Performance Degradation and Reliability Analysis for Redundant Actuation System

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Abstract: Redundant actuator is the key component of Fly-By-Wire (FBW) system in which exists the inherent force fighting among different redundant channels at colligation point. This paper establishes the mathematical model of quad redundant actuator (QRA), investigates the force equalization algorithm and carries out the performance degradation simulation and reliability analysis under the first failure and the second failure. The results indicate that the optimal equalization algorithm can solve the force fighting effectively, and the QRA can operate at degradation performance continuously under the first failure and the second failure. With the dynamic fault tree analysis, this paper calculates the reliability based on the performance of QRA and proves that the redundant actuator has very high reliability and safety.

Keywords: control system simulation; redundant actuator; performance degradation; reliability analysis.

In modern aircraft, redundant actuation system is widely used to achieve high reliability and safety[1]. As a matter of fact, the reliability of single channel of FBW system is low, and the redundant technique is the most effective method to realize the active control with high reliability. Redundant actuator is the last component of FBW whose performance affects the control capability of whole system directly. It is known that many redundant actuation systems are used in advanced aerospace successively[2,3], whereas the corresponding performance degradation due to failure and dynamic process are less investigated in its reliability analysis. In addition, the equalization algorithm, which can eliminate the force fighting and lead to failure recovery, existed in QRA is little to be considered in system analysis.

On account of the characteristics of redundant actuator aforementioned, this paper studies the influence of equalization algorithm, simulates the performance degradation variance under failure occurring and carries out the performance reliability analysis of QRA[3].

1 Mathematical Model of QRA

Single hydraulic actuator is a close-loop system, which consists of displacement sensor, amplifier, servo valve and cylinder shown in Fig. 1. Due
to the output of cylinder is linear displacement, it can be transferred into angle through gearing to realize the real-time angle control of rudder.

![Block diagram of hydraulic actuator](image)

Fig. 1 Block diagram of hydraulic actuator

Fig. 1 shows the hydraulic actuator system in which an input of command $u_c$ is, after passing through the system, transformed into an angle $\theta$ of a load. From the structure of hydraulic actuator, its mathematic model can be established as follows.

1. Servo amplifier equation
   \[ I_c(s) = K_a[u_c(s) - u_b(s)] \quad (1) \]
   where $u_c$ is the control command; $u_b$ is the feedback signal; $K_a$ shows the gain of servo amplifier and $I_c$ expresses the control current of servo valve.

2. Flow control equation
   \[ Q_i(s) = \frac{K_v}{T_s} \frac{I_c(s)}{s} - K_{fp} P_f(s) \quad (2) \]
   where $Q_i$ denotes the load flow; $P_f$ is the load pressure; $K_v$ shows the flow gain of servo valve; $T_s$ is the time constant of servo valve and $K_{fp}$ expresses the flow-pressure coefficient of servo valve.

3. Flow continuous equation
   \[ Q_i(s) = A_t s x_1(s) + C_t P_i + \frac{V}{4E} s P_i(s) \quad (3) \]
   where $A_t$ is the piston area of cylinder; $C_t$ expresses the total leakage coefficient; $E$ expresses the volume elastic module of fluid; $V$ shows the volume of cavity and $x_1$ shows the piston displacement.

4. Force balance equation
   \[ A_t P_i(s) = M s^2 x_1(s) + B_t s x_1(s) + F(s) \quad (4) \]
   \[ F(s) = [x_i(s) - x_p(s)] K_s \quad (5) \]
   \[ x_i(s) - x_p(s) = K_s R = J_1 s^2 \theta(s) + B_1 \theta(s) + K_f \theta(s) \quad (6) \]
   \[ x_p(s) = R \theta(s) \quad (7) \]
   where $M$ expresses the piston quality; $B_t$ shows the piston damping coefficient; $F(s)$ is the load force; $K_s$ denotes the rigid of out put pole; $x_p$ is the output displacement of load; $R$ shows the arm of force; $J_1$ expresses the rotatory inertia of load; $B_1$ is the damping coefficient of load; $K_f$ shows the elastic coefficient of load and $\theta$ denotes the angle of rudder.

