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APPLICATION OF THE MLM TO EVALUATE THE HYDRODYNAMIC LOADS ENDURED DURING THE EVENT OF AIRCRAFT DITCHING

L. MARTIN[1], V. JACQUES[2] AND B. PAUL[3]

[1]Dassault-Aviation
78 Quai Marcel Dassault, 92210 Saint-Cloud, France
ludovic.martin@dassault-aviation.com https://www.dassault-aviation.com

[2] Dassault-Aviation
78 Quai Marcel Dassault, 92210 Saint-Cloud, France
vincent.jacques@dassault-aviation.com https://www.dassault-aviation.com

[3] Dassault-Aviation
78 Quai Marcel Dassault, 92210 Saint-Cloud, France
bertrand.paul@dassault-aviation.com https://www.dassault-aviation.com

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Abstract. The present work proposes a methodology for the evaluation of the hydrodynamic loads endured in the event of aircraft ditching. The determination of the hydrodynamic loads on the full aircraft is necessary to substantiate the aircraft dynamics and structural integrity during ditching. In this context, the semi-analytical method called MLM (Modified Logvinovich Model) presents the advantage of estimating general hydrodynamic loads at reduced computational costs. After depicting the proposed methodology, we compare experimental water impact results to simulation results obtained with our industrial calculation tool ELFINI®. Finally, the extension to full aircraft studies is discussed.

1 INTRODUCTION

Ditching is an extremely rare event for an aircraft when it is forced to make a controlled emergency landing on water, as a consequence of fuel starvation for example. During the impact phase, the aircraft structure is subjected to severe hydrodynamic loads. In particular, the certifying authorities require that aircraft manufacturers take appropriate design measures to minimize immediate injury to persons on board and to make it possible for them to escape before the shipwreck. These requirements as well as the necessity to improve understanding of the physical effects involved during an aircraft ditching have motivated the development of methodologies for the estimation of hydrodynamic impact loads. In particular, we investigate the influence of the hydrodynamic loads on the aircraft dynamics and structural response.

In the literature, several classes of methods devoted to the evaluation of hydrodynamic loads have been experienced, such as numerical methods involving a mesh for the fluid (Coupled Euler Lagrange) or meshless methods (Smoothed Particle Hydrodynamics [1]). Nevertheless, these numerical methods involve stability issues and significant computation costs. An alternative to numerical methods consists in using analytical methods, based on the potential flow formalism. In the present work, a possible variant based on the MLM is presented. The formalism of the MLM method has been introduced by Korobkin [2].

The MLM deals with the water impact of a 2D rigid section. The problem of the water impact of a 3D body is then replaced by a series of 2D water impacts (2D+t strategy). The impacting rigid sections are replaced by plates of similar extension so that the equations are based on the Wagner approximation [3]. The real shape of the section is finally introduced via a Taylor expansion. The impacting body is supposed to have a symmetry plan of equation $y = 0$ in the ground axis and the lateral and longitudinal curvatures should remain positive.

First, we detail the MLM approach for 2D impacting sections and present its extension to 3D impacting bodies. Then, some results obtained with our industrial code are presented. The simulation of elementary rigid bodies with imposed movement is first performed and compared to experimental results. Then, we study the free motion water impact of a NACA shape model and discuss the extension of our methodology to full aircraft studies.

2 SEMI-ANALYTICAL APPROACH FOR A 2D SECTION

We consider a symmetric convex 2D section of equation $x = x_{2D} = constant$ in the ground axis. The coordinates of a point of this section are noted (y_{2D}, z_{2D}).

2.1 Evaluation of the free surface elevation

When using the MLM based on the “Wagner” theory [2], the first step is the evaluation of the free surface elevation c (see Figure 1). This elevation directly controls the pressure of water on the falling object, and consequently the hydrodynamic force. It can be demonstrated [2] that c is the solution of the following equation:

$$\int_0^{\pi/2} z_{2D}(c\sin(\gamma), t)\,d\gamma = 0 \tag{1}$$

With a simple variable change, this equation can be written as follow:

$$f(c) = \int_0^{c} \frac{z_{2D}(y_{2D}, t)}{\sqrt{c^2 - y_{2D}^2}}\,dy_{2D} = 0 \tag{2}$$

where the function f is introduced. The parameter c is determined iteratively by a Newton algorithm.

