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Fastening Function Reliability Analysis of Aircraft Lock Mechanism based on Competitive Failure Method

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Abstract

The functional principle and failure analysis of a landing gear cabin door lock mechanism are researched in this paper. The fastening process is important for achieving the mission of the mechanism. There are two potential risks in the fastening process that may impact the stealthy performance of an aircraft: accidentally open errors and lock hook position errors. These two risks compete with each other. Competing failure models are established for the fastening process of the lock mechanism. The extreme model is used to describe accidentally open failures, while Brownian motion (BM) with non-linear drift and the Poisson process are adopted to model lock hook position error failures. The reliabilities for the lock mechanism are calculated at different working times. Results and conclusions are illustrated and provide helpful insight into the changes and degradation of the fastening process of the lock mechanism.

Keywords: aircraft lock system; competing failure; degradation; system reliability

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1. Introduction

The aircraft lock mechanism studied in this paper is mainly used for locking and fastening the aircraft landing gear cabin door. Failure of the lock mechanism may seriously affect flight safety. For example, if the lock mechanism fails to unlock, the landing gear door would not be opened, ultimately making the aircraft landing gear unable to be put down.

Sun [1] analyzed the probability of open failure of the lock mechanism based on multi-factor coupling, and a simulative trial method was discussed. Guo [2-3] studied the function hazard, failure mode, and effects of the lock mechanism. The unlocking reliability of the lock mechanism based on surrogate models was analyzed. Shen [4] developed a mixed copula model to estimate the reliability of the lock mechanism with two dependent failure modes: the lack of kinematic accuracy and the seizure of the mechanism. Zhuang [5] implemented the simulation of wear for a typical revolute joint of the lock mechanism under periodic loads with a three-dimensional finite element model based on Archard's wear law.

Degradation of reliability is a common phenomenon during the working process of a mechanism. Generally, there are three typical ways to model the degradation. (1) Statistical model: degradation data are necessary to establish the degradation process based on the statistical model. For cases with sufficient failure data, this is the most effective method. (2) General path model: the degradation process is described by an expression path. Appropriate expression with specific parameters could represent the degradation process. (3) Stochastic process model: The Markov process and BM (Brownian motion) are typical stochastic process models for reliability analysis. Correspondingly, there are many cases of degradation failure studies based on the degradation model. Whitmore [6] used Wiener diffusion with a time scale transformation to model accelerated degradation data. Ma [7] estimated the reliability and keeping lifetime of FOG by Brownian movement with drift. Ren [8] studied the prediction method of degradation time based on the current state. A civil aircraft engine was chosen as a case, and it was proven that this method is effective at adapting and easy to realize. Cai [9] studied the failure process of sliding rails due to wearing. The good wear-resisting characteristic of sliding rails makes it hard to conduct failure tests, and BM was chosen to predict the reliability.

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For a mechanism with multiple failure modes, the failures may compete with each other. When any of the failures occurs, the mechanism halts, and no other failures can occur. The definition of competing failure was set by demographers and biostatisticians [10] and is widely used in the mechanism risk analysis model. Pham [11-12] summarized the methods of competing failure modeling and used them to study many practice cases. Ye [13] analyzed the survival probabilities of a mechanism based on the distribution-based reliability model and used the Brown-Proschan model and non-homogeneous Poisson process. Zheng [14] proposed a new estimating procedure for competing risk data with missing causes of failure. Luo [15] developed a testing methodology based on the reliability target allocation for reliability demonstration under competing failure modes at accelerated conditions. Data from previous research were used to illustrate the methodology. There are also many more complicated competing models that are used in numerical cases. Rafiee [16] considered the changing degradation rate when modeling. Diverse rates will lead to different reliability evolution. Shifting thresholds were studied by Jiang [17] to make the modeling challenging and authentic.

