Simulation Study on Failure Mode of Sheave Damper

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Abstract. The carrier-based aircraft arresting the ship’s landing device is an important aviation protection special equipment to ensure the safe landing of the carrier aircraft. Its structure is complex, there are many failure points and failure types. The sheave damper plays a role in reducing the peak tension of the arresting cable in the arresting device. By analyzing the working process of the sheave damper in the carrier-based aircraft arresting system, a dynamic model of the sheave damper at the initial arresting stage was established. This paper analyzed the failure modes of the main hydraulic components in the system, and established the correlation between the changes in the physical parameters of the main hydraulic components and the failure modes. Based on AMESim, a simulation model of the initial sheave damper captured by the carrier-based aircraft was established. By setting virtual monitoring points, simulation curves under different failure modes were obtained. Besides, this paper also analyzed the changing laws of arresting force, speed and displacement in the initial process of arresting the carrier-based aircraft under different failure modes. The results of the study can provide theoretical references to the design optimization and fault diagnosis of the arresting gear.

1. Introduction
At the initial deck-landing arresting stage of carrier-based aircraft, a sheave damper is added between fixed sheaves at two sides of deck and main arresting engine system in order to solve the too-high peak tension of arresting cable during the deck-landing arresting process, which can effectively enhance the stability and reliability of arresting system[1]. Wang et al. analyzed the features of MK7-3 arresting gear[2]. Bi et al. analyzed and optimized the damping characteristics of sheave damper[3], and conducted dynamic modeling and simulation of sheave damper[4]. Wang analyzed and explored the durability of arresting cable[5]. However, the fault diagnosis of arresting gear has been scarcely involved. It is because the arresting gear of carrier-based aircraft is a special equipment, where the quantity and types of sensors installed are limited, so it is impossible to acquire all parametric data. Moreover, the data acquired seem not to have strong describing power for the failure mode. In this study, the MK7-3 sheave damper at the initial arresting stage was taken as the study object. A simulation model was established via AMESim, and then the failure modes of main hydraulic components were analyzed. The corresponding simulation curves of monitoring points were obtained according to different failure modes, and next, the influences of different failure modes on the initial arresting motion were analyzed.

2. Dynamic Modeling at the Initial Arresting Stage of Carrier-Based Aircraft
The arresting diagram of carrier-based aircraft is as shown in Figure 1. During the arresting process of carrier-based aircraft, the motion of aircraft carrier was neglected, while only the centering arresting of carrier-based aircraft is considered. At the initial arresting stage of carrier-based aircraft, the main arresting engine did not exert any effect, and only the sheave damper generated a buffer effect. Moreover,
the frictional relations among tail hook, steel cable and sheave were not considered. The engine was closed immediately after the tail hook hooked the arresting cable. During the arresting process of carrier-based aircraft, only the arresting force, frictional force and wind resistance were taken into account [6].

Figure 1. Arresting diagram of carrier-based aircraft. Figure 2. Schematic diagram of MK7-3 sheave damper.

\[
2T\sin\alpha - F_f = ma = my
\]  \hspace{1cm} (1)

\[
\sin\alpha = \frac{y}{\sqrt{y^2 + L^2}}
\]  \hspace{1cm} (2)

\[
\Delta L = \sqrt{y^2 + L^2} - L
\]  \hspace{1cm} (3)

Where \( T \) denotes the tension of arresting cable; \( F_f \) is the frictional force and wind resistance borne during the arresting process of carrier-based aircraft; \( m \) stands for the mass of carrier-based aircraft; \( a \) is the acceleration of carrier-based aircraft; \( y \) represents the displacement of carrier-based aircraft; \( L \) is the half of distance between two fixed sheaves; \( \alpha \) is the included angle between the position of arresting cable at initial moment and that at one moment after the motion; \( \Delta L \) is the elongated length of arresting cable at one moment.

As the sheave damper was driven by a movable sheave, the piston displacement of sheave damper is expressed as below:

\[
x = \frac{\Delta L}{2}
\]  \hspace{1cm} (4)