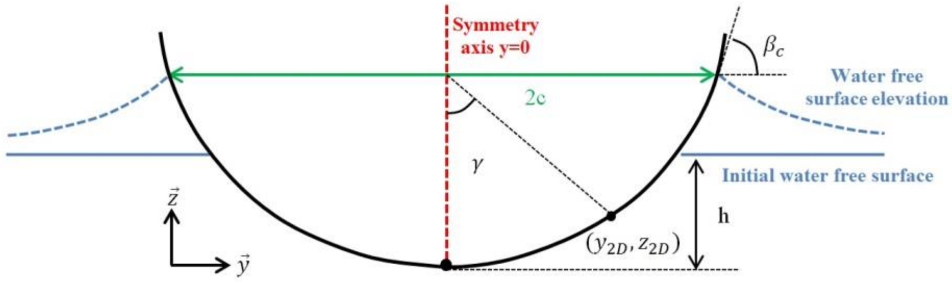


Figure 1: Representation of the impacting 2D section

The deadrise angle β_c corresponds to the angle between the horizontal direction and the tangent to the impacting body at the water elevation point.

2.2 Body extrapolation

During the water impact of a 2D section, the wetted body is delimited by the parameter c. Two reasons can explain the splitting of the fluid from the body depending on the value of c:

- The deadrise angle β_c is high (greater than a user defined deadrise angle β_L). This separation case has both numerical (restriction of the application domain for the MLM method) and physical (water jet for sharp 2D section) origins.
- The 2D section is totally submerged.

At the separation point, the body is automatically extended by a line of constant deadrise angle β_L. The value of β_L corresponds to the inclination of the water jet observed for sharp impacting sections. We note y_{max} the y-location of the point which corresponds to the beginning of this extrapolation. The search for the parameter c is then carried out on this extrapolated 2D section (figure 2).

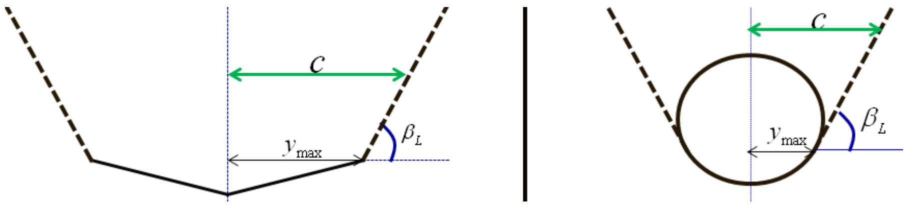


Figure 2: Representation of the body extrapolation (fluid separation) symbolized by black dotted lines

2.3 Analytical expression of the hydrodynamic force

The fluid pressure P from Bernoulli non-linear formulation is given by:

$$\frac{P}{-\rho} = \dot{\phi} - \frac{\dot{z}_{2D} z_{2D,y}}{1 + z_{2D,y}^2} \phi_y + \frac{1}{2} * \frac{\phi_y^2 - \dot{z}_{2D}^2}{1 + z_{2D,y}^2} \tag{3}$$

with ϕ the velocity potential, ϕ_y its partial derivative with respect to y and ρ the fluid density. The main idea of the MLM approach is to express this velocity potential as a first order Taylor expansion, based on the Wagner potential φ:

$$\phi = \varphi + \dot{z}_{2D} z_{2D} \tag{4}$$

The advantage of the previous expression is to benefit from the analytical expression of the Wagner potential φ which represents the 0 order term in the Taylor expansion:

$$\varphi = -2 \frac{\sqrt{c^2 - y_{2D}^2}}{\pi} \int_0^c \frac{\theta(\tau)}{(\tau - y_{2D})\sqrt{c^2 - \tau^2}} d\tau \tag{5}$$

with:

$$\theta(y_{2D}) = -\int_0^{y_{2D}} \dot{z}_{2D}(\tau, t) d\tau \tag{6}$$

Moreover, the term of order 1 in the Taylor expansion (i.e. $\dot{z}_{2D} z_{2D}$) takes into account the shape of the impacting section, which is not the case with the Wagner potential.

