Numerical Simulation of Aircraft Ditching of a Generic Transport Aircraft: Implementation of an Aerodynamic Model

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Abstract

Aircraft certification requires the analysis of water emergency landing (ditching) with respect to passenger safety. In order to support the design and certification processes, models for numerical simulation of aircraft ditching are being developed. Following the work developed in the SMAES project (SMart Aircraft in Emergency Situations, 2011-2014), which consisted in the enhancing of simulation capabilities for aircraft ditching analysis, DLR is transferring the acquired knowledge to full-scale aircraft ditching. Due to the complexity involved in full-scale modeling, a pre-processing tool is currently under development for an automatic model generation of full-scale aircraft ditching models for the explicit solver Virtual Performance Solution (VPS). The overall goal of this work is to implement and validate an aerodynamic model in the numerical simulation to allow an improvement in the state of the art of full-scale aircraft ditching. The developed model physically calculates the loads with proper aerodynamic equations and strongly improves the predictability of loads occurring during a ditching simulation. For the implementation of the aerodynamic model in the numerical simulation, the creation of a new module in the pre-processing tool is proposed. The aerodynamic calculation of lift, drag and pitch moment, based on the evolution of the angle of attack and flight velocity, is accomplished with the implementation of an external user subroutine within the numerical simulation. The superiority of the developed aerodynamic model over the state of the art is demonstrated based on comparison of results of sensitivity and parameter studies.

Keywords: Fixed-wing aircraft ditching, numerical simulation, aerodynamic model, external user subroutine.

1. Introduction

With the number of overwater operations rising and also as many airports are close to water, the potential for a water emergency landing increases. Although impact on water of an aircraft (ditching) is a very rare event, it is an aspect that needs to be accounted for within aircraft certification. Aircraft manufacturers must show compliance to the specific airworthiness regulations associated with ditching. These specify that the aircraft must provide structural integrity to protect all occupants, provide appropriate means for evacuation (doors and emergency exits operative) and float enough time to allow for evacuation of all passengers and crew.

In order to guarantee conformity with ditching regulations, engineers typically perform experimental test campaigns with scaled aircraft models. These test campaigns are naturally very expensive and time consuming, which led the aircraft industry to search for new ways to certificate planned water impact. Therefore, the use of simulation tools capable of predicting the response of aeronautical components has increased over the years, aiming to support experimental tests for ditching certification. Moreover, the progress of computation capabilities along with the development of multidisciplinary tools such as Finite Element Method (FEM) and Smooth Particle Hydrodynamics (SPH) aims to gradually replace experimental model test by powerful numerical tools.

Several projects aim to improve the state of the art concerning numerical tools for ditching. From 2011 to 2014, the project SMAES (SMart Aircraft in Emergency Situations) was held with the overall objective to develop a set of simulation tools to permit cost effective and entry-into-service of aircraft able to protect its occupants during ditching. In the project, water impact was investigated using the coupled FE-SPH method: FE for the structure and SPH for water domain. The results were validated with data originating from guided ditching tests, in which representative plates were experimentally investigated under realistic ditching conditions and test campaigns with sub-scaled air-
craft models. Within this project, the hybrid FE-SPH explicit code VPS (formerly known as PAM-CRASH) from ESI-Group was extended by various features for improvement of water modeling and reproduction of Fluid-Structure Interaction (FSI) phenomena [1].

Following the achievements of the SMAES project, the DLR Institute of Structures of Design is transferring the acquired knowledge into full-scale aircraft ditching. Due to the complexity involved in full-scale modeling, a pre-processing tool is currently under development for an automatic model generation of full-scale aircraft ditching models for VPS. This pre-processing tool (AC-Ditch), developed for preliminary design stage, automatically generates the pre-processing of all the input cards necessary to the numerical simulation in VPS, and all what is left to the user is the post-processing of the results. Besides the automatic feature, two other features of AC-Ditch are important to highlight. First, the parametric feature which allows the conduction of parameter variations in the preliminary design phase, and second the modular layout of the code, which allows new functionalities be added or modified in the future, through inclusion of new modules.

