Research on mission reliability and sensitivity of folding tail mechanism

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Abstract. Folding tail mechanism is widely used in subsonic and super/high sonic missiles, and its mission reliability is directly related to the success or failure of missile launch. Taking the torsion bar folding tail mechanism as the object, the failure modes and failure influencing factors in the mission process are analyzed systematically. The dynamic model of the folding tail mechanism is established. According to its characteristics, the multi-stage correction method of the dynamic model is proposed and realize the high-precision simulation. Finally, the mission reliability and sensitivity analysis is carried out, and the reliability sensitivity of folding tail mechanism is obtained, which lays the foundation for reliability optimization.

1. Introduction

Folding tails are commonly found in subsonic and super/high sonic missiles. The US "Tomahawk" cruise BG-109 series, the "air-launch cruise" AGM-86 series and the "advanced cruise" AGM-129 series etc, as well as the Russian "White Snake" 3M80 and the "Gem" SS-NS-26 supersonic missiles have relevant supporting folding and unfolding mechanisms [1]. The increase in the stealth requirements of the aircraft also makes more missiles need to be placed in the embedded weapon capsule. Therefore, most of the missiles currently equipped and developed in our country also include a folding and unfolding mechanism.

The folding tail mechanism needs to reliably achieve the functions of normal unlocking, continuous movement and positioning locking within the specified time, and its mission reliability is directly related to the success or failure of the missile launch. Therefore, the domestic and foreign countries attach great importance to the reliability analysis of the folding tail mechanism. From a perspective of research, the research on the unfolding mechanism of the folding wing mainly focuses on the analysis of the aeroelastic characteristics of the unfolding process [2][3][4] and the dynamic analysis of the unfolding process of the folding tail mechanism under the aerodynamic load. In the dynamic analysis of the mechanism, Zhao YH [5] and D. Negrut [6] established the differential equations of the folding tail mechanism unfolding process, and obtained the dynamic response of the mechanism unfolding process. Kroyer [7] conducted a finite element simulation on the whole process of the folding wing, and discussed its static, dynamic and strength response in detail. Hu Ming et al. carried out the design and motion characteristics analysis of the folding and unfolding mechanism [8], and carried out related experiments. Hu et al. comprehensively discussed the reliability of its motion accuracy [9]. Pang [10] et al. proposed a synchronous reliability evaluation method for multi-piece
folded tail deployment. It is not difficult to see that the current research on the folding tail mechanism is mainly focused on the functional reliability of the single-piece tail, and there are few studies on the mission reliability of the multi-piece folding tail. Wang [11] analyzed reliability of Folding Wing Deployable Mechanism Considering Common Cause Failure. Hu [12] applied the developed folding wing deployment test device to carry out deployment tests under different torques, and obtained the variation rules of its key performance parameters. In the research on the reliability of motion mechanism similar to folding tail mechanism, the method of "simulation analysis + Monte Carlo simulation" is mainly used [13-15]. The quantitative relationship between input and output is obtained through multi-body dynamic simulation, and then Monte Carlo sampling is used to simulate large samples. On this basis, statistical analysis is carried out. The accuracy of this method is limited by two factors: 1) the accuracy of the dynamic model; 2) the efficiency of simulation and the sample size. This article takes the torsion bar type folding tail mechanism as the object, systematically analyzes the failure mode and failure influencing factors during the mission process, establishes the dynamic model of the folding tail mechanism, proposes a multi-stage correction method of the dynamic model according to its characteristics and realized high-precision simulation. Finally mission reliability and sensitivity analysis were carried out, the reliability and sensitivity of the folding tail mechanism was obtained, which laid the foundation for reliability optimization.

2. Description of the mission reliability problem of the folding tail mechanism

Figure 1 shows a missile, which contains a total of four folding tail wings. The power source of the folding tail fin is the actuating cylinder. The spiral auxiliary converts the linear motion of the actuating cylinder into the rotary motion of the rudder surface to realize the unfolding action of the rudder surface.