The schematic diagram of MK7-3 sheave damper is displayed in Figure 2, and the following kinetic equations are established:

\[
(F_1 + F_2)\cos\theta - F_3 = m_i\ddot{y}_i
\]  \hspace{1cm} (5)

\[
F_3 = P_H A_p = \frac{P_H \left(D^2 - d^2\right)}{4}
\]  \hspace{1cm} (6)

\[
\cos\theta = \frac{S_{im} - x}{\sqrt{(S_{im} - x)^2 + l^2/4}}
\]  \hspace{1cm} (7)
Where $F_1$ and $F_2$ denote the tension of arresting cable; $\theta$ is the included angle between arresting cable and direction of motion of movable sheave; $P_H$ is the hydraulic pressure borne by the hydraulic cylinder piston; $m_i$ represents the piston mass; $A_p$ is the effective area of hydraulic cylinder piston; $D$ and $d$ are the diameter of hydraulic cylinder piston and that of piston rod, respectively; $S_{m_S}$ is the horizontal distance between fixed sheave and initial piston position; $l$ is the distance between two fixed sheaves. The rotational inertia of movable sheave was neglected in order to simplify the model, $F_1 = F_2 = F$ was taken, and the followings could be obtained through the Equations (5) and (6):

$$F = \frac{P_H \left(D^2 - d^2\right)}{8 \cos \theta} - \frac{m_i \dot{y}_i}{2 \cos \theta}$$

(8)

Under the effect of throttling valve, the hydraulic oil entered the energy accumulator after generating a pressure drop. The resistance loss of hydraulic pipe was ignored, and then the flow quantity in the pipeline was calculated as below:

$$q = C_d A_0 \sqrt{\frac{2 \left(P_H - P_0\right)}{\rho}}$$

(9)

Where $C_d = 0.6$ is the flow coefficient of micropore; $A_0$ stands for the throttling area of throttling valve; $P_0$ is the downstream pressure of throttling valve, which is equal to the pressure of energy accumulator if the pipeline loss is neglected.

$$P_0 = \frac{P_{ac0} V_{ac0}^n}{\left(V_{ac0} - x A_p\right)^n}$$

(10)

Where $P_{ac0}$ is the initial pressure of energy accumulator; $V_{ac0}$ represents the initial gas volume of energy accumulator; $n = 1.4$ is a polytropic index. Given the short working time of sheave damper at the initial arresting stage, the gas compression process of energy accumulator can be an adiabatic process[7].

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Figure 3. Simulation model of sheave damper based on AMESim.
3. Sheave Damper Modeling Based on AMESim

According to the dynamic model of sheave damper at the initial deck-landing arresting stage of carrier-based aircraft, the simulation modeling was conducted using the rich component libraries in AMESim, and the simulation model is as shown in Figure 3, where the mass and velocity of carrier-based aircraft were 18 t and 55 m/s, respectively. The frictional force and wind resistance borne by the carrier-based aircraft during the motion process were both 12250 N. The precharge pressure and gas volume of energy accumulator were 20 bar and 40 L, respectively. Leakage modules were introduced into the hydraulic cylinder simulation model. The gap size and length between the piston and inner wall of hydraulic cylinder could be simulated by setting the gap and contact length between the leakage modules. Moreover, the leakage of hydraulic cylinder could be simulated. At the initial arresting stage of carrier-based aircraft, the tension of arresting cable rose very rapidly, accompanied by great energy, and the piston quality of hydraulic cylinder, which did not affect the simulation result, was neglected.

4. Failure Mode Analysis

The main hydraulic components of the sheave damper were plunger-type hydraulic cylinder, throttling valve and energy accumulator. The common failures in a hydraulic cylinder system include large internal leakage of oil cylinder, blocking of throttling valve and too high oil temperature. The leakage flow of hydraulic oil when flowing through the gap is related to the gap height, height difference between two ends of gap, dynamic viscosity and temperature of hydraulic oil, etc., where the gap height can exert a very significant effect[8]. In the failure mode analysis and simulation, the common hydraulic cylinder failures were taken as the study objects, as seen in Table 1.

| Hydraulic component | Failure code | Failure mode                  |
|---------------------|--------------|-------------------------------|
| Hydraulic cylinder  | F1           | Too large internal leakage    |
| Hydraulic oil       | F2           | Reduction of oil viscosity    |
| Throttling valve    | F3           | Orifice blocking              |

It could be known from the above analysis that the failure of any hydraulic component could be judged by its related physical parameters in the simulation system, and the incidence relations between the physical parameters and failure modes are listed in Table 2, where $dc$ represents the gap height of internal leakage module; $fp$ is the dynamic viscosity of oil liquid; $di$ stands for the orifice diameter of throttling valve.

| Parameter | Failure code | Failure feature                                |
|-----------|--------------|-----------------------------------------------|
| $dc$      | F1           | Increasing internal leakage and accelerated piston protrusion out of oil cylinder |
| $fp$      | F2           | Reduced viscosity of oil liquid and accelerated piston protrusion |
| $di$      | F3           | Seriously blocked orifice and reduced flow quantity |

5. Simulation of Failure Mode

The simulation model (Figure 3) was used to simulate the failure modes listed in Table 1 and further obtain the simulation data. According to the literature, it could be known that at 0.3 s of initial arresting stage of carrier-based aircraft, the cylinder displacement of sheave damper reached the maximum value,
so did the energy it absorbed, next, it was mainly the main arresting engine system that absorbed the energy, so the simulation time was chosen as 0.3s in this study[9].

