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ESTIMATION OF STATIC AND DYNAMIC FLOATATION CHARACTERISTICS DURING AIRCRAFT DITCHING

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Abstract

Ditching performance is an essential part of civil aircraft certification procedures. However, there is little research on this area. This paper uses VB language to investigate and analyze floatation characteristics. After importing the simplified plane model the trapezoidal rule is used to complete the integral of the volume below the waterline, so as the principle of Archimedes to calculate the buoyancy and floating moment. Unlike the static floatation characteristics focusing on the problems of buoyancy and stability, an aircraft sinking posture is what the dynamic floatation characteristics research on. The sinking process is simplified as a quasi-static process. With time approaching gradually, the weight of water entering into the plane increases, and the sinking posture changes in three degrees of freedom. In wave environment, the strip method is used to add the disturbed flow resistance. This method keeps an inexpensive computational cost with the guarantee of calculation accuracy. In the end, this paper valuated the security in static floatation characteristics for a plane, within the permitted weight and the Center of gravity (C.G) configuration the static float attitude is obtained. Considering structure damage, the dynamic flooding process of the plane is simulated. The difference in dynamic sinking process between the calm surface and wave environment is also been analyzed.

Keywords: Ditching, Ditching Regulation, Floatation Characteristics, Engineering Estimation, High-wing airplane

1. Introduction

The possibility of aircraft ditching accident increases with the increasing frequency of cross-water flight. Thus the study on aircraft ditching performances appears to be particularly important for safe flight and obtaining the airworthiness certificate.

US DOT (Department of Transportation) and FAA (Federal Aviation Administration) classify the aircraft water impact into two types: planned ditching and unplanned water contact [1][2]. The former one requires the reasonable ditching procedure to ensure the passengers' safety and get enough time for escaping. The procedure is often divided into four stages, approach, impact, landing and floatation [3]. At the approach stage, it focuses on the manipulation and control of aircraft's flying postures. At the impact and landing stage, the aircraft is not controllable. The posture changes fiercely with huge shocking overload. Moreover, at the moment of impacting the water, the aircraft may suffer from structural damages and the safety of passengers will be threatened. There are abundant research results in this stage. Von Karman [4] (1929) adopted added mass theory to provide the methodology for studying wedge-shaped object's ditching. Later, Wagner [5], Zhao and Faltinsen[6] further improved this. In terms of experimental researches, in the middle 20th century, NACA and some other labs successively launched a lot of scale model [7][8] and full-size model tests [9]-[11].

At the floatation stage, it mainly explores into the aircraft's state on water after impact, as well as aircraft's sinking posture and sinking time effects by structural damaged. Moreover, on this basis, it is judged whether the floating time is enough for passengers' escape. There are relatively few researches on the floatation stage, which is the focus of this paper.

2. Numerical calculation method of static floatation characteristics

The study on aircraft's floatation stage is called floatation characteristics, including static floatation and dynamic floatation. In particular, static floatation delves into the free floating posture of aircraft after ditching without buoyance loss on the basis of hydrostatics. The aircraft's initial floating posture obtained by calculating the buoyancy and stability is mainly affected by its weight and C.G position. Starting from hydrostatics, the paper uses VB program as the calculation platform. Import the simplified airplane model into the program, and use the trapezoidal rule to calculate the integral of the airplane volume below the waterline. Archimedes principle is employed to calculate the submerged volume of objects, and further solve the buoyancy moment.

2.1 Solution of static floatation basic parameters

Static floating characteristics mainly study the stable attitude of aircraft floating in static water. The condition is that the buoyancy is equal to gravity and the buoyancy moment is zero. The solution is guided by Archimedes principle and moment equation:

$$\begin{gathered} F_{\text{buoyancy}} = \rho_{\text{water}} V g \\ M = F \times L \end{gathered} \qquad (1)$$