![Figure 1. Missile with four folded tails.](image)

The mechanism of the four-piece folding fin is identical. The main failure modes of the folding fin mechanism after FMEA analysis include: 1) The deployment time out, that is, the deployment function cannot be completed within the predetermined time; 2) The deployment is too fast and the structural load fails (load Stress/impact stress); 3) The movement of the folding tail is stuck, that is, the mechanism fails to expand to a predetermined angle; 4) The motion synchronization of the four-piece rudder does not meet the requirements. The influencing factors of the above failure modes are analyzed, and the influencing factors and their distribution parameters that affect the mission reliability of the folding and unfolding mechanism are shown in Table 1:
Table 1. Factors affecting the mission reliability of the folding tail and its distribution parameters.

| No. | Influencing factors                                      | Variable name | Distribution type | Mean  | Standard deviation |
|-----|---------------------------------------------------------|---------------|-------------------|-------|--------------------|
| 1   | Torsion bar stiffness coefficient                       | $X_1$         | Normal            | 59.549| 2                  |
| 2   | Torsion bar initial torsion angle                       | $X_2$         | Normal            | 60    | 2                  |
| 3   | Torsion spring stiffness coefficient                    | $X_3$         | Normal            | 7.309 | 0.3                |
| 4   | Torsion spring initial torsion angle                    | $X_4$         | Normal            | 114   | 2                  |
| 5   | Locking Pin Spring stiffness coefficient                | $X_5$         | Normal            | 7400  | 200                |
| 6   | Lock pin spring length                                 | $X_6$         | Normal            | 52    | 1                  |
| 7   | Friction coefficient between locking pin and out wing   | $X_7$         | Normal            | 0.27  | 0.02               |
| 8   | Friction coefficient between outer wing and front axle  | $X_8$         | Normal            | 0.27  | 0.02               |
| 9   | Friction coefficient between outer wing and rear        | $X_9$         | Normal            | 0.27  | 0.02               |
| 10  | Friction coefficient between front axle and base       | $X_{10}$      | Normal            | 0.27  | 0.02               |
| 11  | Friction coefficient between rear axle and base        | $X_{11}$      | Normal            | 0.27  | 0.02               |
| 12  | Friction coefficient of limit contact surface          | $X_{12}$      | Normal            | 0.27  | 0.02               |
| 13  | Friction coefficient between outer wing and base       | $X_{13}$      | Normal            | 0.27  | 0.02               |

Obviously, there are common influencing factors among the four failure modes of the tail, namely, the common cause failure. Therefore, there is a strong correlation among the failure modes. Therefore, in the subsequent analysis, it is necessary to establish a simulation model which can consider all failure modes at the same time, which can reflect the common cause problem. In the reliability analysis, for each sample, the characteristic quantity of multiple failure modes is calculated at the same time to solve the failure related problems.

3. Dynamic modeling and correction method of folding tail mechanism

3.1 Dynamic model of folding tail mechanism

According to the composition and function principle of the folding and unfolding mechanism, as well as the analysis of failure modes and influencing factors, the dynamic modeling idea shown in Figure 2 is formed. The dynamic model reflects the influencing factors of each failure mode:
The wing root is fixed, the two rotating shafts at the front end and the rear end are connected to the wing root by coaxial constraints, one end of the torsion bar is fixedly connected to the front end rotating shaft, and one end is fixedly connected to the wing tip. One end of the torsion spring is fixed to the rear axle, and the other end is fixed to the wing tip, the two locking pins are connected to the wing root through a translation pair, and are constrained by the contact force with the outer wing. The movement and rotation of the front and rear shafts are constrained by the contact limit and affected by the clearance.

