Research on Aircraft Ditching State Selection Based on Floating Characteristics of Water Surface

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Abstract: When an airplane is forced to ditching on water, slight state changes, such as weight, center of gravity, initial attitude, etc., will have great influence on the ditching performance and floating ability of the airplane. In order to study the floating ability of the aircraft under the above parameters, this paper takes a fixed-wing aircraft as the basis model, and based on hydrostatics, divides the water inflow into several tiny water inflow segments. By studying the floating attitude and floating time of different aircraft states, the influence law of the center of gravity position parameters on the floating time is mastered. The research shows that the floating time and water inflow volume of the aircraft will be significantly increased when the higher center of gravity position and the non-most unfavorable longitudinal range of the center of gravity are adopted, and forced landing on water in this state can provide emergency evacuation and escape for the aircraft personnel.

1. Introduction
Due to the high speed and heavy fuselage of modern fixed-wing aircraft, in the event of an accidental emergency landing, the aircraft will impact the water surface at a higher speed. At this time, the aerodynamic and hydrodynamic loads on the airframe will cause serious damage to the airframe, wing fracture and even rollover at the moment of impact. Under the above severe conditions, the aircraft will quickly enter the water until the floating performance is lost. A large number of studies and ditching accidents show that the main reason for the aircraft sinking is that the external fluid enters the fuselage after the aircraft is damaged. Among them, the aircraft sinking too quickly is the fatal reason for the failure of ditching. According to incomplete statistics, at least 50% of the failure ditching is caused by the submergence of aircraft [1, 2].

In order to reduce or even avoid such accidents, the floating characteristics after ditching as one of the aircraft safety performance index should be fully considered and verified during the aircraft design and development phase. Part 23 and Part 25 of CAAC's aviation regulations clearly stipulate the floating performance of the aircraft on the water surface, and point out: "it must be shown that under the reasonable and possible water conditions, the floating time and trim of the aircraft can enable all passengers to leave the aircraft and board the rescue boat required by the regulations." [3, 4]

Under the current technical conditions, the research on aircraft floating characteristics often adopts two methods: model test and numerical simulation. However, the model test is often carried out after the plan is frozen, and the overall planning and implementation cycle of the test is long, it is unable to
provide guidance for the layout optimization of aircraft structure in the process of scheme design. Although the numerical simulation is not affected by the finalization of the plan, there are still major shortcomings in the simulation and analysis of the airframe water ingress and the aircraft motion coupling, and it cannot completely and efficiently solve the aircraft motion time-domain analysis of the damaged water ingress process.

This paper takes a single-wing fixed-wing aircraft as a background model, and proposes a time-domain prediction method of aircraft motion response that can fully express the process of damaged cabin water ingress. By carrying out the research on the visual analysis technology of the floating process based on CATIA, the estimation of the floating time of the aircraft damage and flooding process has been realized. On this basis, based on different aircraft states, a study on the correlation between the aircraft’s center of gravity and the floating time is carried out, and a set of aircraft state parameter selection methods that are beneficial to the aircraft's surface floating and emergency evacuation are proposed.

2. Basic Theory

After ditching on water, the aircraft continuously sinks due to the existence of various leakage sources, and its floating posture also changes due to the change of draft. According to the anti-sinking theory in ship statics, the sinking and attitude changes of the aircraft during the floating process can be analyzed by the weight increase or loss of buoyancy method. Among them, the weight increase method regards the water inflow as the increased liquid weight of the aircraft. After the aircraft is damaged, the displacement of the aircraft should be equal to the sum of the displacement before the damage and the water inflow weight; The law of lost buoyancy is to deduct the volume of water from the underwater part of the floating aircraft, and the weight and center of gravity of the aircraft remain unchanged before and after water entry. In order to solve the floating state matrix of aircraft, this paper analyzes the floating characteristics of aircraft by adding weight method [6].