AC-Ditch comprises four main modules: the Aircraft module, which is responsible for the aircraft model generation; the Water module responsible for the generation of the water pool; the Master module, which includes the global settings of the simulation and the contact definitions; and finally, the Start module responsible for the start of the simulation at the end of the pre-processing phase. The Aircraft module is further divided in two modules: Fuselage and Wing/Empennage. In the Fuselage module the generation of the FE model for the fuselage is performed by AC-Crash, an automatic design tool developed by the DLR Institute of Structures and Design, using the aircraft fuselage geometry contained in a CPACS file. The wing and empennage structures are modeled as representative beam elements in the Wing/Empennage module, where rigid and flexible options are provided. Also in this module, the aerodynamics are modeled by a simple lift model where at the beginning of the simulation the lift force compensates the aircraft weight, and then the lift is reduced linearly to zero by the end of the simulation time (see Figure 1).

This simple linear assumption of lift reveals some limitations and raises a number of unanswered questions. First, this model only considers the aerodynamic lift. Therefore, other aerodynamic loads, as drag and pitch moment are not considered. The lift force is approximated to be a linear function; nevertheless, no experimental results are available to substantiate this assumption, which may not correspond to the true evolution of this aerodynamic load. Finally, even if the linear prediction is assumed correct, it is not possible to predict a suitable slope for the lift function.

As consequence of the limitations of the current lift model and knowing that more complete aerodynamic models can be accomplished in a numerical simulation of aircraft ditching, the present research aims to implement a more complete aerodynamic model within AC-Ditch. The desired aerodynamic model should include lift, drag and pitch moment. These loads, contrary to the lift model that is prescribed, are physically calculated with proper aerodynamic equations based on the evolution of velocity and angle of attack of the aircraft model.

For the implementation of the aerodynamic model in the numerical simulation the creation of a new module in AC-Ditch is proposed. The inclusion of this new module cannot compromise the automatic and parametric features of the tool. The aerodynamic calculation of lift, drag and pitch moment, based on the evolution of the angle of attack and flight velocity, is accomplished with the implementation of an external user subroutine within the numerical simulation.

2. Aerodynamics

During flight an aircraft is subjected to aerodynamic loads in all six degrees of freedom. In the predictive ditching simulation tool, developed for preliminary design, only rectilinear flight with zero roll, sideslip, and yaw angles is considered, allowing to greatly simplify the aerodynamic modeling with a good level of accuracy to only three loads: lift, drag and pitch moment. In Figure 2 the aerodynamic loads applied on aircraft center of gravity are illustrated.
The aerodynamic lift, drag and pitch moment are given by the following relations:

\[ L = \frac{1}{2} \rho V^2 S C_L(\alpha, Ma, Re) \]  
\[ D = \frac{1}{2} \rho V^2 S C_D(\alpha, Ma, Re) \]  
\[ M = \frac{1}{2} \rho V^2 S C_M(\alpha, Ma, Re)l \]

where \( \rho \) is the density of air, \( V \) the flight velocity along the flight path, \( S \) the wing area and \( l \) the aircraft reference length. \( C_L \), \( C_D \) and \( C_M \) are, respectively, the lift, drag and pitch moment aerodynamic coefficients, which are dependent on Mach number \( Ma \), Reynolds number \( Re \) and angle of attack \( \alpha \).

All the physical complexity of the flow field around the aerodynamic body is implicitly buried in \( C_L \), \( C_D \) and \( C_M \). Therefore the appropriate aerodynamic coefficients must be established. One means for this purpose is presented in the next subsection.

\[ \rho \] 
\[ V \] 
\[ S \] 
\[ l \] 
\[ C_L(\alpha, Ma, Re) \] 
\[ C_D(\alpha, Ma, Re) \] 
\[ C_M(\alpha, Ma, Re) \] 
\[ \alpha \] 
\[ Ma \] 
\[ Re \] 
\[ \alpha, Ma, Re \] 
\[ 1 \] 
\[ 2 \]

2.1. Aerodynamic data

The aerodynamic coefficients are obtained with the LIFTING LINE tool. This physical-based tool uses a multi-lifting-line method, capable of calculating force and moment coefficients for almost arbitrary non-planar configurations of multiple thin wings. The obtained aerodynamic data is organized in an “Aero Performance Map” and it is included in the CPACS file containing all aircraft data. The “Aero Performance Map” includes the aerodynamic coefficients for loads in all the six degrees of freedom, and it is generated for a set of yaw angles, Mach and Reynolds numbers.