The total hydrodynamic pressure on the impacting section can be divided into three parts:

$$P = P_v + P_a + P_p \tag{7}$$

The terms P_v and P_a respectively depend on the vertical velocity $\dot{z}_{2D}$ and acceleration $\ddot{z}_{2D}$ of the impacting body and P_p accounts for the "Archimede pressure". The detailed analytic formulations of these three parts are depicted in [2],[4].

The vertical hydrodynamic force $F_{z,hydro}^{(2D)}$ acting on the 2D impacting section is finally obtained by a numerical integration of the pressure terms along the wetted area.

$$F_{z,hydro}^{(2D)} = F_{z,hydro,v}^{(2D)} + F_{z,hydro,a}^{(2D)} + F_{z,hydro,p}^{(2D)} \tag{8}$$

Specific restrictions must be applied for the integration of P_a and P_v depending on the phase of the water impact [4]. The "Archimede" force is computed by integrating the "Archimede" pressure P_p along the wetted area (without taking into account the extrapolation part).

3 2D+T APPROACH FOR A 3D WATER IMPACTING BODY

The water impact of a 3D rigid body is now considered. The 3D rigid body is supposed to have a symmetry plan of equation $y = 0$ in the ground axis so that all movements belong to the plane(Oxz). The lateral and longitudinal curvatures should remain positive. The coordinates of the center of gravity (COG) of the rigid body in the ground axis are denoted (X, Z) and the attitude of the impacting body is noted θ.

3.1 Strategy for the evaluation of the horizontal hydrodynamic force

At each time step, we determine the interval $[x_{max,w}, x_{min,w}]$ that corresponds to the longitudinal length of the wetted part of the body. Considering the symmetry and the curvature of the body, this interval is determined in the plane $y = 0$. We then divide the wetted part of the body into a series of lateral sections with thickness DX (see Figure 3). Each section may be considered as a plane of equation $x = x_{2D} = cste$ (median plane of the lateral section) in the ground axis, for which we evaluate the vertical hydrodynamic load $F_{z,hydro}^{(2D)}$ according to the methodology detailed in the previous paragraphs. The section thickness DX has to be well adapted to the length of the impacting body in order to properly approximate the total hydrodynamic load at minimum computational cost.

The impact of the 3D rigid body is therefore divided into a series of 2D sub-problems via the intersection with 2D ground sections.

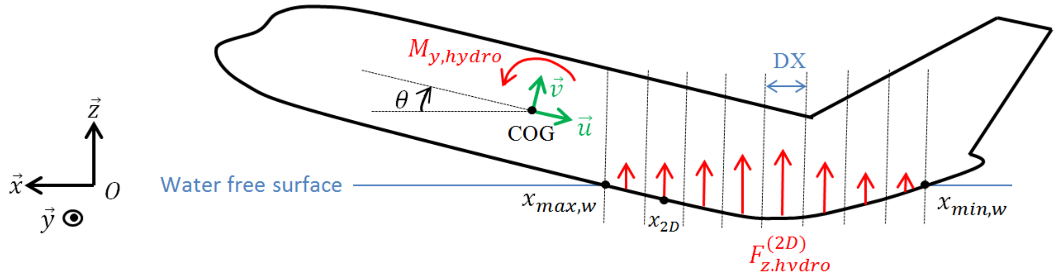


Figure 3: 2D+t strategy for the 3D impacting body

The global vertical component of the hydrodynamic force $F_{z,hydro}$ and associated moment around the y ground axis $M_{y,hydro}$, applied at the center of gravity of the 3D body, are deduced by the following summations:

$$F_{z,hydro} = \sum_{sections} F_{z,hydro}^{(2D)} * DX \quad \text{and} \quad M_{y,hydro} = \sum_{sections} (x_{2D} - X) * F_{z,hydro}^{(2D)} * DX \quad (9)\ \&\ (10)$$