For the aircraft lock mechanism studied in this paper, there are multiple competing failure modes. It is necessary to model these failures and obtain the reliability of the system. The outline of this paper is as follows. Section 2 gives the working principles of the lock system. A failure analysis is also performed to obtain the potential failures. A quantitative analysis is performed in Section 3 for both failures as well as the reliability of the lock mechanism. Section 4 provides the results and conclusions obtained with specific parameters and given data. Finally, a summary of the paper is given in Section 5. Additionally, the potential future work is also proposed in this section.

2. Working Principle and Failure Analysis

2.1. Mission of the Lock Mechanism

The main mission of the lock mechanism is to lock the door when the door is closed, to ensure that the gap between the door and the surrounding fuselage skin is lower than a prescribed requirement and to achieve the purpose of aircraft stealth.

2.2. Functional Principles

The structure of the lock is showed in Figure 1. It is composed of ten parts: lock body, nozzle A, nozzle B, push rod, rocker, connecting rod A, connecting rod B, tension spring, lock hook, and lock ring. To ensure that the landing gear door is closed tightly, the lock mechanism needs to be normally locked, and the lock hook and the lock ring can be in close contact. Adversely, the lock mechanism needs to be unlocked before the door is opened.

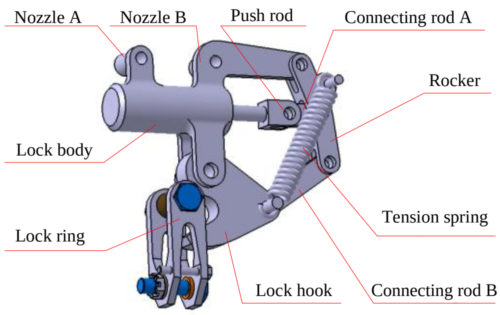


Figure 1. Structure of lock mechanism

In short, the lock mechanism has three functions to achieve its working mission: the unlocking function, locking function, and fastening function. All of the functions are accomplished by the cooperation of the components of the lock mechanism. The detailed processes of the three functions are presented below:

The unlocking process: When the aircraft sends an unlocking signal, the hydraulic system delivers oil to nozzle A. Then, the push rod is pushed outward by the hydraulic oil, the rocker is rotated anticlockwise, and connecting rod B is pulled by the rocker. When the push rod reaches the maximum movement, the lock hook is opened completely.

The locking process: Similarly, when the aircraft sends a locking signal, the hydraulic system delivers oil to nozzle B. The push rod is then pushed inward by the hydraulic oil, the rocker is rotated clockwise, and connecting rod B is pushed by the rocker. When the push rod reaches the maximum movement, the lock hook is closed completely.

The fastening function: Finally, the lock mechanism maintains the fastening function to keep the cabin door tightly closed.

2.3. Failure Analyses

Among the three functions of the lock mechanism, the fastening function directly affects the stealthy performance of an aircraft. Figure 2 shows the ideal position when the cabin door closes and the lock mechanism locks accurately. The lock ring and lock hook come in contact compactly to maintain the closed status. There are two possible failures that can cause a degradation in stealthy performance. One involves the lock mechanism accidentally opening, and the other involves the position error of the lock hook exceeding the requirement after the lock is closed.

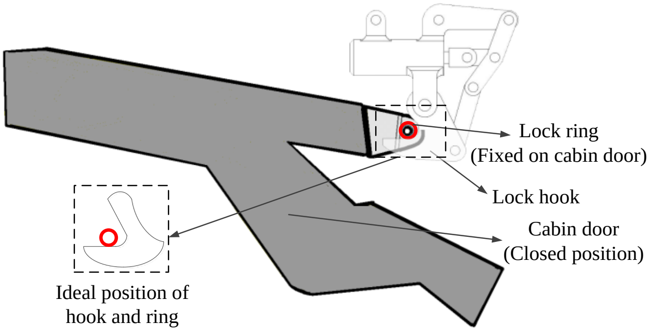


Figure 2. Ideal position of lock and cabin door

2.3.1. Failure Mode 1: *Accidentally Open*

An aircraft will vibrate during its working process due to various reasons, such as vibrations from mechanical production and gust. Vibrations can be treated as external shocks for the lock mechanism with random magnitude and frequency. Once the magnitude of a shock exceeds the limit threshold, the lock is opened passively, as shown in Figure 3. If the lock accidentally opens because of external shock, the cabin door will not maintain the closed position, which will lead to a degradation in stealthy performance and result in a task failure.