Simplify the fuselage model first. The complete pressurized parts are kept: Passenger cabins, cargo cabins and wing tank. Discrete simplified aircraft model, the fuselage is sliced along the axial direction, and the wings are sliced along the span direction.
In the calculation, two sets of coordinate systems are used in the calculation: the body coordinate system (x_c, y_c, z_c) records the original coordinates of the model itself, and the ground coordinate system (x, y, z) records the aircraft's floating state. The Coordinate origin is on the water surface. The coordinate shift matrix is shown as follows:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha\sin\beta & \sin\alpha\cos\beta \\ 0 & \cos\beta & -\sin\beta \\ -\sin\alpha & \sin\beta\cos\alpha & \cos\alpha\cos\beta \end{bmatrix} \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} - \begin{bmatrix} 0 \\ y_{cg}\cos\beta - z_{cg}\sin\beta \\ -x_{cg}\sin\alpha + y_{cg}\sin\beta\cos\alpha + z_{cg}\cos\alpha\cos\beta \end{bmatrix} \qquad (2)$$

In this formula, α is the trim angle and β is the roll angle. (x_{cg}, y_{cg}, z_{cg}) is the coordinate of the C.G in the body coordinate system.

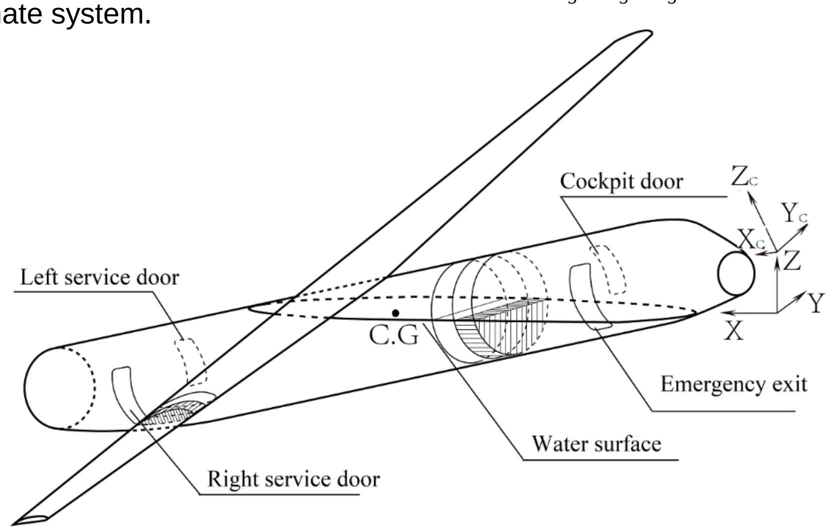

Figure 1 – Coordinate and strip method

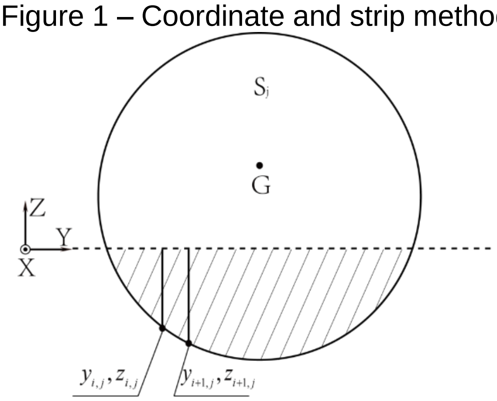

Figure 2 – Solution of trapezoidal rule area

The submerged volume of the fuselage is the volume at z<0. First, use the trapezoidal rule to find the submerged area of each slice. Then convert the submerged area to the body coordinate system and multiply it by the distance between two slices. Finally, calculate the integral of the submerged volume along the axis of the fuselage.
When solving the buoyant moment, it is necessary to find the force arm from the center of the submerged area of each slice to the center of gravity. Calculate the drainage gravity of the submerged volume of the slice, and then take the moment of the center of gravity. Finally, the buoyancy moment of each slice is accumulated, that is, the total buoyancy moment.
The same goes for wings.