3.2 Vertical velocity and acceleration on a 2D ground section

For each 2D sub-problem, the numerical integration of the hydrodynamic loads requires the discretization of the intersected section. To this aim, we allocate regularly spaced points with coordinates (y_{2D}, z_{2D}) in the plane $x = x_{2D}$ (figure 5). A point of this 2D section only has a vertical motion. The vertical velocity $\dot{z}_{2D}$ and acceleration $\ddot{z}_{2D}$ differ from the vertical velocity and acceleration of a body point and notably depend on the local shape of the body along the longitudinal direction (gradient $z_x = \frac{\partial z_1}{\partial x_1}$ and curvature $z_{xx} = \frac{\partial^2 z_1}{\partial {x_1}^2}$, with (x_1, z_1) the coordinates of the point in the body axis $(\vec{u}, \vec{v})$ depicted in figure 4).

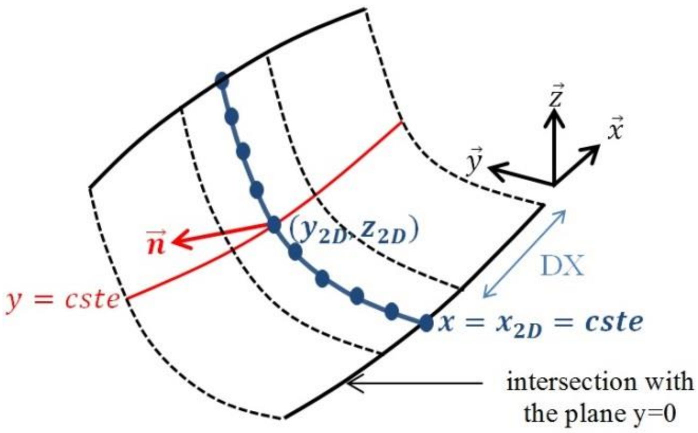


Figure 4: Discretization of the intersected section

The gradient $z_x = \frac{\partial z_1}{\partial x_1}$ is directly obtained from the normal unit vector $\vec{n}$ to the body surface at the considered point: $z_x = (\vec{n}.\vec{u})/(\vec{n}.\vec{v})$. The evaluation of curvature z_{xx} requires more attention. We build discretized body lines $y = cste$ parallel to the x-axis around the considered point. A second-order polynomial approximation is applied on the body line and the curvature z_{xx} is finally equal to the double of the second-order coefficient of this polynom.

4 APPLICATIONS

In order to validate the proposed method implemented in our industrial tool, a set of test-cases with a growing complexity has been performed so that a step-by-step evaluation of the method is led. Hereafter, we present two cases with imposed movements: a 2D elementary vertical impact and a 3D high speed water impact. Then, the free motion water impact of a NACA shape model is discussed and the extension to a full aircraft study is attempted.

4.1 Entry phase for a circular section

The vertical water impact of a 2D circular section is here considered. The radius R of this circular section is 1m. The vertical velocity is constant $\dot{Z} - 1.5m/s$. The only active force is the hydrodynamic velocity force (the "Archimede" force is not taken into account). We focus on the evolution of the vertical non-dimensional force $\bar{F}_{z,hydro}$ towards the non-dimensional time $\bar{t}$ (figure 5). The reference $\bar{t} = 0$ corresponds to the beginning of the impact.

$$\bar{F}_{z,hydro} = \frac{F_{z,hydro}^{(2D)}}{\rho \dot{Z}^2 R} \quad \text{and} \quad \bar{t} = \frac{|\dot{Z}|t}{R} \qquad (11)\ \&\ (12)$$

We compare the simulation results with experimental results from Armand and Cointe [5]. The MLM method seems to be well-adapted to approximate the initial peak of hydrodynamic and hydrodynamic force evolution for low penetration depth. .