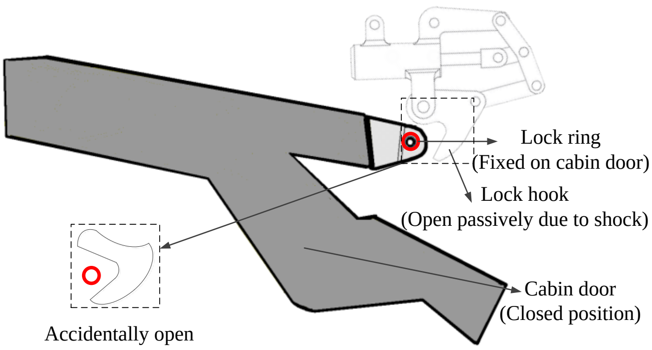


Figure 3. Lock accidentally open failure

2.3.2. Failure Mode 2: *Position Error*

The lock hook needs to come in contact with the lock ring in the appropriate position to guarantee stealthy performance. According to the working principles of the lock system, the lock hook is actuated by several components such as the push rod, rocker, and connecting rods. These components are connected by revolute joints. In order to achieve movement, there are certain gaps in these joints. In addition, the wear of the joints will cause these gaps to increase further. These can cause the hook position error to increase. As a result, as shown in Figure 4, the gap between the door and the surrounding fuselage skin gradually increases until it exceeds the required limit.

In short, there are two failure modes that can cause the degradation of the stealthy performance of aircraft. One is the accidentally open failure mode, and the other is the position error failure mode.

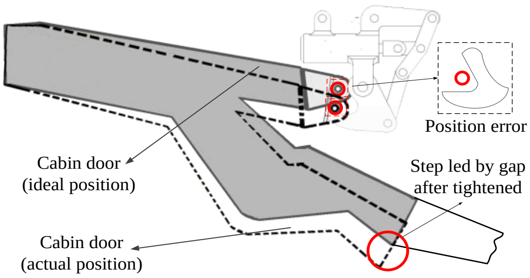


Figure 4. Lock position error failure

3. Competing Failure Modeling

In Section 2, we discussed the two failure modes for stealthy function. Either failure would occur during the actual work process. If the position error is too large (failure mode 2 occurs), the stealthy performance will be degraded, which will result in aircraft mission failure. In the same way, if the lock mechanism accidentally opens (failure mode 1 occurs), the door actuator will not be able to withstand the aerodynamic forces acting on the landing gear door, causing the door to open. The stealthy shape will be destroyed, causing the task to fail. For failure mode 1, the reason is that there are shocks (caused by vibration) with excessive magnitudes larger than the threshold. The threshold means endurance to shocks of the lock mechanism. An extreme shock model can be used to describe failure mode 1. For failure mode 2, degradation of the joints leads to wrong lock hook positions. As a result, the cabin door cannot be locked successfully or exactly. The degradation model is used to express this deterioration.

3.1. Modeling for Failure Mode 1

The extreme shock model is used to model failure mode 1. The lock mechanism is under shocks with random magnitude and indeterminate frequency. The magnitude of shock should be modeled by a random variable with a specific distribution, such as the normal distribution or Weibull distribution. Indeterminate frequency indicates that the time intervals between two continuous shocks are uncertain. In other words, the shock number during unit time is not determinate. The Poisson process is used to model the frequency of shocks.

