Numerical Study on the Extreme Impact Load of Wavy-Water Ditching

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Abstract. In this paper, numerical method is used study the extreme impact load and its physical causes during the wavy aircraft ditching. the finite volume method and VOF method are used to capture the free surface, six degrees of freedom model and global motion mesh to deal with the relative motion between water and aircraft, and simulate the forced landing process of the aircraft. By choosing the place with the largest vertical velocity relative to the water as the impact position, the extreme impact load on the fuselage is predicted. In this paper, during the impact stage of the wavy water surface, the fuselage encountered an impact peak which is unforeseen on the calm water surface, and the magnitude of the impact peak was related to the sinking speed of the aircraft relative to the water surface. This paper also compares the movement attitude and overload history of aircraft ditching under five sea conditions with different wave height, and gives the influence rules of wave height on the extreme impact load and the peak values of other parameters, which provides a reference for the design of aircraft load distribution.

1. Introduction
With the increasing number of cross-water flight routes, the possibility that an aircraft encounters an accident in the air and needs to perform an emergency landing on water will also increase. The U.S. Department of Transportation stipulates that a planned water emergency landing is called ditching [1]. By executing a scheduled water emergency landing procedure, the longitudinal and lateral loads on the aircraft will be within the design range [2][3], and passengers will have several minutes of posture preparation time to withstand the impact.

At present, the research on aircraft ditching mainly focuses on calm water, which forms the general understanding of ditching. The process of ditching can be divided into four stages: contact, impact, planing and floating. The dramatic changes of extreme impact load and attitude during the ditching mainly occur in the stage of contact-impact, which usually ends in a few seconds and the entire process changes dramatically non-linearly. The common research methods for ditching include theoretical analysis, model experiment and numerical simulation.

The ditching belongs to the problem of water impact. The pioneer research work was achieved by Von Karman in 1929 when completing the analysis on the problem of water impact of seaplane [4], in which Von Karman used theoretical analysis method to analyse of body load during the impact. In 1932, Wagner improved the Von Karman’s theory by using added mass theory [5], taking the influence of sur-face deformation of water in the process of impact into account. The study of characteristics of different shapes of the fuselage in the ditching is accomplished by McBride, Fisher et al. in 1953 [6], whose report contains 9 kinds of different shapes of the fuselage which have
different effect on the water impact. After the 1980s, the numerical simulation method gradually replaced the model experiment method. The boundary element method [7] is applied to the vertical water impact of the simple object, and there is little related literature for complex three-dimensional objects impacting with larger speed. SPH method is used in the water entry problem calculation of the rigid body and elastic body. And due to the existence of relatively large horizontal velocity in the process of ditching which produces the positive pressure, negative pressure also appears because of the curvature of the aircraft shape. But at present, the SPH method that makes the constitutive equation as the control equation, which is relatively mature, can’t simulate the negative pressure, so the SPH method that makes NS equation as the control equation should be developed if you want to apply SPH to the ditching problem. Serious mesh distortion and higher calculation cost will appear when using finite element method (FEM) to calculate the ditching problem [8]. Streckwall et al. [9] using VOF method to simulate the water-air interface to study the water impact characteristics of a single fuselage; Qu et al. [10] used the Global Motion Mesh (GMM) technology to process the relative motion between the aircraft and the water surface, and the numerical simulation results are in good agreement with the experimental results.

In the actual ditching process, the wave environment is often encountered. If an aircraft touches water in a dangerous wave position, there will be an unforeseen extreme impact load on a calm water surface. This paper uses numerical simulation method to study the ditching characteristics of a high-wing regional aircraft in wave environment with different wave height.

2. Numerical Method and Verification

2.1. Numerical methods

The computational approaches include four parts: flow solver, VOF method, six-degree-of-freedom (6DOF) model, and GMM method. The VOF method is used to capture free water surface. The 6DOF model is used to compute the motion trajectory of the object. The GMM method is used to deal with the motion of the whole computational domain.

In this paper, the whole computational domain (including the cells and boundary) moves together with the object like a rigid body. Thus there is no need to use any re-meshing or mesh deformation techniques, which will ensure the quality of the cells in the whole computational domain to improve numerical accuracy (especially the accuracy of free water surface capture) and save computation cost. The volume fraction boundary conditions can ensure that the free water surface keeps a stationary level when the computational domain moves. This condition is set according to the cell coordinates of the boundaries in the earth fixed coordinate system. That is, the volume fraction of water \( a = 0.5 \) for the cell located on the interface between air and water; \( a = 0 \) for the cells located above the interface; \( a = 1 \) for the cells located below the interface.