2.2 Method of calculating static floatation characteristics

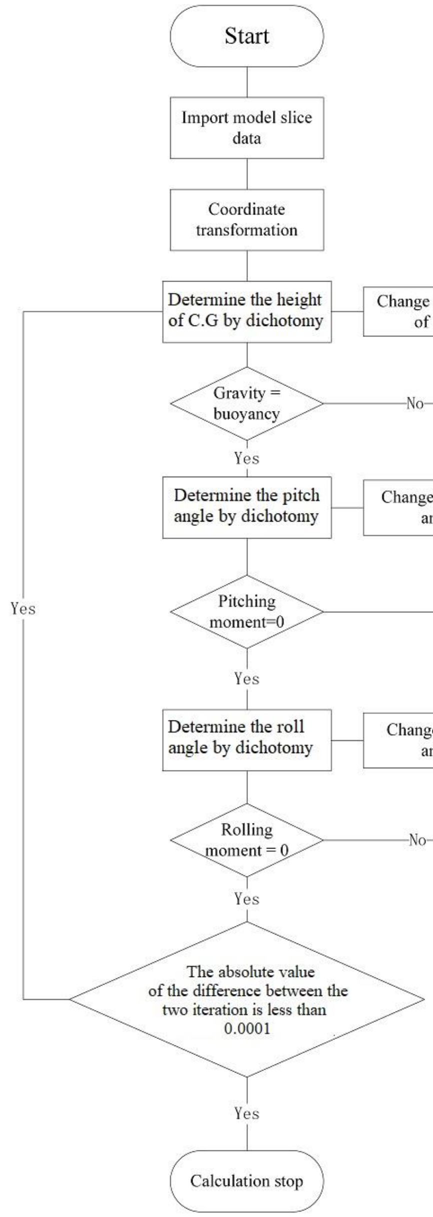

Figure 3 – Solving process of static floatation characteristics

In the calculation, the three-layer nested dichotomy of the height of C.G, the pitch angle, and the roll angle is used to solve the initial floating state of the aircraft. When the buoyancy is equal to gravity, the pitch moment is zero, and the roll moment is zero, the calculation is stopped.

2.3 Analysis of static floating characteristics of an aircraft

Due to its shape and structure characteristics, high-wing airplanes face more severe problems in terms of floating characteristics than low-wing ones. The center of gravity of the high-wing is high, and the roll angle may change greatly during the floating process, which affects the escape process. Therefore, this paper chooses the high-wing as the research object.

The length of the fuselage is 25m. The maximum cross-sectional area of the fuselage is 6.0m2. The wingspan is 27.5m. The wing root chord length is 3.3m. The wing tip chord length is 1.3m.

Table 1 – The bottom midpoint coordinates of each door

	X coordinate(m)	Y coordinate(m)	Z coordinate(m)
Cockpit door	5.565	-1.229	0
Emergency exit	7.095	1.229	0
Left service door	22.530	-1.109	0
Right service door	22.530	1.109	0

Table 2 – Calculation parameters of the high wing airplane

Ixx($kg \cdot m^2$)	Iyy($kg \cdot m^2$)	C.G in Z (m)	C.G in X (m)	C.G in Y (m)
333577	1092718	0.630	14.102	0.020

The range of the position of C.G. of the aircraft is on the mean aerodynamic chord of the aircraft from 15% to 35%, and the range of the weight change is from 14500kg to 26500kg. Calculate the initial floating state of the aircraft in equilibrium on the water surface. The distance between the bottom end of each cabin door and the water surface is calculated by the results of the height of C.G, the pitch angle and the roll angle.

Looking forward from the rear of the fuselage, when the roll angle is negative it is tilted to the right, and when it is positive it is tilted to the left. Take the right side tilt as an example, as shown in Figure 1. When the height of the center of gravity is lower, the pitch angle and roll angle are larger, and the distance from the right service door to the water surface is smaller and more dangerous. The contour map of the distance from the bottom of the right service door to the water surface (as shown in Figure 4) can be used to determine whether the given C.G position and weight are in the danger zone. It can be found that the design range of the aircraft's center of gravity is outside the danger zone. Since the parameters of the aircraft's C.G are symmetrical, the same applies if the aircraft is tilted to the left