5. Feedback equation
   \[ u_b = K_b x_1(s) \]
   where $K_b$ is the gain of displacement sensor.

Supposing that the QRA is synthesized at force colligation point, i.e., the sum of four single actuator forces is the output of QRA system shown as follows.

\[ F_m = \sum_{i=1}^{4} F_i \quad (9) \]

where $F_m$ expresses the mean force of QRA; $F_i$ is the force of the $i$th channel of QRA.

Then the block diagram of QRA is obtained as shown in Fig. 2.

2 Force Equalization of QRA

Although the consistency of separated channels should be guaranteed in actuator system design, there exist some differences among separated channels more or less. When the QRA is synthesized at colligation point, the output difference among different channels will lead to force fighting because of the manufacture error, assemble error and performance error. The force fighting will affect the output precision and operation life of actuator system and lead to the damage of actuator in the serious condition. So the effective force equalization must be considered in the design of redundant actuator so as to eliminate and restrain its force fighting.

Because the force fighting is rooted in the difference among separated channels, the conceivable equalization is to design a close-loop control law to trace the mean value of QRA. In order to improve the dynamic performance and control precision of QRA, this paper adopts the proportion-integral law and mean value selector to realize the force equalization. Its structure is shown in Fig. 3, in which $a_0$ and $a_1$ express the proportion and integral coefficient respectively. Selecting proper parameters, the
equalization algorithm can eliminate the mismatching among separated channels effectively.

In order to verify the effect of equalization algorithm based on proportion-integral law, the simulations on force fighting and dynamic performance are carried out in different proportion coefficient and integral coefficient shown in Fig. 4, in which \( F \) means force fighting and \( t \) is operational time.

In Fig. 4, curve 1 shows the force fightings of QRA at \( a_0 = 0.015 \) and \( a_1 = 2 \); curve 2 expresses the those at \( a_0 = 0.015 \) and \( a_1 = 2 \); and curve 3 denotes the those at \( a_0 = 0.15 \) and \( a_1 = 2 \). It is obvious that the force fighting among separated channels of QRA decreases rapidly when the integral co-

![Fig. 2 The block diagram of QRA](image)

![Fig. 3 Force equalization algorithm of QRA](image)

![Fig. 4 Force fightings in different coefficients of equalization algorithm](image)
3 Performance Degradation Analysis of QRA

In spite of the fact that the QRA can reach high fault-tolerant level when failure occurs, its performance degradation and failure reconfiguration become complex enough. In order to describe the dynamic performance variance process, this paper simulates the performance degradation of QRA under the first failure and the second failure.

Supposing the input of QRA is unit step signal, insert the first failure and the second failure on short circuit of amplifier at 0.3 s. The system can detect the failure and cut-off the failed channel in 0.04 s after failure occurring, then the dynamic performance curves can be obtained as shown in Fig. 5, in which \( \theta \) is the pitch angle and \( t \) is operational time.

![Fig. 5 System step responses when short circuit of amplifier occurs](image)

In Fig. 5, curve 1 and curve 2 express the system step responses under the first failure and the second failure on short circuit of servo amplifier separately. It indicates that the variance of system performance is not too big between one failure and two failures occurrences, so QRA can operate when failure occurs. In addition, curve 3 shows the normal system response of QRA. Comparing the normal system performance (curve 3) to degradation performance (curves 1 and 2), the output of QRA exists positive error under failed condition. So on the one hand, the redundant actuator can improve the reliability and safety greatly and the QRA can reach fault-tolerance level to FO/FO/FS; on the other hand, the performance of QRA will descend under failure occurring.

4 Reliability Analysis of QRA

Fault tree analysis is an effective reliability method to evaluate the reliability of complex system. In order to simplify the system and describe the dynamic performance degradation process, this paper adopts the simulation template based on dynamic fault tree to calculate the reliability of single channel of redundant actuator shown in Fig. 6.