2.2. Validation of numerical methods

The ditching process of NACA TN 2929 model F is simulated and compared with the experimental results [6]. In this case, a half mesh of Model F is used. Except the symmetry boundary and no-slip wall boundary, the other outer boundaries are set as velocity-inlet conditions. A mix of unstructured and Multi-block structure mesh of the total cell number of 2.7 million is used. The numerical results and the experimental results from reference are compared in figure 1. The numerical results of pitch attitude and CG height show a satisfactory agreement with the experiment results.
3. Physical Model and Wave Model

3.1. Physical Model and Computational Grid
The model studied in this paper is a high wing high tail regional aircraft with normal configuration, which is basically the same as the model F of NACA TN 2929 model. A half mesh of the model is used and the aircraft is located at the centre of the cube computational domain. The boundary is set at 5L (L is the body length) away from the model. A mix of unstructured and structure mesh of the total cell number of 3.8 million is used, as Figure 2 shows.

3.2. Wave model
Water surface is rough with swell in most cases. In this section, a sinusoidal curve is used to represent the swell. Wavy water ditching can be separated into two characteristic situations: vertical to swell and parallel to swell. Ditching parallel to the swell approaches calm water ditching. Ditching vertical to swell is more dangerous when an aircraft flies against the wave propagation direction. The impact load is related to the vertical relative velocity between the aircraft and water surface. In order to study the extreme impact load during ditching, ditching vertical to swell is selected for research.
The aircraft moves from right to left. The ground coordinate system is taken as a reference, the X axis is positive to the right, the y axis is positive upwards, and the pitch angle $\theta_z$ of the aircraft is positive to nose up. A sinusoidal wave with small amplitude is selected in the calculation.

$$\Delta h = \frac{H}{2} \sin \left( \frac{2\pi}{L} x - \frac{2\pi}{T} t \right)$$

(1)

$$v_y = -\frac{\pi H}{T} \cos \left( \frac{2\pi}{L} x - \frac{2\pi}{T} t \right)$$

(2)

Where $\Delta h$ is the position of wave surface, and $v_y$ is the vertical velocity of wave. In this paper, the wavelength is 37.5 m, the wave height is 0.6m to1.8m, and the period is 4.9 s. The above conditions belong to level 3 to 4 sea conditions.

Von Karman [4] shows that the impact load is proportional to the square of the impact velocity. In this paper, the most dangerous landing condition is located at the phase $\pi$ of the water surface where the vertical relative velocity between the aircraft and water surface is the largest, as shown in Figure 3.

4. Analysis of Typical Ditching Process in Wave Environment

According to the parameter range recommended by ditching procedure [2], the landing velocity is 1m/s, pitch attitude is 10.79° (the angle of attack is 12°), the airspeed of the aircraft is 47.5m/s, and the sideslip angle is 0°. At the beginning of the cases, the lower surface of the fuselage is 0.2m away from the water surface. In the following analysis, the load coefficient is calculated by Equation(3) and (4):

$$F_x = \frac{x}{mg}$$

(3)

$$F_y = \frac{y}{mg}$$

(4)

Where $F_x$ is the horizontal load, $F_y$ is the vertical load, $f_x$ is the horizontal force, $f_y$ is the vertical force. Figure 4 shows comprehensive curves of aircraft ditching on calm surface and wavy surface, where $\alpha_z$ is pitch angle acceleration. According to the curve, the ditching process can be divided into the following three stages: 1, the contact stage, which occurs in 0 to 0.3s. The fuselage just touches the water surface. 2, the impact stage, which occurs in 0.3 to 4s. The fuselage impacted into the water and accompanied with planing. The change of load is violent in this stage. 3, the planing stage. After 4s the planing in horizontal direction is dominant at the end of the ditching behavior. The stress situation of the aircraft in this stage tends to be stable, and there is no more load peak.

In the contact stage, there are obvious difference between the calm surface and the wavy surface ditching. Figure 5 shows the comparison of the aircraft attitude and water surface shape in the contact phase. Figure 6 shows the comparison of the aircraft ditching load process in this phase.
Figure. 4 Load history of ditching on calm and wave surface

(a) Calm surface at 0.18s  (b) Wave surface at 0.18s

(c) Calm surface at 0.3s  (d) Wave surface at 0.3s

Figure. 5 Aircraft attitude and water surface during water contact stage

(a) Horizontal load  (b) Vertical load

Figure. 6 Motion and load history during water touch stage
Figure 6(a)(b) shows ditching in calm surface. The rear of the fuselage evenly contacts the water surface, showing a planing attitude. As can be seen from Figure 8, the planing behavior leads to an increase in horizontal drag. At this moment, the depth of the fuselage tail in water is shallow. The aircraft continues to plan underwater and gradually transitions to the impact stage. As can be seen from Figure 5(c) and 6, when the abdomen of the fuselage touches the water facing the wave slope the rear of the fuselage has not yet touched the water. A small drag peak appears in the horizontal direction at 0.19 s during the fuselage penetrating the wave crest, and the horizontal load reaches 0.80. At this time, the vertical relative velocity between the aircraft and water surface is the largest. A big impact load peak appears and the vertical load is as high as 3.27 when the fuselage penetrates the wave.