Figure 5 shows the extreme shock model for a lock mechanism. W_i is the magnitude of each shock at a specific time t_i. The appearing time t_i is uncertain due to the randomness of shocks occurring. Magnitude W_i is an independent identically distributed (i.i.d.) variable W. D_0 is the threshold of the lock mechanism or the maximum magnitude that the lock could sustain. All shocks with magnitudes larger than D_0 will result in the occurrence of failure mode 1.

The probability that the lock mechanism maintains a normal state after a shock W_i is

$$P(W_i < D_0) = F_W(D_0), \quad i = 1, 2, 3, \cdots \tag{1}$$

Where $F_W(D_0)$ is the cumulative distribution function (CDF) of i.i.d. W_i. Supposing shocks arrive by the Poisson process with a rate of λ and there are $N(t)$ shocks until time t, the probability that the lock mechanism maintains a normal state is

$$R_1(t) = P(W_1 < D_0) \times P(W_2 < D_0) \times \cdots \times P(W_{N(t)} < D_0) = F_W{}^{N(t)}(D_0) \tag{2}$$

When variable W_i follows normal distribution $W_i \sim (\mu_W, \sigma_W{}^2)$, the probability will become

$$P(W_i < D_0) = \Phi\left(\frac{D_0 - \mu_W}{\sigma_W}\right), \quad i = 1, 2, 3, \cdots \tag{3}$$

and

$$R_1(t) = \Phi^{N(t)}\left(\frac{D_0 - \mu_W}{\sigma_W}\right) \tag{4}$$

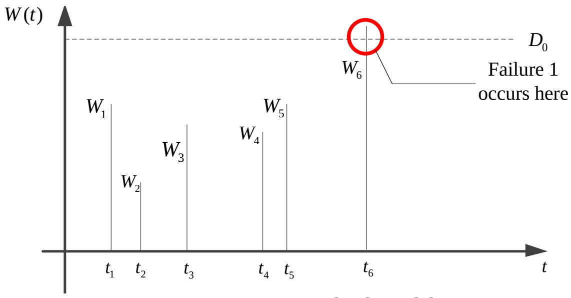


Figure 5. Extreme shock model

3.2. Modeling for Failure Mode 2

According to the analysis of failure mode 2, it is essential to develop a method to degrade $\Delta(t)$ in order to model failure mode 2. Then, the failure rate (or reliability) for failure mode 2 can be calculated accordingly. The degradation $\Delta(t)$ consists two parts. One is the pure degradation part $\Delta_1(t)$ caused by wastage such as wear, corrosion, and aging. The other is instantaneous degradation increments $\Delta_2(t)$ caused by random shocks.

Brownian motion (BM) with non-linear drift is selected to model the pure degradation. BM with non-linear drift is

$$\Delta_1(t) = \sigma B(t) + \mu t^q + \Delta_0 \tag{5}$$

Where μ is the drift parameter and σ is the diffusion coefficient. μ and σ can be constants or random values. $B(t)$ is standard Brownian motion. $\Delta_1(t)$ denotes the Brownian motion value at time *t*, and Δ_0 denotes the value at the initial time. *q* is the power time transformation. When *q* is larger than 1, the degradation accelerates with time. There are some advantages of using BM with non-linear drift here. First, BM with non-linear drift has the continuous samples path. Second, the wearing of a mechanical system accelerates, so the time transformation *q* can model the accelerating degradation process properly.

Another part of degradation involves the instantaneous degradation increments $\Delta_2(t)$ caused by random shocks. External shocks may cause mode 1 failure. In addition, each shock W_i will lead to an increment Y_i for the degradation process. The magnitude of increments Y_i is also i.i.d. with its distribution type and parameters. Shocks arrives with a Poisson process $\{N(t),\ t \geq 0\}$ that has a rate of λ. The cumulative increments due to random shocks until time *t* are expressed as

$$\Delta_2(t) = \sum_{i=1}^{N(t)} Y_i \tag{6}$$

Where $N(t)$ is the total shock number until time *t*.