During ditching, the aircraft will naturally encounter low flight velocities, in a similar manner as in a typical landing condition, making therefore necessary the use of high-lift devices. The LIFTING LINE tool, only allows the calculation of aerodynamic coefficients for a clean configuration, which restrains their use in a ditching simulation. To circumvent this limitation, a correction of the lift coefficient data is made using real flight data of an Airbus A320-232, which is of similar size as the generic aircraft investigated in this research.

Finally, the influence of the ground on the aerodynamic loads acting on the aircraft throughout a ditching event was considered in the course of this work. For this effect, which is not covered by the LIFTING LINE tool, no experimental data or flight test results are available to quantify its influence on the aerodynamic loads for the aircraft considered. Hence, a literature review on this topic has been performed. The survey, based on experimental test campaigns and simple mathematical models using the Prandtl lifting-line concept, has shown that as consequence of the high angles of attack and high-lift devices employment, ground effect is assumed to have a minor influence on aerodynamics during ditching. For this reason, ground effect is not considered on the aerodynamic data used on the implemented aerodynamic model.

2.2. Aerodynamic module

The focus of this work is to implement an aerodynamic model in the pre-processing tool, AC-Ditch, developed for automated model generation. One of the main features of this tool, as described in section 1, is the modular layout of the code, which allows new modules to be implemented. Within this context, a new module was created to account a realistic aerodynamic model. This module, named Aerodynamics is qualified to model aerodynamics through a simple lift model (previously inside the Wing/Empegnage module) or through a more complex and complete aerodynamic model developed as part of this work. A description in how the Aerodynamics module generates the aerodynamic model for a rigid aircraft is here presented.

During a ditching simulation, the kinematics of the aircraft is changing. Consequently, even though the aerodynamic forces are not explicitly dependent on time, they are dependent on angle of attack and flight velocity, which change with time during the simulation. Therefore, despite simple aerodynamic equations are considered, see equations (1–3), due to the indirect dependency of aerodynamic loads on time, the way of modeling aerodynamics in VPS is not trivial.

The aerodynamic model comprises two major parts: specific VPS input cards, which allow the aerodynamic modeling in the simulation, and an external user subroutine that performs the aerodynamic calculation during the simulation run time. The Aerodynamics module is responsible for generating these two components fully automatic, whenever the aerodynamic model is requested by the user.

Concerning the input data, VPS uses input cards with fixed format. These contain the necessary data for the model, the simulation setup, as well as the definition of the desired outputs of the simulation.
A special input card is used to treat the dependency of aerodynamics on time: the user data definition. When the user data card is executed, the simulation expects an external user subroutine. The nodal kinematics transmitted by the user data card allow the subroutine to perform the aerodynamic calculations at each simulation cycle. The aerodynamic loads calculated in the external user subroutine are transmitted to the user data cards, which store the results in function cards, by modifying the ordinates of respective curves. The modified curve ordinates overwrite the original values, even for the very first cycle, allowing the aerodynamic loads to be updated at each cycle of the solution phase. This process makes it possible for the aerodynamic loads to be calculated during the simulation run time based on aircraft kinematics, as illustrated in Figure 3. The reader should note that each user data and function card pair only includes one aerodynamic load, and as Figure 3 portrays, each pair calls the user subroutine once per simulation cycle.

Figure 3: User data card and external user subroutine interaction.

The aerodynamic forces are applied on the aircraft center of gravity, making use of concentrated nodal loads cards. Each of these cards is dependent on a function card, where forces and moments are defined. Consequently, nodal loads cards invoke the function cards that are responsible for storing the aerodynamic loads calculated in the external user subroutine. The directions of the concentrated loads refer to a aircraft-fixed local frame of reference \( \{xyz\} \), defined with the local coordinate frame card of VPS. The Figure 4, illustrates the aircraft-fixed local frame of reference \( \{xyz\} \) and the global frame \( \{XYZ\} \).