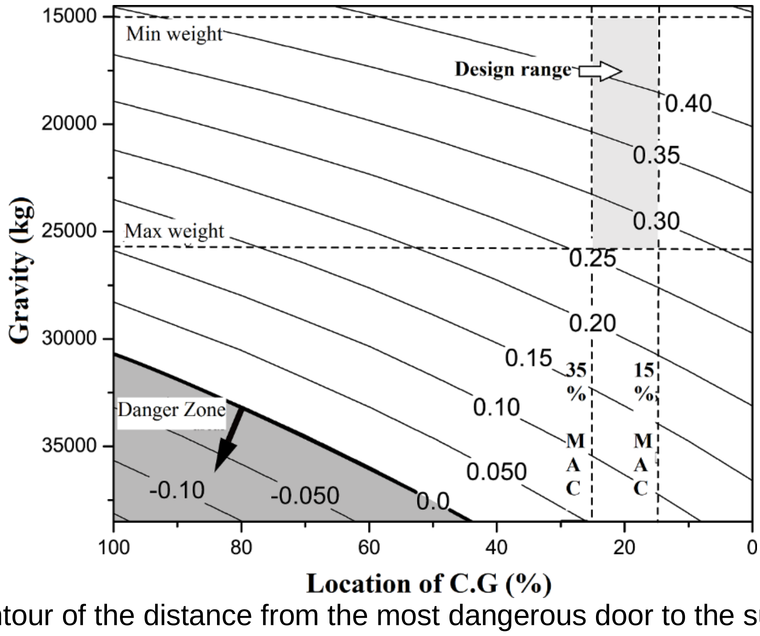

Figure 4 – The contour of the distance from the most dangerous door to the surface of the water

3. Method of calculating dynamic floatation characteristics

The dynamic floating characteristic is to study the change of the attitude of the aircraft during the sinking process when the aircraft is damaged in the pressurized area. What is concerned is the time required for the sinking of the aircraft and whether there is an emergency exit for passengers to evacuate during the sinking process. To analyze the dynamic floating characteristics, first determine the leaking area.

In the analysis of dynamic floating characteristics, use the strip method to calculate the flow resistance of the aircraft. Simplify the sinking process into a quasi-static process. The method of approaching with time is used to increase the weight of the water intake, and the three-degree-of-freedom sinking attitude of the aircraft is solved.

3.1 Solution of dynamic floatation basic parameters

The dynamic floating characteristic takes the static floating calculation result as the initial value to study the sinking process of the water inflow in the pressurized area caused by the damage of the aircraft. The force change caused by the water entering the body, the change in speed is derived, and the change in position is obtained. Specifically, the solution is guided by the momentum theorem and the momentum moment theorem:

$$F = m\ddot{r}, M = I\ddot{\theta}$$
$$\dot{r} = \ddot{r} \bullet \Delta t, \dot{\theta} = \ddot{\theta} \bullet \Delta t$$
$$r = \dot{r} \bullet \Delta t, \theta = \dot{\theta} \bullet \Delta t \tag{3}$$

When calculating the buoyancy moment of the wing, the resistance moment MD is added in order to simulate the turbulence resistance. The strip method in ship researches is adopted. The resistance is determined by the flat turbulence formula (4), and the resistance coefficient is set as 2.

$$D_{\mathrm{D},j} = \mathrm{C_D} \cdot \frac{1}{2}\rho\left\{\dot{\beta}\left[\frac{1}{2}(\bar{y}_j + \bar{y}_{j-1}) - y_\mathrm{g}\right]\right\}^2 S_j$$
$$M_{\mathrm{D},j} = D_{\mathrm{D},j} \cdot \left[\frac{1}{2}(\bar{y}_j + \bar{y}_{j-1}) - y_\mathrm{g}\right] \tag{4}$$

- Solving the water inflow: Simplify the leaking area into multiple holes and give each hole an area.The hydraulic formula(5) is used to solve the ideal flow rate per unit area, and then the flow rate is determined according to the actual hole area [12].

$$Q_{m,n} = \mu \cdot S \cdot \sqrt{2g\Delta h_{m,n}}$$
$$W_{\mathrm{in},n} = \sum_{m=1}^{M} Q_{m,n}\Delta t \tag{5}$$

In this formula, $Q_{m,n}$ is the flow rate of hole m at time n. $W_{\mathrm{in},n}$ is the total quality of water intake at time n. μ is the flow coefficient of small holes (In the paper, it is 0.8). S is the hole's area. $\Delta h_{m,n}$ refers to the Water surface height distance between in and out.

- Solution in the wave environment: In a wave environment, the water surface needs to be changed to a traveling wave that travels in the positive direction of the X axis and changes with time.