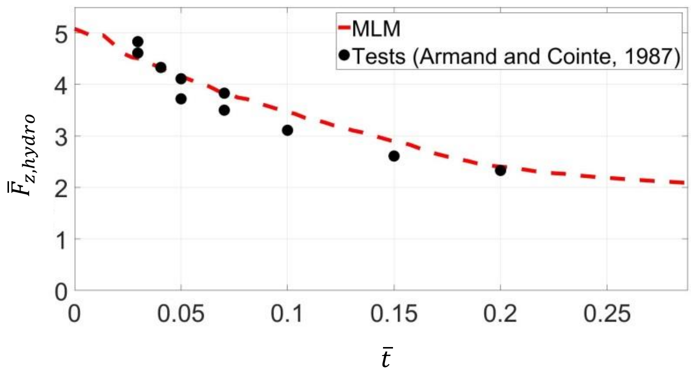


Figure 5: Evolution of non-dimensional force with respect to non-dimensional time for the 2D circular section

4.2 High speed water impacts

Guided ditching tests were led by INSEAN-CNR, consisting in the water impact of a rigid aluminum plate ($1m$ X $0.5m$) fixed to a trolley moving along a guide (figure 6). A detailed description of the facility and of the experimental setup is provided in [6]. We focus on two configurations performed by the INSEAN-CNR: the first one involving an infinite radius of lateral curvature R and the second one involving a lateral curvature representative of an aircraft fuselage ($R = 2m$).

	V_x (m/s)	V_z (m/s)	θ	$R\ (m)$
Config n° 1	40	-1.5	6°	infinite
Config n° 2	40	-1.5	6°	2

Table 1: Parameters for the 2 guided ditching tests

Figure 6: Visualization of the ditching facility of INSEAN-CNR [5]

The test results as well as the simulation results for both configurations are depicted in figure 7. The experimental results for the flat plate were thoroughly analysed in [7]. For both cases, the MLM is able to reproduce the global behaviour for the vertical hydrodynamic force, which can be decomposed into 3 stages. The first stage is the beginning of the impact (up to 0.02s). The hydrodynamic force quickly grows, with a constant slope. The second stage deals with the water impact up to the complete submergence of the plate. The hydrodynamic force grows with a constant slope inferior to the slope of the first stage. The third stage corresponds to the complete submergence of the plate (the hydrodynamic force quickly decreases).

These two comparisons demonstrate the ability of our MLM method to evaluate the hydrodynamic loads for water impacts with a high horizontal velocity (ditching configurations) in the case of a plane impacting body and in the case of an impacting body curved in the lateral direction.

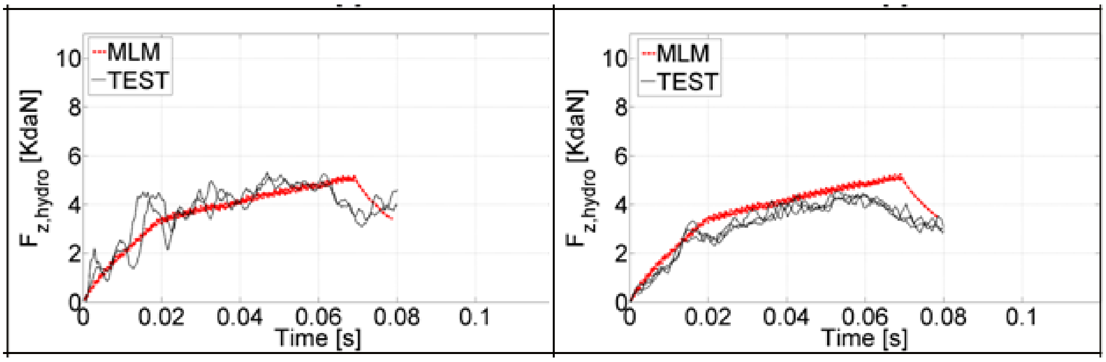


Figure 7: Comparison between MLM and experimental results for config n° 1 (left) and config n° 2 (right)

4.3 Free motion water impact of a NACA model

The free motion water impact of a NACA shape model is now considered and compared with experimental data [8]. This test-case is particularly suited to evaluate the influence of the longitudinal curvature of the impacting body.