Based on Archimedes principle, the following formula can be used to calculate the aircraft floating state equation after water entry:

\[
\begin{align*}
\mathbf{V} - (\mathbf{V}_0 + \mathbf{v}) &= 0 \\
M_{XZ} + M_{XY} \tan \Phi &= 0 \\
M_{YZ} + M_{XY} \tan \Theta &= 0
\end{align*}
\]

(1)

In the formula, \(\mathbf{V}\) is the drainage volume of the flooded plane; \(\mathbf{V}_0\) is the initial drainage volume of aircraft; \(\mathbf{v}\) is the influent volume; \(M_{XZ}\), \(M_{XY}\), \(M_{YZ}\) are the moment of resultant force of gravity and buoyancy relative to \(XZ, XY, YZ\) plane; \(\Phi\) is the roll angle; \(\Theta\) is the pitch angle.

Due to the above equations is the function of average draft \(T\), roll angle \(\Phi\) and pitch angle \(\Theta\). So the formula (1) can be expressed below:

\[
F(X) = 0
\]

(2)

In the formula,

\[
F(X) = \begin{bmatrix}
f_1(X) \\
f_2(X) \\
f_3(X)
\end{bmatrix}, \quad X = \begin{bmatrix} T \\ \tan \Phi \\ \tan \Theta \end{bmatrix}, \quad 0 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
\]

Based on the successive linearization method, equation (2) can be rewritten as:

\[
DF(X) \delta X + F(X) = 0
\]

(3)
In which, \( DF(X) \) is the jacob matrix of \( F(X) \) with \( X; \delta X = \begin{bmatrix} \delta T \\ \delta \tan \phi \\ \delta \tan \theta \end{bmatrix} \).

As the aircraft is floating, the volume of water entering directly affects the floating state of the aircraft. Assume there is a certain volume of water entering, it must exist a corresponding set of draft and attitude angles \( T, \phi, \theta \) that satisfy the balance equations. For this reason, the discretized water intake segment analysis method is used when solving the aircraft attitude. The basic idea is as follows: discretizing the total water inflow of the aircraft into multiple water inflow fragments of equal volume. In the calculation, the draft and the attitude angle \( T_0, \phi_0, \theta_0 \) of the aircraft before the water flooding are used as the initial attitude parameters. When the aircraft enters the water \( \Delta v \), the draft and attitude angle change slightly on the basis of the initial attitude parameters. After the state equations, the corresponding draft depth and attitude angle are the parameters of the aircraft's stable floating state under the water intake volume, which can be used as the initial attitude parameters in the latter state (when the water intake volume continues to increase \( \Delta v \)). According to this iterative method, the draft and attitude angle corresponding to the final floating state of the aircraft can be obtained.

According to the principle of hydrodynamics, there is a relationship between the water inflow segment and the corresponding water inflow time

\[
\Delta t = \frac{\Delta v}{q} = \frac{\Delta v}{\mu A/2g_0(H-h)}
\]

Among them, \( \Delta t \) is the water intake time corresponding to the water intake segment; \( \Delta v \) is the water intake flow segment; \( q \) is the water intake flow; \( \mu \) is the flow coefficient, usually 0.6; \( A \) is the leakage source area; \( H \) is the height of the center of leakage source from the surface outside the fuselage; \( h \) is the height between the center of leakage source and the water surface inside the fuselage [5, 7].

According to CAAC's aviation regulations, once the waterline outside the fuselage reach the emergency export, this state is the final state of floating time calculation, and the time between the aircraft stop taxiing on the water surface and the waterline arrived emergency export is the floating time of the aircraft. On these conditions, the total floating time of the aircraft on the water surface can be calculated by the following formula:

\[
T = \sum_{i=1}^{n} \Delta t_i
\]
3. Programming

The floating progress of aircraft on water surface is a slowly and continuity course. The dynamic process is discretized into a time continuous static process, and each static process satisfies the Achimdean equilibrium condition (still water surface). To realize the automatic convergence of each quasi-static process and improve the computational efficiency. Combined with CATIA graphics processing platform and the calculation method of floating time based on water infl ow segment, the external import and visualization platform of floating parameters was built by self programming. In addition, many studies such as motion characteristics, time segment realization mechanism and CATIA secondary development technology of the aircraft surface floating process have been carried out to obtain the calculation model of the position of internal and external liquid level, the real-time monitoring of motion attitude and the construction of floating time[5]. The specific research ideas and calculation framework are shown in Figure 2 and Figure 3 respectively.
4. Verification of the accuracy of the calculation program
In order to ensure the reliability of the calculation program, this part verifies and analyzes the accuracy of the calculation program based on the existing test results of fixed-wing aircraft floating characteristics on static water surface. The calculation model selects a fixed-wing aircraft test model, and the model weight, center of gravity position, leakage source location and area size are consistent with the test model.
Fig 4 Comparison between calculated floating state and test floating state at a certain time