2.3. External user subroutine

Until the current subsection, the external user subroutine is being treated as a black box whose function is to calculate aerodynamic loads. The subroutine is automatically generated by AC-Ditch and interacts with the simulation in the solution phase. Therefore, the Aerodynamics module writes the subroutine with all the inputs necessary for the aerodynamic calculation, i.e. aerodynamic coefficients, wing-fuselage relative incidence angle, density of air, wing area and reference length. Besides the inputs defined by the Aerodynamics module, the subroutine also receives the nodal kinematics from the simulation. This data comes from the user data cards and is listed below.

- Center of gravity velocity, \( \mathbf{v} = [v_X, v_Y, v_Z] \)
- \( N1 \) and \( N2 \) coordinates

As portrayed in equations (1–3), the aerodynamic loads are dependent on flight velocity and angle of attack. The velocity is computed as magnitude of the center of gravity (COG) velocity vector, \( \mathbf{V} = |\mathbf{v}| \) and the angle of attack must be calculated using the nodal kinematics. The angle of attack can be written as the difference between the pitch angle \( \theta \) and flight path angle \( \gamma \), plus the wing fuselage relative incidence angle \( \beta \), leading to

\[
\alpha = \theta - \gamma + \beta .
\]  \( (4) \)

The pitch angle \( \theta \) is defined as the angle between the longitudinal axis of the aircraft, in this case the \( x \)-axis, and the horizontal, i.e. the \( X \)-axis. Considering this definition and the illustration in Figure 5, it is possible to write

\[
\theta = \arctan \left( \frac{Z_{N1} - Z_{N2}}{X_{N1} - X_{N2}} \right) .
\]  \( (5) \)

The flight path angle \( \gamma \), is the angle between the horizontal and the velocity vector, which describes whether the aircraft is climbing or descending. Consequently, one can write

\[
\gamma = \arctan \left( \frac{v_Z}{v_X} \right) .
\]  \( (6) \)

The aerodynamic coefficients are given as a set of points in an array format, where each component of the array corresponds to an angle of attack. Therefore, after the angle of attack has been calculated...
using equation 4, the code selects the corresponding components of the aerodynamic arrays. If the exact angle of attack does not exist, the code interpolates between the two nearest points. This guarantees that the aerodynamic coefficients used in the calculation are given with a good level of precision. When the calculated angle of attack exceeds the maximum allowed value, the code writes a stall alert in the output file and prescribes \( \alpha = \alpha_{\text{max}} \) within the aerodynamics computation. Hence, this model approximates the stall by limiting the lift coefficient to \( C_{L,\text{max}} \), which is the \( C_L \) of \( \alpha = \alpha_{\text{max}} \).

Once the aerodynamic coefficients are selected based on the angle of attack, the aerodynamic loads are finally calculated using equations (1–3), where the absolute value of velocity is given by

\[
V = \sqrt{v_x^2 + v_y^2 + v_z^2}.
\]

Lift and drag forces act in direction normal and parallel to the flight path, respectively. However, defining a system of reference that follows the flight path is hardly possible, since the velocity vector is one of the problem variables. Thus, the aerodynamic loads are projected in the aircraft-fixed local frame of reference \( \{xyz\} \), see Figure 4. The projection angle is the difference between the pitch and the flight path angle. The projection yields

\[
L_x = -L \sin(\theta - \gamma),
\]

\[
L_z = L \cos(\theta - \gamma),
\]

\[
D_x = D \cos(\theta - \gamma),
\]

\[
D_z = D \sin(\theta - \gamma),
\]

\[
M_y = M.
\]

Due to the direction of the \( x \)-component of lift in the local frame of reference, equation 8 has a minus sign. As one can see in Figure 5, for a positive angle of attack the \( L_x \) component is contrary to the \( x \)-axis, whereas the opposite situation is verified for a negative angle.

Figure 5: Aerodynamic loads projected in the aircraft-fixed local frame of reference.

As the reader can verify in Figure 5, in total there are five loads to be applied to the model. This means that five sets of user data, function and concentrated loads cards are necessary in the aerodynamic model. Each user data card invokes the user subroutine once, which means that five user data cards are executed per simulation cycle. Everytime the subroutine is called the five loads are calculated, but only the respective one is given to the simulation and written in the external file.

3. Validation

In order to run trustworthy ditching numerical simulations with the implemented aerodynamic model, it is crucial to perform a model validation. Therefore, the numerical results obtained using the implemented aerodynamic model in VPS are compared with theoretical ones obtained from the solution of the equations of motion. For the solution of these equations a semi-analytical tool was developed during the course of this research.