Therefore, the total degradation of the lock hook position $\Delta(t)$ is

$$\Delta(t) = \sigma B(t) + \mu t^q + \Delta_0 + \sum_{i=1}^{N(t)} Y_i \tag{7}$$

Figure 6 shows the degradation process of $\Delta(t)$.

If the position of the lock hook meets the requirement, $\Delta(t)$ should be less than the allowable value Δ_a. Thus, the probability of failure mode 2 is derived as

$$\begin{aligned} R_2(t) &= P\left(\Delta(t) < \Delta_a\right) = \sum_{j=0}^{\infty} P\left(\Delta_1(t) + \Delta_2(t) < \Delta_a \mid N(t) = j\right) P(N(t) = j) \\ &= \sum_{j=0}^{\infty} \left(P\left(\sigma B(t) + \mu t^q + \Delta_0 + \sum_{i=1}^{N(t)} Y_i < \Delta_a \mid N(t) = j \right) P(N(t) = j) \right) \end{aligned} \tag{8}$$

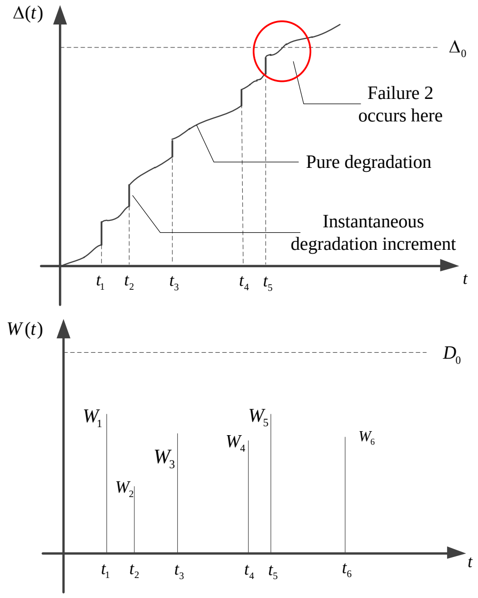


Figure 6. Degradation process

Supposing the CDF of $\Delta(t)$ is $F(x)$ and $f_Y^{<k>}(y)$ is the PDF of the sum of k i.i.d. Y_i, and according to the convolution theorem, Equation (8) can be converted to

$$R_2(t)=\sum_{j=0}^{\infty}\left(\int_0^{\Delta_a}F(\Delta_a-u,t)\,f_Y^{<k>}(u)du\right)\frac{\exp(-\lambda t)(\lambda t)^j}{j!} \tag{9}$$

Similarly, if the increment Y_i follows normal distribution $Y_i\sim N(\mu_Y,\sigma_Y^2)$, the expression will be more specific.

$$R_2(t)=P\left(\Delta(t)<\Delta_a\right)=\sum_{j=0}^{\infty}\Phi\left(\frac{\Delta_a-(\Delta_0+\mu t^q+j\mu_Y)}{\sqrt{\sigma^2 t+j\sigma_Y^2}}\right)\frac{\exp(-\lambda t)(\lambda t)^j}{j!} \tag{10}$$

3.3. Reliability of Lock Mechanism

There are two failure modes for the fastening function of the lock mechanism. Either failure cannot occur if the lock mechanism needs to achieve the mission. The reliability of lock mechanism can be expressed as Equation (11).

$$\begin{aligned}R_{sys}(t)&=\sum_{j=0}^{\infty}P(\Delta(t)<\Delta_a,W_1<D_0,W_2<D_0,\cdots,W_j<D_0\mid N(t)=j)\\&=\sum_{j=0}^{\infty}\left(F_W^{\,j}(D_0)P(\sigma B(t)+\mu t^q+\Delta_0+\sum_{i=1}^{N(t)}Y_i<\Delta_a\mid N(t)=j)P(N(t)=j)\right)\end{aligned} \tag{11}$$