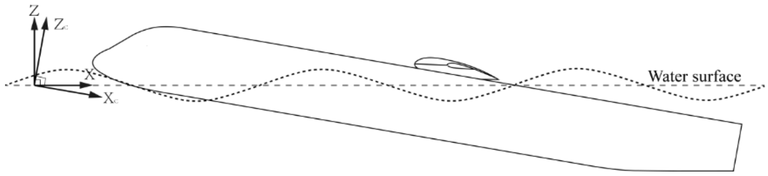

Figure 5 – Water surface in wave environment

$$h_{wave}(x,t) = A\sin(\frac{x}{L} - \varphi + T \times t) \tag{6}$$

In this formula, h_{wave} is the height of wave water surface, which is the function of x and time t. A refers to the height of the wave. L is the wavelength. T is the wave motion period. φ is the initial phase.

3.2 Method of calculating dynamic floatation characteristics

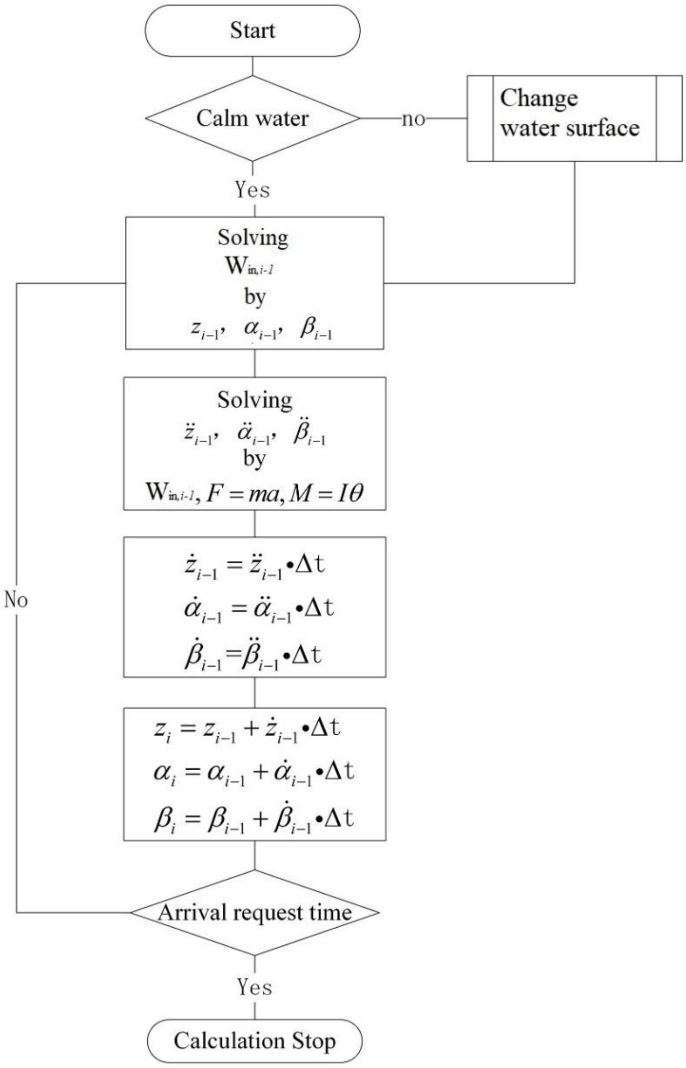

Figure 6 – Solving process of dynamic floatation characteristics

3.3 Analysis of dynamic floating characteristics of an aircraft

Refer to the structural damage form of A320 during the forced landing of the Hudson River in 2009 [13]. In the calculation, it is assumed that the floor of the fuselage has a leakage area of 0.1m2, and the rear ball frame has a leakage area of 0.3m2. The weight of airplane is 26500kg. The position of C.G is at 15% MAC.

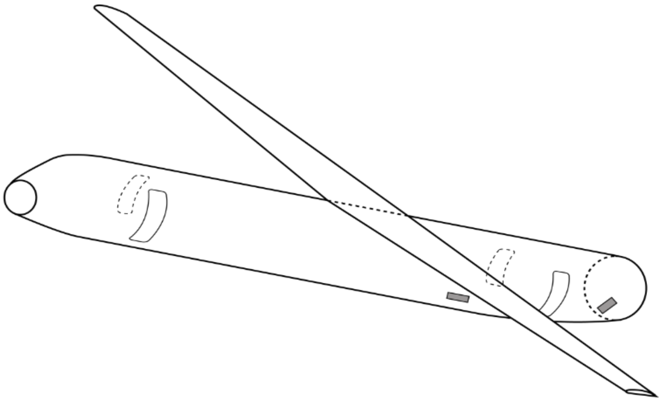

Figure 7 – Leakage area of the model

In terms of the parameters of wave's conditions, the wave is 39m in length and 1.25m in height. The period is 5s. The most dangerous situation when the ditching direction is vertical to the wave.