3.2. Modified method of folding tail dynamic model
The calculation accuracy of the dynamic model of the folding tail mechanism directly affects the reliability calculation results. The simulation results are compared with the test results, and the results are shown in Table 2. It can be seen that the result has large errors, especially for the $0^\circ$ rudder surface, the in place angular velocity error reaches 700%. Therefore, it is necessary to modify the model.

The error of the dynamic model mainly comes from the friction coefficient of the hinge and the resistance moment introduced by the test system. According to the error source, a multi-stage correction method of dynamic model is proposed. The flow chart is shown in Figure 3.
Figure 3. Modification method of the dynamic model of the folding tail mechanism.

1) The friction coefficient of hinge is determined according to the rotational resistance torque of the no-load state without the test device.

   The torque required to rotate the rudder surface at a constant speed without test device under no-load condition is measured, that is to obtain the friction resistance moment M2 in the process of rotation of the mechanism itself. Therefore, in the case of eliminating the two power sources of torsion spring and torsion bar, the friction resistance moment M1 in the model is consistent with the test by adjusting the friction coefficient in the model, that is to determine the hinge in the model Friction coefficient.

2) The resistance moment introduced by the test system is determined according to the rotational resistance torque of the no-load state with the test device.

   Since the folding deployment mechanism test is not carried out in the wind tunnel, but is applied through a set of load simulation device driven by a motor. The device contains multiple supports and bearings, which will cause additional additional resistance moment when loaded. Therefore, the total resistance moment m3 can be obtained by measuring the torque required to rotate the rudder at no-load and uniform speed with the test device. It can be seen that the resistance moment of m3-m2 is introduced into the loading system.

3) According to the results of the last two steps, the accuracy of the model is verified and the power source parameters in the model are corrected.

   In the simulation model, the friction coefficient is set as the friction coefficient obtained in step (1), the resistance moment of M3-M2 is increased in the load, and the two power sources of torsion bar and torsion spring are set according to the design value, then the simulation calculation is carried out, and the core characteristic parameters of deployment time and in place angular velocity are obtained, and compared with the experimental measurement results. At this time, the error mainly comes from
the parameters of the two power sources. Therefore, by adjusting the parameters, the error between the simulation results and the test results is less than 20%, that is to obtain the actual values of the two power source parameters. At the same time, the dynamic simulation model of the mechanism whose accuracy meets the requirements is obtained.

The model is modified by the above method, and the comparison results after correction are shown in Table 3. It can be seen that the error between the modified model and the test can be controlled within 20%.

Table 2. Error analysis of model and test results before correction.

| Tail No. | Deployment time /ms | Angular velocity in place /rad/s | Error/ % |
|---------|---------------------|--------------------------------|----------|
| Test    | Simulation          |                                  |          |
| 0°a     | 81                  | 57.2                            | -29.38   |
| 90°b    | 37                  | 36.23                           | -2.08    |
| 180°c   | 42                  | 37.84                           | -9.9     |
| 270°d   | 46                  | 39.52                           | -14.09   |

* a Maximum headwind; b Maximum downwind; c Smaller downwind; d Minimum downwind

Table 3. Error analysis of modified model and test results.

| Tail No. | Deployment time /ms | Angular velocity in place /rad_s | Error/ % |
|---------|---------------------|---------------------------------|----------|
| Test    | Simulation          |                                  |          |
| 0°a     | 81                  | 68.47                           | -15.47   |
| 90°b    | 37                  | 36.6364                         | -0.98    |
| 180°c   | 42                  | 38.5609                         | -8.19    |
| 270°d   | 46                  | 40.54                           | -11.87   |

* a Maximum headwind; b Maximum downwind; c Smaller downwind; d Minimum downwind

4. Mission reliability analysis and sensitivity analysis

4.1 Mission reliability and sensitivity analysis method

According to the mission reliability requirements of the folding tail mechanism, on the one hand, it is required that the four pieces of folding tail do not unfold too slowly, impact damage and motion clamping failure respectively, and at the same time, the motion synchronization of the four folded tails should meet the index requirements. Therefore, the mission reliability can be regarded as a system with four folded fins in series, that is, when any of the above failure modes occurs, the mission fails, otherwise it is reliable.