According to Equations (2) and (9), the expression of the fastening reliability of the lock mechanism becomes

$$R_{sys}(t)=\sum_{j=0}^{\infty}\left(F_W^{\,j}(D_0)\left(\int_0^{\Delta_a}F(\Delta_a-u,t)\,f_Y^{<k>}(u)du\right)\frac{\exp(-\lambda t)(\lambda t)^j}{j!}\right) \tag{12}$$

Based on the normal distribution in Equations (4) and (7), the more specific expression of Equation (12) is

$$R_{sys}(t)=\sum_{j=0}^{\infty}\left(\Phi^j\left(\frac{D_0-\mu_W}{\sigma_W}\right)\Phi\left(\frac{\Delta_a-(\Delta_0+\mu t^q+j\mu_Y)}{\sqrt{\sigma^2 t+j\sigma_Y^2}}\right)\frac{\exp(-\lambda t)(\lambda t)^j}{j!}\right) \tag{13}$$

4. Results and Analyses

The reliability for the stealth maintaining function of the lock system is calculated according to Equation (13). The necessary parameters are listed in Table 1.

Table 1. Parameter values

Name	Notation	Value (unit)	Sources
Maximum shock stress that the lock could sustain	D_0	1.5 (Gpa)	Test data
Magnitude of each shock	W_i	Normal distribution~N(1.2,0.2^2) (Gpa)	Test data
Allowable position error	Δ_a	0.0025 (m)	Product request
Initial value of position error	Δ_0	0	Assumption
Magnitude of increments caused by shocks.	Y_i	Normal distribution~N(2×10^{-4},$(4.5\times10^{-5})^2$) (Gpa)	Assumption
Rate of Poisson process	λ	2.5×10^{-5}	Assumption
Time transfer in BM model	q	1.01	Assumption
Diffusion coefficient	μ	8.5×10^{-9}	Assumption
Drift parameter	σ	6.0×10^{-10}	Assumption

Figure 7 shows the reliability of the lock mechanism. The x-axis is the working cycle, which has the same meaning as time t. The y-axis is the reliability of the lock mechanism. From Figure 7, it can be seen that the reliability of the lock mechanism decreases with time. The decreasing rate accelerates because the value of the time transfer q is larger than 1. Additionally, the reliability approaches 0 at 250000 working cycles, because at that time the degradation $\Delta(t)$ is so large that it exceeds the threshold Δ_a .