In Fig. 6, FDEP denotes the function dependency gate, i.e., the top event happens on the condition of monitoring normal and basic events takes place. Fig. 6 shows that not only the function failure has been considered, but also the performance parameters excursion of control system can be described in dynamic fault tree.

While the separated single actuators are combined at colligation point, the QRA are formed based on redundant technology to achieve high reliability, which has failure performance degradation and high fault-tolerant level. Based on the sub-fault tree of single actuator shown in Fig. 6, this paper establishes the dynamic fault tree of QRA shown in Fig. 7 considering the system performance variance.

In Fig. 7, the sub-fault tree of signal channel, such as channel X failure or channel Y failure, is shown in Fig. 6.

Suppose the system is steady and reliable, the system performance should satisfy the following condition under step signal (\( u=0.5 \text{ V} \)).

\[
\begin{align*}
Y &= 1 \\
T_r &\leq 0.07 \text{ s} \\
E &< 0.05
\end{align*}
\]

where \( Y \) is the system output of QRA; \( T_r \) shows the response time of actuation system and \( E \) expresses the steady error of QRA.

It is assumed that the life distribution of component is related to time and the failure probabilities are shown in Table 1.
Table 1 The failure probabilities of component

<table>
<thead>
<tr>
<th>Component</th>
<th>Failure probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Servo amplifier</td>
<td>$0.5(1-e^{-300\times10^{-6}})$</td>
</tr>
<tr>
<td>Servo valve</td>
<td>$0.7(1-e^{-360\times10^{-6}})$</td>
</tr>
<tr>
<td>Displacement sensor</td>
<td>$0.8(1-e^{-130\times10^{-6}})$</td>
</tr>
<tr>
<td>Cylinder</td>
<td>$0.7(1-e^{-270\times10^{-6}})$</td>
</tr>
<tr>
<td>Abnormal of force sensor</td>
<td>$0.5(1-e^{-150\times10^{-6}})$</td>
</tr>
<tr>
<td>Colligation failure</td>
<td>$0.9(1-e^{-270\times10^{-6}})$</td>
</tr>
<tr>
<td>Failure of bypass valve</td>
<td>$0.6(1-e^{-200\times10^{-6}})$</td>
</tr>
<tr>
<td>Miscut</td>
<td>$1-(0.6+0.4e^{-300\times10^{-6}})\times(0.7+0.3e^{-180\times10^{-6}})$</td>
</tr>
<tr>
<td>Monitor failure</td>
<td>$0.9(1-e^{-5\times10^{-6}})$</td>
</tr>
</tbody>
</table>

Input the failure probabilities of components into fault tree shown in Fig. 7, the failure probability of QRA can be calculated shown in Fig. 8, in which $P$ is reliability of QRA and $t$ is operational time. Curve a shows the failure probability when two channels failing; curve b expresses the failure probability at tri-channels. It is obvious that QRA can reach high fault tolerant level to FO/FO/FS and its reliability in mission time can reach 0.999 999 999 when mission time is 10 h.

With so high reliability, FBW system can complete its flight mission and keep airplane safety in mission time, so FBW has replaced the mechanical control system roundly.
Performance degradation and reliability analysis of QRA have been carried out based on control template and dynamic fault tree. It has been shown that QRA can reach the fault-tolerant level of FO/FS; and it can operate under two failures. Through considering the parameter excursion of control system, the combination reliability of function and performance are calculated to realize the accurate reliability analysis of fault-tolerant control system. The results indicate that QRA can operate and complete its flight mission in very high reliability.

5 Conclusions

References


Biographies

WANG Shao ping Born in 1966, she is a professor at School of Automation Science and Electrical Engineering of Beijing University of Aeronautics and Astronautics. Her research interests include reliability analysis of fault tolerant control system, simulation engineering, fault diagnosis and Fly-By-Light system.

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