An excellent agreement between the theoretical and numerical results has been obtained for all the flight conditions used in the validation process. For instance, in Figure 2 the pitch angle time histories are in excellent agreement for a typical ditching condition. Similar results were obtained for all the analyzed parameters in different flight conditions.

Figure 6: Validation - Pitch angle time histories.

4. Numerical investigations

Numerical investigations are performed in order to assess the influence of the aerodynamic model on the ditching behaviors of a generic transport aircraft model.

The aircraft model consists of a generic transport aircraft geometry with a capacity to hold approximately 150 passengers. The fuselage of the aircraft is generated by AC-Crash and converted to a rigid body by AC-Ditch. The fuselage length is approximately 36.5 m with a maximum height of 4.1 m. The aircraft rigid wing and tail are modeled as representative beam elements with a wingspan around 32 m, a sweep back angle of 25° and a vertical tail.
9.5 m high from the lowest fuselage point. No landing gear or engines are modeled. The aircraft total mass is assigned to the aircraft COG, where different mass load cases are offered by AC-Ditch.

For the water model, the investigations performed in [2] were taken as reference. The water model is constituted by a hybrid FE-SPH model as portrayed in Figure 7. Classic FE are placed in the area where less deformation is expected, whereas SPH particles fill the central section of the water basin where splash and larger deformations are expected. The total cross-section of the pool is constant with \( H = 5 \text{ m} \) and \( W = 10 \text{ m} \), and the SPH domain measures \( H = 1 \text{ m} \) and \( W = 5 \text{ m} \) (H-height, W-width). The pool length is computed as the sum of the aircraft length and the product of the initial horizontal velocity with the simulated time, i.e. \( l_T = \text{aircraft length} + v_X \cdot \text{time} \). The ratio between particle spacing and individual finite element length is 1:2, with 100 \( \text{mm} \) particle spacing and 200 \( \text{mm} \) for the FE. Finally, according to reference [2], the active box is the modeling option (offered within AC-Ditch) that showed the lowest computational time and therefore it is selected for the present investigations.

![Figure 7: Water model with adaptive active box.](image)

The active box consists of a virtual box where SPH particles are active. This box moves with the aircraft and deactivates particles over a certain transition region where no water impact is happening. This process is illustrated in Figure 7, where the dark blue portion corresponds to the active SPH particles, red the transition region and gray the deactivated particles. The initial length of the active box is \( l_A(t = 0) = 16 \text{ m} \), as only a small part of the aircraft structure is in contact with the water. Throughout the simulation the box grows linearly, and in the end of the simulation, when the aircraft fuselage is completely in contact with the water, the length of the box is \( l_A(t = t_{\text{final}}) = 40 \text{ m} \). Deviations from the presented water model are referred in the following sections, when justified.

Interaction between the fluid, constituted by SPH particles, and the aircraft structure is modeled with a standard penalty contact, see [3].

All the simulations are performed with zero roll, sideslip and yaw angles, accordingly the velocity component in Y-direction \( (v_Y) \) is set to zero. The remaining initial conditions, namely pitch angle \( \theta \), horizontal and descent velocities \( v_X \) and \( v_Z \) are selected depending on the case studied. During the approach phase it is required that the aircraft holds a trim condition, i.e. \( L = W \). The old lift model, as consequence of its definition imposes a trim condition in the beginning of the simulation regardless of the initial conditions prescribed by the user. On the other hand, the aerodynamic model, which is based on aerodynamic equations (1–3), only holds the trim condition in the beginning of the simulation, if a suitable set of initial conditions is prescribed to allow the fulfillment of \( L = W \).

4.1. Sensitivity analysis

The influence of the aerodynamic model on aircraft kinematics during ditching is investigated through a sensitivity analysis. For this study, the aircraft model presents a Maximum Takeoff Weight (MTOW) of \( m = 72547 \text{ kg} \) and a COG position on the \( x \)-direction of \( x_{\text{COG}} = 16.5 \text{ m} \). The initial conditions are set to \( v_X = 70 \text{ m/s} \) and \( v_Z = -1.5 \text{ m/s} \) and \( \theta = 8^\circ \), and allow a trim condition in the beginning of the simulation when the aerodynamic model is used. The lift model assumes a linear evolution, where the slope is predefined by the user. For the current investigation the slope was chosen so that lift equals zero in the end of the simulation at \( t = 1000 \text{ ms} \).