Figure 4 is the schematic diagram of the floating state comparison between the calculation results and the test results in the same state. From the perspective of the distribution ratio of the fuselage above/below the waterline, the position of water surface and the attitude of the aircraft, the two are very close. Figure 5 is the compare curves of the trim angle versus floating time corresponding to the two methods. It can be seen from the position of the curve that the calculation result is bigger than the test result, the floating time error is about 4%, and the maximum pitch angle error is about 6%. The results show that the calculation results are more conservative than the test experimental values. The calculation method has higher accuracy for judging the aircraft’s floating characteristics, and can be used to analyze the floating characteristics of the background aircraft and the selection analysis of ditching state.

Fig 5 Comparison of calculated results of pitch angle and floating time with experimental results

5. Analysis of the influence of the position of the center of gravity on the floating characteristics

Base on the proposed floating characters calculation and analysis program, a fixed-wing aircraft is used as a program model to analyze the floating characteristics after ditching. The calculation environment is static water surface, and the model is a full-machine model with inherent leakage sources of the fuselage. In the calculation, the longitudinal range of the model’s center of gravity is 10%MAC~40%MAC, and the vertical height has two types: a lower position and a higher position. The weight of the aircraft, the location of the leakage source and the area of the leakage source are always same in each state.

Figure 6 and Figure 7 are the curves of floating time and influent volume with the longitudinal for different conditions of the height of the center of gravity. It can be obtained from the change of the curve that the height of the center of gravity has a more obvious effect on floating time and influent volume. When the longitudinal center of gravity is fixed, the higher the height of the center of gravity, the longer the aircraft floats and the larger the volume of flooded water.

Since the aircraft will go through a series of dynamic balance processes when floating on the water surface, the corresponding stable equilibrium state will be reached only when the force and moment of the aircraft satisfy the balance equation. For different heights of the center of gravity, the higher the
center of gravity, the greater the restoring moment that the wing needed. In this case, the aircraft’s heel angle and the distance between the exit door and the outer water surface increase, and the aircraft’s final floating time increases. The volume of incoming water increases. Among them, when the longitudinal position of the center of gravity is the same, the floating time of the high center of gravity is about 20% longer than that of the low center of gravity, and the water intake volume increases by about 15%.

Fig6 Comparison curve of floating time at different gravity center positions

Fig7 Comparison curve of inlet water volume at different gravity center positions

When the height of the center of gravity is the same, the floating time and inlet water volume change curve with time have the same changing law. The Figure6 and Figure7 show that as the longitudinal center of gravity move backward, the floating time and inlet water volume first decrease and then increase, and achieve the minimum value at the longitudinal center of gravity between 15%MAC and 20%MAC. The center of gravity range corresponding to the minimum value of the curve is defined as the most unfavorable center of gravity during the floatation of the aircraft. Under such center of gravity,
the motion attitude, distance between door and outside water surface and other parameters are smaller than other center of gravity states. The floating time and inlet water volume should also be correspondingly small.

It can be seen from the above analysis that increasing the height of the center of gravity and selecting the outside the most unfavorable longitudinal position of the center of gravity can effectively increase the aircraft's floating time and water intake volume. Under such state, the ditching can provide favorable conditions for emergency evacuation for the crew[8].

6. Conclusion
Base on the calculation principle of aircraft floatation on water surface, combine with the Catia graphics processing platform and discrete floating time calculation method, the paper proposes a visual calculation program which can be used for real-time monitoring the water surface, aircraft motion attitude and floating time calculation. It is verified by test comparison that the program has high calculation accuracy and credible results.

Though analysis the floatation characteristics of the aircraft under different center of gravity, the influential of the position of center of gravity on the floating time and inlet water volume is mastered. The calculation shows that when the position of the center of gravity is higher and the longitude center of gravity is not the unfavorable range, the floating time and water intake volume will be significantly increased. The above characteristics can be combined in the selection of the ditching state based on the surface floating characteristics, and then prepare emergency evacuation procedures.

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