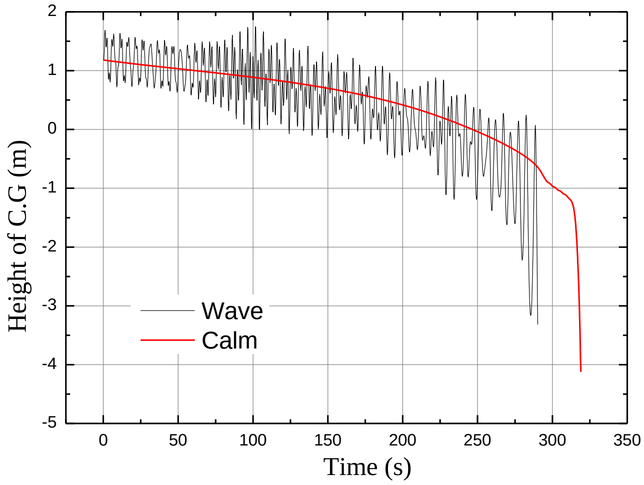

Figure 8 – The C.G height in sinking process

As shown in Figure 8, in the calm water, the leaking area of the rear ball frame in the early stage has not touched the water, so it sinks slowly. After 300s, the rear ball frame starts to sink when it touches the water. In wave environment, because the leaky area of the ball frame contacts the water surface earlier, it sinks faster in the later stage than in calm water.

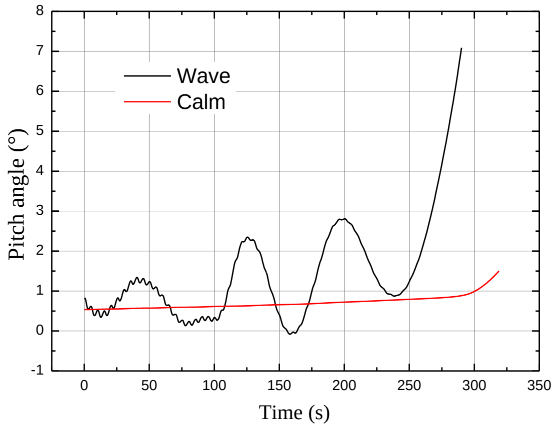

Figure 9 – Pitch angle in sinking process

As shown in Figure 9 the pitch angle of the calm water surface changes monotonously and slightly before the tail frame hits the water. In wave environment, the pitch angle oscillates with the wave. With the increase of the water intake of the fuselage, the oscillation amplitude of the pitch angle is getting bigger and bigger.

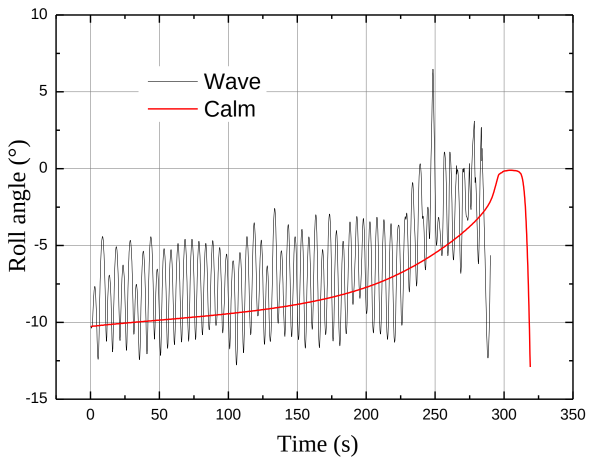

Figure 10 – Roll angle in sinking process

As the position of the center of gravity drops, the wings gradually rise out of the water, so the roll angle gradually decreases. When the wing immersion volume is reduced to such an extent that the spanwise balance cannot be maintained, the aircraft quickly rolls into the initial direction again.