**Comparison of conventional lift model against aerodynamic model**

To investigate the differences between the two modeling options, a comparison of results is here presented. The simulations last 1000 ms and the aircraft motion comprehends different phases. First the aircraft impacts the water domain and then bounces off to impact again several meters ahead of the first impact. At the first impact only the rear part of the aircraft fuselage contacts the water particles, while at the second impact the aircraft bottom contacts the water and the aircraft finally lands.

The lift force evolution with time for the regarded models are compared in Figure 8. The lift force computed by the aerodynamic model is illustrated in a black solid line, whereas the red one illustrates the linear evolution of the lift model where the curve equals zero at the end of the simulation. As can be seen, at the initial time of the simulation, the aircraft is trimmed using both models. The results show that the lift calculated by the aerodynamic model is higher than the one prescribed by the lift model during all the simulation time. The difference between the curves increases with time and, at the end the simulation, the lift force computed by the aerodynamic model still equals 400 kN, while the one computed by the lift model equals zero.

The lift curve obtained by the aerodynamic
model shows a quasi-linear behavior. As such, a linear curve in solid blue was added to the results in order to compare the lift force coming from the aerodynamic model to a prescribed linear lift force. The slope of this blue line was chosen so that lift equals zero at \( t = 2000 \text{ ms} \). Figure 8 demonstrates how the lift model is subjected to engineering judgment, since according to the slope defined by the user: the lift model will allow a more or less realistic aerodynamic modeling.

![Figure 8: Comparison of lift force time histories.](image)

The acceleration time histories of the center of gravity of the aircraft model are portrayed in Figure 9. The acceleration curves are filtered with a CFC60 filter [4]. As result of the trim condition in the beginning of the simulation, the acceleration in both models starts in zero. Accordingly, the acceleration deviation results from the impact on water and the change provoked by it in the aircraft kinematics.

The first peak in the acceleration curves is due to the first impact, between 10 \( \text{ms} \) and 200 \( \text{ms} \). For this impact the models are in good agreement. After this, when the aircraft bounces, the curves assume a linear behavior, where the acceleration resulting from the lift model decreases more than the one coming from the aerodynamic model. This is a consequence of the higher lift in the aerodynamic model than in the lift model, as shown in Figure 8. At the second impact the acceleration curve coming from the lift model increases almost until 3.5 \( g \), considerably more than the almost 2 \( g \) coming from the aerodynamic model. Moreover, as the simulation using the aerodynamic model has more lift the aircraft flies longer and, as consequence, the second impact is delayed about 100 \( \text{ms} \) for the aerodynamic model. The acceleration histories obtained from the two models show a clear difference in the results.

![Figure 9: Comparison of acceleration time histories.](image)

**Influence of aerodynamic drag and pitch moment**

In order to investigate the influence of the aerodynamic drag on the aircraft kinematics two simulations are compared: a reference case using the aerodynamic model, and a simulation using the aerodynamic model with the drag force set to zero, i.e. where only lift and pitch moment are modeled. As a full agreement was verified for the majority of the parameters investigated, it is possible to affirm that the aerodynamic drag has a minor influence on the aircraft behavior during a ditching simulation.

Analogously, the influence of pitch moment is evaluated through a comparison of two simulations: a reference case using the aerodynamic model, and a simulation using the aerodynamic model with the pitch moment set to zero, i.e. where only lift and drag are modeled. The obtained results have shown clear differences between the two simulations for the pitch angle and acceleration time histories. Therefore, an influence of the pitch moment on the aircraft kinematics during a ditching simulation can be claimed. This is an important result since it highlights one of the limitations of the lift model, which does not include pitch moment.