The above contents confirm the hypothesis of this paper that ditching in wavy surface may have unexpected impact load peak due to the different position of water contact.

5. The Characteristics of Ditching in Different Wave Heights

As shown in Figure 7, that oscillation velocity of the water surface are different for different waveforms. According to equation (2), the oscillation velocity of the water surface is proportional to the wave height at the same phase.

In this section, the simulation results of ditching in wavy surface in five different wave heights are compared with the result in calm surface, and the corresponding peak values are extracted for lateral comparison under different wave heights.

Figure 8 Horizontal load comparison

Figure 8(a) shows the peak of the horizontal load in the impact stage, and the peak of the horizontal load in the wave surface is greater than that in the calm surface. The differences between them is small. As shown in Figure 8(b), with the increase of the wave height, the increase of the peak relative to the
calm surface is smaller. When the wave height/wavelength is 0.016, the peak of the horizontal load will be greater than 6.5% of the calm surface. This is because as the wave height increases, the peak of horizontal load in the contact stage increases, the horizontal velocity decreases, so the peak of horizontal load in the impact stage decreases.

Two vertical load peaks are in the wavy surface. The first one is in the contact stage and the second one is in the impact stage. Both of them are compared with the only one vertical load peak in the calm water surface. The differences among the first impact peaks in the wavy surface are obvious. It is because the landing velocity of the aircraft is small, so the influence of the water surface oscillation velocity is obvious in the vertical relative velocity between the aircraft and water surface. The vertical impact peak value increases obviously with the increase of the wave height. Figure 9(c)(d) shows that with the increase of the wave height, the first impact peak value increases, and the second impact peak value basically decreases. This is consistent with general cognition. It is known that there is at least one vertical impact peak value greater than that in calm surface for any wave height. When the wave height/wavelength is 0.048, the extreme impact load peak value will exceed 30% of that in calm surface.

6. Conclusion
In this paper, Ansys Fluent software combined with the GMM is used to simulate the ditching process of an aircraft in five different wave heights. The results are compared with that in calm surface. In order to study the extreme load during the wavy surface ditching, this paper chooses the π phase as the landing point. When the aircraft approaches the water surface with the recommended landing attitude, the landing point is the abdomen of the fuselage, which is different from the rear of the fuselage in the
calm surface. Therefore, there is an unexpected impact peak in the wavy surface in the contact stage. Through the parametric analysis, it is found that with the increase of wave height, the impact peak value in the contact stage increases gradually. When the wave height is large enough, the vertical impact peak value in this stage will far exceed the vertical load of the calm surface and become the extreme load in the whole ditching process. In the impact stage, the horizontal load peak value in the wavy surface is slightly larger than that in the calm surface. With the increase of wave height, the vertical impact peak value decreases gradually. However, during the whole ditching process, at least one of the two vertical impact peaks in the wavy surface is larger than that in the calm surface.

7. References
[1] NTSB. Revised 12-98, Aviation Coding Manual[S], NTSB: Washington DC, 1998.
[2] PATEL A A, GREENWOOD R P Jr. Transport water impact and ditching performance, Final Report DOT/ FAA/ AR-95/54 [R]. US Department of Transportation: WASHINGTON DC, 1996.
[3] THOMSON R G, CAIIFA C. Structural Response of Transport Airplanes In Crash Situations, DOT/FAA/CT83/42[R]. NASA: United States, 1983.
[4] VON KARMAN T. The impact of seaplane floats during landing, NACA TN 321[R]. NACA: Washington DC, 1929.
[5] WAGNER H. Phenomena associated with impacts and sliding on liquid surfaces[J]. Journal of Applied Mechanics, 1932, 12: 193-215.
[6] MCBRIDE E E, FISHER L J. Experimental investigation of the effect of rear-fuselage shape on ditching behavior, TN 2929[R]. Washington DC, NACA: 1953.
[7] XU G D, DUAN W Y, WU G X. Numerical simulation of water entry of a cone in free-fall motion[J]. Quarterly Journal of Mechanics and Applied Mathematics, 2011, 64: 265-285.
[8] HUA C, FANG C, CHENG J. Simulation of fluid-solid interaction on water ditching of an airplane by ALE method[J]. Journal of Hydrodynamics, 2011, 23(5):637-642.
[9] STRECKWALL H, LINDENAU O, BENSCH L. Aircraft ditching: a free surface / free motion problem[J]. Archives of Civil and Mechanical Engineering, 2007, 7(3):177-190.
[10] QU Q L, HU M X, GUO H, et al. Study of Ditching Characteristics of Transport Aircraft by Global Moving Mesh Method[J] Journal of Aircraft, Volume 52, Issue 5, 2015, Pages 1550-1558.