Numerical and experimental studies of plate ditching

A. Iafrati, D. Calcagni, INSEAN-CNR (Italian Ship Model Basin- National Research Council), Rome, Italy,
E-mail: alessandro.iafrati@cnr.it

SUMMARY

The present paper deals with the water entry of a flat plate with a high horizontal speed. The activity is motivated by the need of achieving a better comprehension and more reliable simulation tools for the aircraft ditching phase. This first part of the study is focused to the ditching of a flat, rigid, plate. The problem is analyzed both numerically and experimentally. Numerically, the problem is studied in two dimensions and the self-similar solution is derived within the potential flow approximation of an ideal fluid. The problem is also addressed experimentally with the aim of building a dataset to be used for validation of computational tools. Due to the difficulties in scaling all the relevant physical parameters, experiments are performed at (almost) full scale velocity, with vertical component of 1.5 m/s and horizontal velocity in the range 30 to 50 m/s. The experimental campaign is starting soon and results will be shown at the Workshop. Here the experimental setup and the instrumentation adopted are presented. Numerical results are reported in terms of pressure distributions and free surface shape. The dependence of the pressure peak on the horizontal/vertical velocity components and on the plate inclination over the free surface is briefly discussed.

1. INTRODUCTION

In order to assess the ditching capabilities of an aircraft, the industry needs simulation tools which can model, with reduced computational effort, the fluid structure interaction taking into account the elastic/plastic structural behavior, including failure. However, simulation tools commonly adopted in the modelling of the aircraft ditching phase display strong limits in the accurate description of the complex phenomena such as highly localized pressure distributions, air cushioning, hydroelastic coupling, cavitation and ventilation (Climent et al., 2006).

For the development and validation of those simulation tools a reliable dataset is needed. Due to the difficulty in achieving a correct scaling of all the physical parameters involved, a full scale experiment is needed. Experiments of such kind are going to be performed at CNR-INSEAN under the SMAES-FP7 project. To this aim, a large high speed ditching facility has been built and installed at the end of towing tank # 1 of CNR-INSEAN. Tests will be carried out on aluminum plates 0.50 m wide, 1.00 m long. Similar experiments were already done in the early fifties (Smiley, 1951). Differently from past experiments, this experimental campaign is planned for higher horizontal components (from 30 to 50 m/s), and more detailed measurements, involving pressure, accelerations, strain and loads. The aim is to study the role played by the horizontal/vertical velocity ratio, plate incidence, shape, material and thickness on pressure distributions, acceleration and fluid structure interaction. The experimental campaign is starting soon and preliminary results for a rigid flat plate are expected by the beginning of the Workshop. In the following a description of the facility and of the experimental setup is provided only.

The design of the facility required estimates of the solution in terms of free surface shape and loads generated during the impact. As a water entry problem, a jet develops beneath the plate together with a pressure peak occurring at the root. The jet propagates along the plate until reaching the leading edge when the flow separates and the pressure and loads drops suddenly. Beside providing the loads to be used for the structural design of the guide, additional information on the time and space needed for the ditching phase to be completed can be also derived.

Due to some uncertainties in the more complex three-dimensional simulation tools, it was decided to derive those information also from a two-dimensional potential flow solution. Assuming a constant velocity and neglecting the finite length of the plate, the solution is self-similar and can be derived by using the same numerical procedure adopted in Iafrati & Korobkin, 2005. Note that the water entry problem of a wedge with a horizontal velocity component was already investigated in Faltinsen and Semenov (2008) and in Judge et al. (2004). However, in those cases the horizontal/vertical velocity ratio was much lower than that characteristic of aircraft at ditching. The incidence of the plate is also lower than that adopted in those papers.

In the following the numerical procedure is briefly recalled and results are presented in terms of free surface shape and pressure distribution. Comparisons between numerical solution and experimental results will be established as soon as the experimental results become available. Of course it is expected that load and pressures are overestimated by the two-dimensional solution as important three-dimensional effects related to the outflow at the sides are missing.

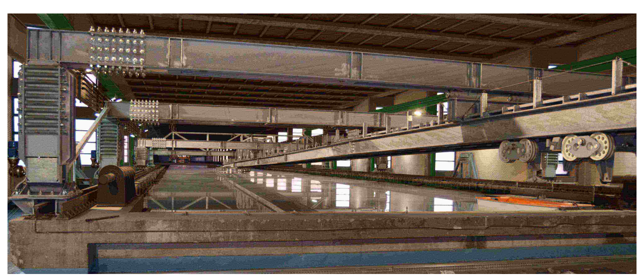

Figure 1: View of the CNR-INSEAN guided ditching facility. The guide is supported by bridges which can be varied in height in order to get the correct U/V velocity ratio. The main trolley can be also seen on the right.

2. FACILITY AND EXPERIMENTAL SETUP

In order to perform guided ditching tests, a new facility has been designed and installed at CNR-INSEAN, at the opposite end of the towing tank # 1, which is 470 m long, 13.5 m wide and 6.5 m deep.

The guide, which has a total length of about 64 m, is supported by five bridges which can be positioned at different heights, thus allowing the variation of the horizontal velocity keeping constant the vertical component, the latter being 1.5 m/s according to aircraft regulation. The model is supported by a main trolley which keeps it always attached to the guide. The main trolley is accelerated by a catapult which is designed to reach a final speed in a range 30 to 50 m/s (Fig. 1). The total mass to be accelerated is about 900 kg, whereas the mass which undergoes the impact is about 750 kg. The acceleration system is composed by a total of six elastic cords which can be elongated up to 250%.