**Comparison of lift model against aerodynamic model with presence of suction**

Suction effects can play an important role on aircraft kinematics during ditching, see [5]. In fact, due to the high horizontal velocity the pressure drop in the rear part of the lower fuselage originates a suction force that induces a nose up attitude and results in the attachment of the aircraft to the water during the ditching event. In the previous investigations, suction effects were not modeled which resulted in a nose down attitude and a ricochet after the first water impact. To model suction effects in the simulation, the separation stress feature available in VPS is used, see [2]. Since suction effects are not correctly portrayed for small SPH particle spacing, a few changes were
performed in the water model. The SPH particle spacing was increased from 100 mm to 200 mm, in the water model used in the numerical investigations, when suction effects are modeled. The ratio between particle spacing and individual finite element length was kept at 1:2, with 200 mm SPH particle spacing and 400 mm for the FE.

The lift force time histories are presented in Figure 10. The results show, in an identical manner as in Figure 8, that the lift force calculated by the aerodynamic model is higher than the one prescribed by the lift model throughout all the computational time. The larger difference is verified in the beginning of the simulation due to the larger pitch angle, caused by suction effects in the simulation. The increase in the pitch angle led to an increase in the lift force calculated by the aerodynamic model, while the lift model decreases the lift regardless of the evolution of the pitch angle. Contrary to observations in the lift comparison without suction effects in Figure 8, the quasi-linear behavior is not found in the results of the aerodynamic model in Figure 10. Moreover, it is possible to verify that the solid blue line, representing the linear lift model ending in 2000 ms, is now quite far from matching the results of the aerodynamic model. This exposes the strength of the aerodynamic model, which is able to physically calculate the lift force for any motion of the model in the simulation, contrarily to the lift model that it is not versatile and strongly depends on its setup (engineering judgment).

4.2. Parametric analysis

Due to the parametric and automatic features of AC-Ditch, it is possible to conduct parameter variations in the preliminary design phase without the generation of numerous different, though similar, models. Based on this premise, a parametric study is performed for different COG positions and impact conditions. In all the following simulations suction effects are considered due to their important role during ditching. Consequently, the simulation model previously presented, together with the modifications introduced on the water model in the sensitivity analysis with suction model, is adopted. The modeling of aerodynamic loads in the simulation is performed using the aerodynamic model.

**COG position**

To assess the COG influence, two simulations are compared: a reference case with the same aircraft mass, COG position and initial conditions as in the sensitivity analysis and another simulation with the same aircraft mass and initial conditions, but different COG position. The reference case presents a COG position of \( x_{\text{COG}} = 16.5 \) m and is compared with a model with \( x_{\text{COG}} = 17.14 \) m.

The pitch angle time histories are shown in Figure 11. The results portray that the aircraft with the forward COG presents a higher decrease of the pitch angle throughout the simulation. The overpressure region creates forces that cause a nose down pitch moment at the aircraft COG, while the suction forces cause a nose up pitch moment. Depending on the position of the COG, the lever arm of these forces can be larger or smaller. As can be seen in Figure 12 this lever arm is bigger for the aircraft with the forward COG. Therefore, the pitch angle evolution of the simulation with COG position at 16.5 m results in a lower pitch angle. The difference between the pitch angle curves increase throughout the time, with the biggest difference at the end of the simulation.
investigation shows that the COG position has a clear effect on the aircraft kinematics during ditching. As previously discussed, the difference in the results arise from the different lever arms for suction and overpressure forces related to the COG position.

![Figure 12: Typical pressure distribution on rear part of the lower fuselage during impact with two COG positions. Overpressure represented in black and suction in red.](image)

Impact conditions

The investigation of different impact conditions is extremely important due to the influence that these can have in the ditching event; for instance, it is expected that water impact with higher velocities cause larger structural damages.

Therefore, simulations with different initial velocities are performed in this investigation to evaluate the kinematics of the aircraft. The same aircraft model is used for the three compared simulations. The impact conditions were investigated varying the initial horizontal velocity 5 m/s higher and lower than the reference condition of 70 m/s. The initial vertical velocity is kept constant at −1.5 m/s as suggested by ditching regulations, and the velocity component in the Y-direction is kept at zero, as only rectilinear flight is considered in the model. In order to fulfill the trim condition at the beginning of the simulation, any change in the initial velocity implies a change in the initial pitch angle or in the weight configuration. As the weight is kept constant for the three cases (m = 72547 kg), higher horizontal velocities imply lower pitch angles, and vice versa. Therefore, the impact condition 1 presents the lower pitch angle of 5.25°, whereas the impact condition 2 yields the higher one with 11°.