The failure mode $F_1$ was the large internal leakage of oil cylinder, which was mainly ascribed to high energy and intensity during the arresting process of carrier-based aircraft as well as the wear induced by the long-term motion. The simulation data of this failure are as shown in Figure 4, Figure 5, Figure 6 and Figure 7, which respectively show the internal leakage flow curve of oil cylinder, cylinder displacement curve, the velocity change curve and displacement change curve at initial arresting stage of carrier-based aircraft under the failure mode of $F_1$. The gap height was set as 0, 0.02, 0.15 and 0.25 mm under normal circumstance, slight leakage, moderate leakage and serious leakage, respectively. It could be clearly seen from the curve changes at different monitoring points that with the increase in internal leakage of oil cylinder to different degrees, the motion displacement of cylinder piston was enlarged, the energy absorbed was reduced, and the buffer action was weakened, and consequently, the arresting force borne by the carrier-based aircraft in the motion process was reduced, and the sliding displacement was enlarged[10]. The velocity change in case of serious leakage in the hydraulic cylinder of carrier-based aircraft was $29.77 \, \text{m/s}$, which was 0.84 times of that under normal circumstances. The too small velocity change generated severe impacts on other components like main hydraulic cylinder, thus leading to serious accidents.

![Figure 4. Leakage flow curves of oil cylinder under failure mode F1.](image)

![Figure 5. Cylinder displacement curves under failure mode F1.](image)

![Figure 6. Velocity curves of carrier-based aircraft under failure mode F1.](image)

![Figure 7. Displacement curves of carrier-based aircraft under failure mode F1.](image)

The failure mode $F_2$ was featured by the reduction of dynamic viscosity of oil liquid under the fixed leakage gap of 0.1 mm, which was mainly caused by the rising oil temperature. The simulation data of this failure are displayed in Figure 8, Figure 9, Figure 10 and Figure 11, which respectively represent the leakage flow curves of oil cylinder, cylinder displacement curves and velocity and displacement change curves at initial arresting stage of carrier-based aircraft under failure mode $F_2$. The dynamic viscosity of oil liquid was set as four levels: normal viscosity (50 cp), partially low viscosity (45 cp), low viscosity (25 cp) and extremely low viscosity (5 cp). It could be obtained through the simulation curves that as the oil viscosity was reduced to different degrees, the leakage flow in oil cylinder was...
enlarged, so was the motion displacement of cylinder piston, the oil pressure borne by the piston was reduced, so was the energy absorbed by the sheave damper and arresting force borne by the carrier-based aircraft, and thus the sliding displacement was enlarged. The velocity change of carrier-based aircraft under extremely low oil viscosity was 31.35 m/s, which was about 0.9 times of that under normal circumstances.

The failure mode F3 was the orifice blocking of throttling valve, which generally resulted from oil liquid. The simulation data of this failure are as shown in Figure 12 and Figure 13, which respectively show the cylinder displacement curves and change curves of arresting force borne by the carrier-based aircraft in the arresting process. The orifice diameter of throttling valve was set as 20, 17, 11 and 2 mm under normal circumstance, slight blocking, moderate blocking and serious blocking, respectively. It could be clearly seen that as the orifice blocking of throttling valve became more and more serious, the flow quantity in the orifice was smaller and smaller, the motion displacement of cylinder piston was reduced, while the arresting force borne by the carrier-based aircraft was greater and greater, the peak arresting force was 11,150,671 N under serious blocking condition, which was 2.8 times of that under normal circumstances, so the requirements for the arresting indexes were far from being satisfied[11].
6. Conclusion
Aiming at the problem that it was difficult to install various sensors to collect parameter data for the carrier-based aircraft arresting gear, this paper used AMESim to establish a simulation model of the sheave damper at the initial blocking stage. The physical parameters and possible failure modes of the main hydraulic components in the model were analyzed, and the influence of different failure modes on the running process of the sheave damper was quantified, which provided a new way for the failure diagnosis and prevention of the sheave damper. The next step could focus on the simulation data of the failure mode, study the fault diagnosis algorithm, and carry out the fault diagnosis of artificial intelligence.

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