The model shape is initially just over the free surface, with attitude $\theta = 10°$ and with the following velocity: $\dot{X} = 12.2m/s$ and $\dot{Z} = -0.7m/s$. The model mass is $m = 5.67kg$ and its inertia around the y ground axis is $I_y = 0.29kg.m^2$.

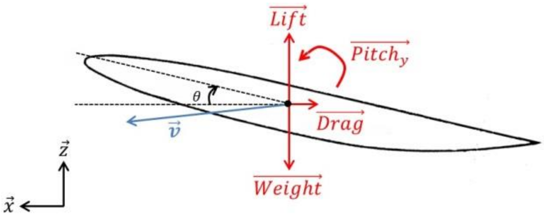
The active forces applied on the NACA model during a simulation are: the weight, the vertical hydrodynamic force (acceleration, velocity and "Archimede' parts), the horizontal hydrodynamic forces and aerodynamic forces.

For the horizontal hydrodynamic force $F_{x,hydro}$, we consider a friction drag proportional to the length of the wetted area $(x_{max,w} - x_{min,w})$:

$$F_{x,hydro} = -\frac{\rho * k_{drag}\dot{X}|\dot{X}|}{\cos(\theta)} * (x_{max,w} - x_{min,w}) \tag{13}$$

The coefficient $k_{friction}$ is fixed such that the time evolution of the horizontal velocity is similar to the experiment.

The aerodynamic forces (drag, lift and pitching moments) depend on the speed v and attitude θ of the impacting body. They are determined with the aerodynamic system [8].



$Lift = \frac{1}{2}\rho S_{ref} C_z v^2$ with C_z =0.092*θ+0.852

$Drag = \frac{1}{2}\rho S_{ref} C_x v^2$ with $C_x = 0.0007 * \theta^2$ +0.0015*θ+0.2157

$Pitch_y = \frac{1}{2}\rho L_{ref} S_{ref} C_m v^2$ with $C_m = -0.0197$*θ-0.1693

S_{ref} =0.3345m^2 L_{ref} =1.6764m

Figure 8. NACA J-shape model (left), and associated aerodynamic system (right) [8]

The comparison between experimental and simulation results is depicted in figure 9. The decrease in the horizontal velocity is accurately captured as the coefficient $k_{friction}$ is chosen to match the experiments. However, the simulation leads to an excessive pitching of the aircraft. The maximum attitude θ reaches 42° instead of 32° for the experiments and the maximum elevation of the center of gravity is twice the value observed experimentally. This behaviour is due to significant negative vertical hydrodynamic loads during the first stage of the impact, overestimated with our MLM approach.

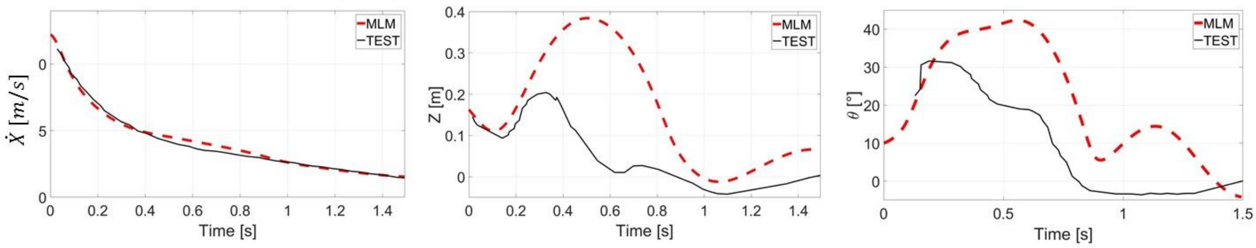


Figure 9. Comparison between MLM and experimental results for NACA model J

In this case, that involves a high horizontal impact speed as well as a significant longitudinal curvature of the impacting area, the MLM method brings significant negative hydrodynamic pressure fields. These negative hydrodynamic pressure values may become non physical as they reach the cavitation pressure threshold.