The pitch angle time histories are plotted in Figure 13 as the difference between the pitch angle θ and its initial value θ₀. Since all the three simulations present different initial pitch angles, this normalization was necessary to make a proper comparison of the obtained results. The highest (θ − θ₀) difference is obtained for the impact condition 1 with the lowest initial pitch angle (5.25°), whereas the impact condition 2 with the highest initial pitch angle (11°) present the lowest change of pitch angle.

![Figure 13: Impact conditions investigation: comparison of pitch angle time histories.](image)

Depending on the pitch angle upon impact, the wetted structure can be larger or smaller. For lower pitch angles the structure in contact with the water particles is bigger, which causes more particles to remain attach to the fuselage structure (suction model, see [5]). As consequence, there is a higher nose up pitch moment, leading to a larger change of the pitch angle. Moreover, the pressure gradient along the wetted fuselage is strongly affected by the horizontal velocity component of the aircraft. Therefore, suction effect has a greater influence on the aircraft kinematics for impact conditions with higher velocities and lower pitch angles as observer in reality (see [6] and [7]).

The presented investigation permits to infer the influence of different impact conditions during ditching. In particularly, it could be noticed that simulations with higher initial velocities are more affected by the suction forces in the rear part of the lower fuselage.

5. Conclusions

In the present work an aerodynamic model was developed, which computes aerodynamic forces and moments acting during ditching as a function of flight velocity and angle of attack during the simulation. The developed model allows for an increase of the predictability of loads occurring during ditching. The main achievements of this research are here presented, followed by a summary of the major findings.

The Aerodynamics module has shown to be effective in generating the specific VPS cards and the external user subroutine required for the aerodynamic modeling, without compromising the automatic and parametric features of the tool. Moreover, the module proved to be well prepared for handling different aerodynamic data provided in the CPACS data file. This important feature allows a continuous improvement of the aerodynamic model,
since more accurate data could be obtained within a multidisciplinary environment and passed to the aerodynamic model using the developed module.

An excellent agreement between the semi-analytical solution of the equations of motion and numerical results has been demonstrated for all the flight conditions used in the validation process. Therefore, it is possible to conclude that the aerodynamic model is correctly implemented and that a correct computation of aerodynamic forces and moments acting during ditching, based on flight velocity and angle of attack, is achieved. Finally, numerical investigations were conducted in a set of sensitivity and parametric studies, from which some major findings can be highlighted.

In the sensitivity analysis the conventional lift model was compared with the aerodynamic model. Although a quasi-linear behavior was obtained for the lift curve computed by the aerodynamic model, considerable differences in the magnitude of the lift force were verified between the lift curves obtained with the two models. Moreover, the lift force time histories have clearly shown how the lift model is subjected to engineering judgment. For the accelerations it was verified that at the second impact, the acceleration value obtained with the lift model is the double of the one obtained by the aerodynamic model. Moreover, studies concerning the influence of drag and pitch moment revealed that the former has a minor influence on the aircraft behavior during ditching, whereas for the second an important influence on the aircraft kinematics during a ditching simulation can be claimed. This is an important result since it highlights one of the limitations of the lift model. Finally, the sensitivity study with presence of suction effects exposed the strength of the aerodynamic model, which is able to physically calculate the aerodynamic loads for whichever motion of the model in the simulation, contrarily to the lift model that is not versatile and strongly depends on engineering judgment. Despite no experimental results exist to perform a validation, the results obtained with the aerodynamic model showed a significant improvement in the predictability of loads during ditching, since the aerodynamic loads are physically calculated based on the aircraft kinematics.

The parametric analysis has shown that different parameters can significantly change the aircraft behavior during ditching. From the analyzed parameters, the impact conditions are the ones that claim the biggest influence on the ditching behavior. Nevertheless, the COG position have shown a considerable influence on the aircraft kinematics, in particularly on the pitch angle.

Other important findings relate with the computational time. Studies regarding this topic have shown that, despite the frequent interaction between the external user subroutine and the solver, the computational cost of the aerodynamic model is insignificant. Moreover, it was also verified that the aerodynamic model does not increase the execution time of the model generation tool, i.e. AC-Ditch takes the same time to generate a model with the lift or the aerodynamic model.

References