Using Monte Carlo method for Reliability and sensitivity analysis, the mission failure probability of folding tail mechanism is as follows:

\[
\hat{P}_f = N^{-1} \sum_{j=1}^{N} I_F(x_j) = N_f \times (N^{-1})
\]  

(1)

\(N\) is the total number of samples, \(N_f\) is the number of failure samples, \(I_F(x) = \begin{cases} 1 & x \in F, \\ 0 & x \notin F \end{cases}\) is the indication function of failure domain.
The dimensionless reliability sensitivity of failure probability to the distribution parameters of influencing factors is as follows:

\[
S_{n_i}^{(k)} = \left( \frac{\partial P_f}{\partial \theta_n^{(k)}} \right) \times \left( \frac{\partial S_{n_i}}{\partial n_i} \right)^{-1}
\]  

(2)

4.2 Reliability and sensitivity analysis results of folding and unfolding mechanism

According to the design requirements of folding tail mechanism, the failure criteria of each failure mode are shown in Table 4:

Table 4. Determination of failure criteria for each failure mode.

| No. | Failure mode                  | Variable name | Unit      | Failure criterion |
|-----|-------------------------------|---------------|-----------|------------------|
| 1   | Slow deployment               | ActionTime   | ms        | >60ms            |
| 2   | Impact failure                | EndAngleSpeed| /rad_s    | >70rad/s         |
| 3   | Motion seizure                | MaxAngle     | °         | <90°             |
| 4   | Movement out of synchronization| ΔT           | ms        | >30ms            |

In order to improve the efficiency of reliability analysis, firstly, the surrogate models of four rudder surfaces are constructed by using the quadratic response surface, and the accuracy of the surrogate model is verified. On this basis, 100000 samples are extracted by Monte Carlo method for reliability and sensitivity analysis.

Figure 4. Normalized reliability sensitivity of distribution parameters of influencing factors of mission reliability.

4.3 Result discussion

Based on the Monte Carlo sampling, the mission reliability and sensitivity analysis of the system is 0.88629. From the analysis results, the main failure mode of the folding tail is 0 ° rudder movement timeout. Further analysis shows that the increase of torsion bar stiffness, initial torsion angle, torsion
spring stiffness and the average value of initial torsion angle of torsion spring will reduce its failure probability, while the increase of standard deviation of all variables will increase the failure probability of rudder surface.

0° tail is reverse load, and the main failure mode is stagnation or long movement time. Therefore, increasing torsion bar stiffness and initial torsion angle can reduce the failure probability; while 90° tail is forward loading, and the main failure mode is impact fracture of structure caused by too fast positioning. Therefore, increasing torsion bar stiffness and initial torsion angle will increase the failure probability.

Therefore, for the folding deployment system composed of four rudder surfaces, the failure probability of the rudder surface can be significantly reduced by increasing the average values of the four parameters, namely, the stiffness of the torsion bar, the initial torsion angle, the stiffness of the torsion spring and the initial torsion angle of the torsion spring. At the same time, the failure probability of the rudder surface can be reduced by strictly controlling the dispersion caused by materials and manufacturing.

5. Conclusion
1. Four failure modes affecting the mission reliability of the folding tail mechanism were analyzed, and 13 failure influencing factors were obtained.
2. The multi-body dynamic modeling method of the mechanism is given, and the multi-stage modification method of the model is proposed, which reduces the number of variables in the single correction process and improves the calculation accuracy of the model. It solves the problem that there are many variables to be modified in the traditional correction method.
3. Based on the Monte Carlo method, the reliability and sensitivity of the folding tail mechanism are analyzed, and the main failure modes and key influencing factors are obtained, which can be used for the optimal design of the supporting folding tail mechanism.

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