\max} - x_{\min}) \times \text{Rand}(0,1) & \text{Failure} \end{cases}$$

where $x_i$ is the value of sensor, $x_n$ the normal operating value of roll rate sensor, and Rand (0,1) a random number in the region of (0,1). The failure value of aileron deflection is $(-5^\circ, 3^\circ)$. Histogram of failure angle of elevator or aileron is established, as shown in Fig. 13.

The non-linear six-degree-of-freedom mathematical model of aircraft flight dynamics is programmed in MATLAB 7.4. pilot manipulation model in critical situation which is illuminated in Section 2.2, is chosen as the pilot model in this example.

After the establishment of pilot, aircraft and failure models, a virtual flight testing method based on the connection of MATLAB/Simulink and Flightgear is proposed. The simulation framework of the method is shown in Fig. 14.

![Fig. 14 Simulation framework based on connection of MATLAB/Simulink and Flightgear.](image)

Failure deflection and pilot manipulation are the inputs of the simulation, and the outputs are AOA, $n_z$ and $p$, etc. Flight after two sensors’ malfunction is simulated, and part of simulation results is shown in Figs. 15-17.

![Fig. 15 Pilot’s visual in the beginning of simulation.](image)

![Fig. 16 Rapid pitching of aircraft caused by $n_z$ sensor’s failure.](image)
6.3. Calculation of flight risk as caused by single failure

The complex system is simulated with the Monte-Carlo method. And extremum samples of $\alpha$, $n_z$ or $p$ can be obtained.

1) Flight risk probability caused by overload sensor

Repeat the simulation with Monte-Carlo for 100 times, and 100 values of elevator angle were obtained; 57 values are negative, and the others are positive.

Risk probability calculated by the small probability assessment method based on EVT (nonlinear regression model) is 0.0336, which evaluates negative failure deflection. The relationship between extreme value and standard warp is shown in Fig. 18.

![Fig. 18 Sample extreme value and standard warp (AOA).](image)

Similarly, the extreme values of $n_z$ are used to calculate the flight risk based on EVT (linear regression model). The result is 0.0366. The relationship between the extreme value and standard warp is shown in Fig. 19.

![Fig. 19 Sample extreme value and standard warp (negative overload).](image)

The failure probability of this overload sensor conforms to Weibull distribution according to the conclusion in Section 3. In this case, it has been used for 100 h, so the failure rate is $\lambda(100) = 2.0 \times 10^{-7}$. So the flight risk probability caused by this overload sensor is

$$Q = P\lambda = 1.4 \times 10^{-6}$$  \hspace{1cm} (18)

It is shown that aircraft loss probability in one hour caused by the failure of this system satisfies the quantitative requirement of GJB2878-97. Thus, it cannot satisfy the requirement of MIL-HDBK-516B.

2) Risk probability caused by roll rate sensor

The largest permitted value of roll rate is $90^\circ$/s. Similarly, risk probability obtained from the small probability assessment method based on EVT is 0.0545.

The reliability of roll rate sensor in landscape orientation channel submits to exponential distribution, and the failure probability is $3.0 \times 10^{-4}$. The total risk of each flight in one hour is

$$Q = 3.0 \times 10^{-4} \times 5.45 \times 10^{-7} = 1.64 \times 10^{-5}$$  \hspace{1cm} (19)

It means that the flight risk caused by this failure does not satisfy the quantitative demand of GJB2878-97.

In summary, this flight control system cannot satisfy the requirement of the Clause 6.2.4.2 in MIL-HDBK-516B. Thus, corresponding flight safety measures must be taken to improve it. The flight risk caused by equipment failure is closely related to the reliability of components and the interaction between components. Therefore, three pieces of advice are brought forward. First, the reliability of this $n_z$ sensor should be improved, or it should be changed to a new one at earlier time. Second, the influence of failure must be weakened, so as to improve the robustness of the pilot-aircraft system. Third, pilot training of such kind of situation should be emphasized.

7. Conclusions

A method has been developed for airworthiness compliance verification based on pilot-aircraft-environment complex system simulation. Special researches are conducted on verification scenarios, stochastic pilot modeling, optimized risk evaluation model and virtual flight testing. The method is fit for both civilian and military aircraft.

The distinguishing advantages of this method include its low cost, good repeatability and controllability in airworthiness verification research. The proposed method can also focus on complex and high-risk situations difficult to research by real flight testing. Thus, more valuable conclusions can be obtained for airworthiness verification and aircraft safety design.

The challenge of future work may include modeling and simulation of aircraft safety critical systems and
their dynamic performance analysis after failure. Meanwhile, validation of simulation results is another challenge.

References


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