To address this issue, we propose to account for the cavitation phenomenon in our MLM approach by limiting the hydrodynamic pressure value to the cavitation pressure P_{cav}:

$$F_{z,hydro}^{(2D)} = \int_{-c}^{c} \max(P_v + P_a + P_p, P_{cav}) dy_{2D} \tag{14}$$

The cavitation pressure P_{cav} is set to $-10^5 Pa$. The simulation results obtained after this modification are depicted in figure 10.

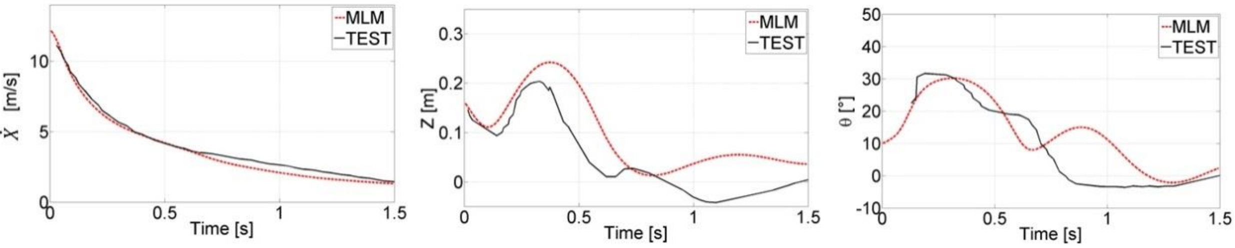


Figure 10. Comparison between MLM (with cavitation treatment) and experimental results for NACA model J

The treatment we applied to negative pressure values allows to recover the maximum pitching angle observed in the experiments (around 32°). The general behavior of the impacting body is fairly captured by our MLM simulation tool. This study illustrates that the integration of the pressure field may no longer be performed without accounting for cavitation and ventilation phenomena when dealing with high impact speeds.

In particular, these phenomena represent a major issue for the extension to full aircraft studies, involving very high water impact speeds (around 50m/s) and double curvature of the lower rear fuselage shape. In the context of the project SARAH (Increased SAfety & Robust Certification for ditching of Aircrafts & Helicopters), a series of experimental tests is being performed to develop a better understanding of these complex phenomena and improve their numerical treatment. The test matrix notably includes controlled water impacts of plates with double curvature, representative of a lower rear fuselage structure. It also includes controlled water impacts of fuselages with dynamic pitch in order to assess the effects of the variation of the attitude on the resulting hydrodynamic loads. The analysis of these experiments will aim at improving the numerical treatment of complex phenomena (cavitation and ventilation) and serve the purpose of calibrating and validating our model for full aircraft studies.

Another challenge in the extension to full aircraft studies is the simulation of the horizontal hydrodynamic force. For high impact speeds we can no longer consider uniquely a friction term for the horizontal hydrodynamic force. We could for instance add a term to account for the mass of displaced fluid.

5 CONCLUSIONS

In the proposed approach, the 3D impacting body is replaced by a series of equally spaced vertical ground sections. The initial 3D problem gives birth to 2D sub-problems (2D+t approach). For each 2D sub-problem, a vertical hydrodynamic force is evaluated based on the Wagner formulation. A first order Taylor expansion is used to account for the real shape of the impacting section.

The proposed MLM strategy is implemented in Dassault-Aviation industrial tools and has been validated for various impact conditions. The challenges associated to the extension to full aircraft studies have been highlighted. In particular, experimental high speed controlled ditching tests involving double curvature of the impacting body and variations of the attitude during the impact are being performed to investigate the complex phenomena (cavitation and ventilation) arising in the circumstances of an aircraft ditching. This test matrix will constitute a basis for the calibration and the validation of our numerical model when it comes to full aircraft studies. High fidelity computational methods (VOF, SPH) will also be evaluated to improve the numerical treatment of these phenomena.

Finally, to complete the MLM approach and evaluate the pressure distribution at large penetration depth or perform detailed analyses involving local flexibility effects, other methodologies (CEL, VOF or SPH methods) should be further investigated.

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