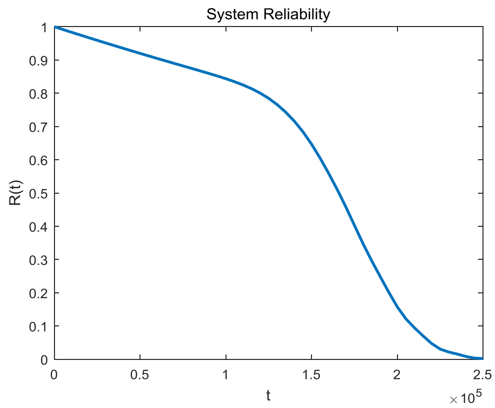
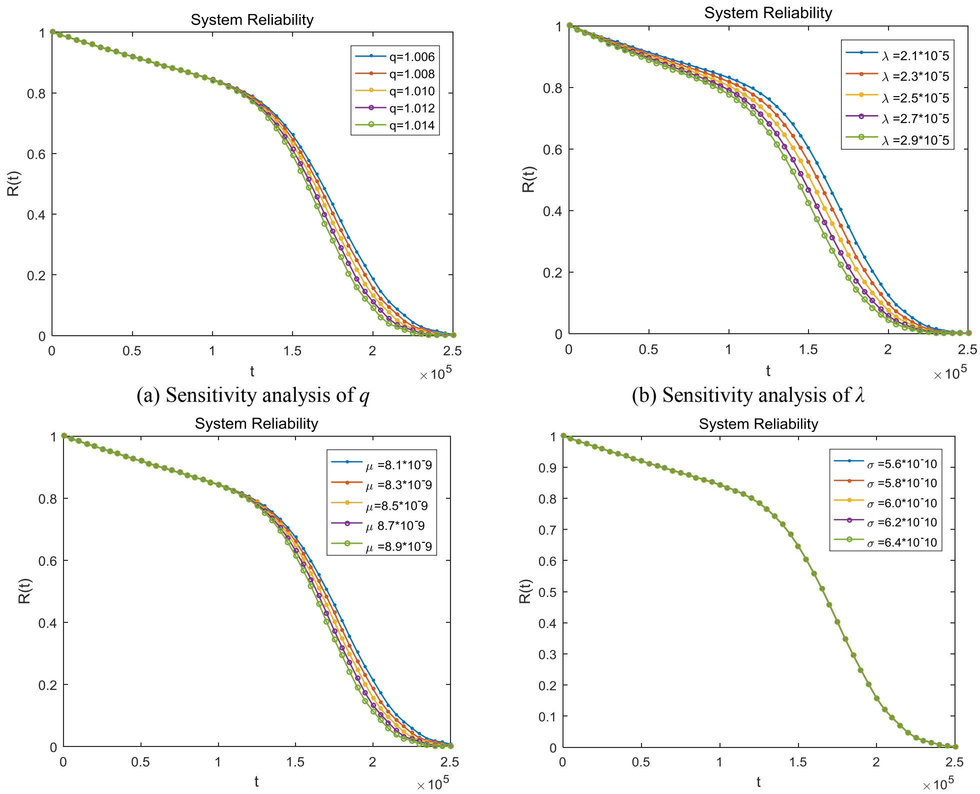


Figure 7. Lock mechanism reliability

To determine the impact of assumed parameters on the reliability results, sensitivity analysis for the assumed parameters is performed with different values. Figure 8 demonstrate the results. As can be seen from the figure, a larger q value leads to higher risk probabilities (low reliability) (Figure 8(a)). This is because the larger the q, the faster the degradation rate. It is evident that a larger λ value has a lower reliability than a smaller λ value (Figure 8(b)). λ indicates the frequency of shocks. A larger λ value indicates that there are more shocks in unit time, so the risk probability is consequently lower. In Equation (7), μ is the coefficient of the time-term. A larger μ value leads to a larger degradation rate, similar to q (Figure 8(c)). Thus, a larger μ value has a higher risk probability and lower reliability. Comparatively, there are no distinct differences between the drift parameter σ with different values (Figure 8(d)). This illustrates that the risk (or reliability) is not sensitive to the drift parameter σ.

5. Conclusions

The fastening risk of a lock mechanism for a landing gear cabin door of an aircraft was analyzed. Structures and working principles were introduced at the start, and the failure modes affecting the stealthy performance of aircraft were analyzed. There are two failure modes in the fastening process that compete with each other. The extreme shock model was used to analyze failure mode 1, also called accidentally open failure. Brownian motion (BM) with non-linear drift was chosen to model failure mode 2. With these two kinds of failures considered, the reliabilities of the lock mechanism were obtained at various working cycles. The results illustrate that the reliability of the locking mechanism decreases with time. Different variables have various sensitivities with reliability.



(a) Sensitivity analysis of q (b) Sensitivity analysis of λ

(c) Sensitivity analysis of μ (d) Sensitivity analysis of σ

Figure 8. Sensitivity analysis of system reliabilities

There are still some ideas that could be studied in future works. The lock mechanism has three functions. The reliability will become more complex when the risks for all the functions are considered comprehensively. Compared with risk (reliability) analysis, the maintenance is more effective at avoiding failures and risks. Maintenance policies based on competing failure model could be formulated.

Acknowledgements

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