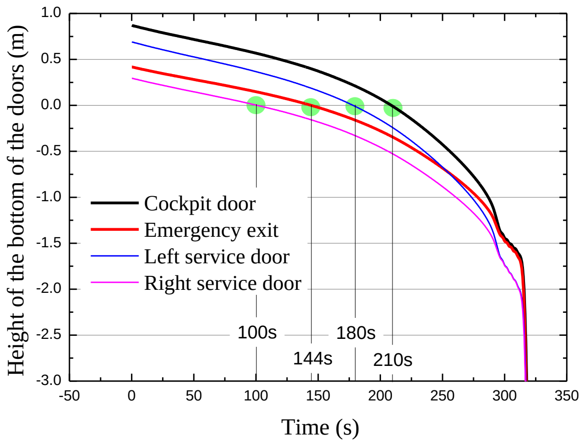

Figure 11 – The height of the bottom of doors on calm water in sinking process

The order and time of each door's contact with the calm water surface are as follows: Right service door at 100s, emergency exit at 144s, left service door at 180s, and cockpit door at 210s. Taking into account the configuration of the high-wing airplane, when none of the escape exits sink below the waterline, it is recommended that passengers evacuate to both sides evenly to maintain a spanwise balance. At first, all four doors were opened as escape exits. In order to prevent the influx of water into the door, the right service door is closed in advance when the time is approaching 100s. After that, the emergency exit and the left service door were sequentially closed every 40s, and finally only escaped from the cockpit door. In addition, it is considered that the aircraft may encounter structural damage during ditching, resulting in deformation of the cabin door. It is recommended to open the cockpit door or left service door which in the highest position before entering the water.

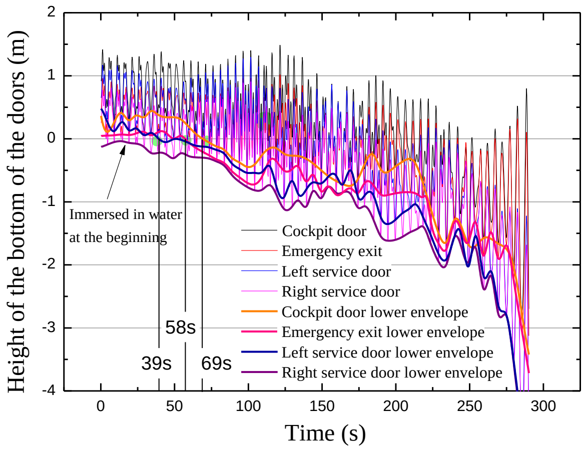

Figure 12 – The height of the bottom of doors on wave water in sinking process

It can be found that the right service door will enter the water from the beginning in wave environment. Due to pitching, heaving and other movements, the time for each door to touch the water surface was significantly earlier: emergency exit at 39s, left service door at 58s, and cockpit door at 69s. The following escape suggestions are given: When evacuating, keep evacuating evenly to both sides. The right service door remains closed, and the other three doors are opened as escape exits. When the time is close to 39s, the left service door is closed in advance. Close the emergency exit after 20s. After that, there was another 10s to escape from the cockpit door. It is also recommended to open the cockpit door before ditching to ensure a clear exit during escape.

4. Conclusion

In this paper, a set of calculation methods is established by writing code in Visual Basic for the floatation characteristics of the aircraft during ditching. Use the strip method to reduce the force from three-dimensional to two-dimensional. Starting from hydrostatics, the Archimedes principle is used to solve the problem of buoyancy and stability of static floating characteristics. Use the water inlet holes to express the leaky area of the aircraft structure. Simplify the aircraft sinking process into a quasi-static process to solve the aircraft sinking process. By changing the shape of the water surface, the sinking process of the wave environment is obtained. This method obtains a lower calculation cost while ensuring a certain calculation accuracy.

This method is specifically applied to an high-wing airplane in the paper. The result is that the aircraft's static and stable floating state is that the nose is slightly raised, and the one-sided wings enter the water. Within the design range of weight and center of gravity, a safe static floating characteristic result is obtained. When studying the dynamic floating characteristics of the aircraft, the sinking attitude of the aircraft is analyzed, and escape suggestions are given based on the calculation results. In calm water, the aircraft has an escape time of about 200s, but only 69s in a wave environment.

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