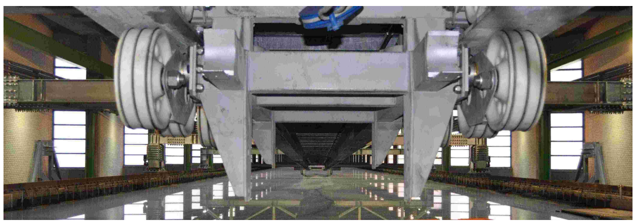

Figure 2: Picture of the main trolley which brings the model and specimens.

The trolley run on the inner side of the beam wings (Fig. 2). In order to get a measure of the forces acting beneath the plate, the model with the specimens to be tested is connected to the trolley by four Kistler 9343 for the z components and two 9363 load cells for the x component. As the cells can only undergo forces along their axes, the installation is done in such a way that transversal components and moments do not act on the cell. Attention is also posed in avoiding possible coupling in the measurements of loads in x and z directions. The load in the y direction is not measured but it is transferred from the model to the trolley by two articulated rods (Fig. 3).

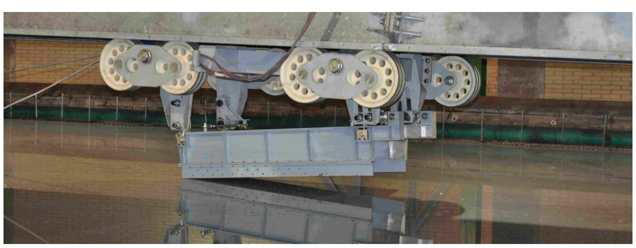

Figure 3: Picture of the trolley with model at the touch of the free surface. Note that the specimens is not installed yet.

For the first part of the test campaign, which is the one considered in this paper, a 15 mm thick, aluminum flat plate is considered. The plate is clamped to the frame which is 75 mm wide, thus leaving a free space of 350 mm by 850 mm (Fig. 4). In order to measure strains, six biaxial strain gauges are stick to the internal side of the plate. Pressures at 18 points are also measured through Kulite XTL123B pressure transducers. The position of the transducers is chosen in order to get information about the longitudinal and transversal pressure distributions, as well as about the symmetry in the impact. Velocity and displacement of the trolley are measured by a non-contact optical sensor, Correvit LFII. The acceleration components in the three directions at different positions are measured, for a total of 6 acceleration channels. Accelerations are measured by piezo-resistive Kistler M101A and M301A accelerometers.

All the data are acquired on-board by four Sirius Dewesoft modules and one Dewe 43, for a total of 40 channels. In order to correctly capture the pressure variations, data are acquired at 200 kS/s. The five acquisition systems are connected to a Sbox Dewesoft PC which communicate in wireless mode to an external PC. All the electronics is installed in a waterproof box which is positioned inside the model. Also the latter is sealed against water penetration.

Tests will be done at three different values of the horizontal component 30, 40 and 50 m/s, with the vertical component always equal to 1.5 m/s. The plate incidence with respect to the free surface will be varied from 4 to 10 degrees.

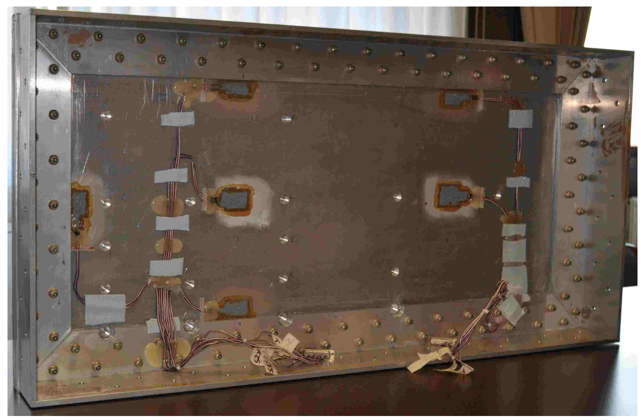

Figure 4: Instrumented aluminum plate. The strain gauges and the holes for the pressure probes can be seen. The two rows of bolts can be also recognized, which clamps the plate to the frame.

3. NUMERICAL MODEL AND RESULTS

The flow generated by the water entry of a plate with horizontal velocity component can be studied within the potential flow approximation. The fluid is assumed to be ideal and incompressible, and the action of gravity is neglected. In this conditions the problem is self-similar and the solution can be derived by using a pseudo-time stepping approach, similar to that used in Iafrati & Korobkin (2005). The problem is formulated in terms of the self-similar variables

$$\xi = \frac{x}{Ut} \quad \eta = \frac{y}{Ut} \quad \varphi = \frac{\phi}{U^2 t} \tag{1}$$

so that the initial boundary value problem in the physical variables can be transformed into the following boundary value problem for the self-similar velocity potential:

$$
\begin{aligned}
&\nabla^2\varphi = 0\\
&\varphi_\nu = \sin\gamma + \frac{V}{U}\cos\gamma \qquad \text{on } \eta = -\frac{V}{U} + (\xi-1)\tan\gamma\\
&\varphi - (\xi\varphi_\xi + \eta\varphi_\eta) + \frac{1}{2}\left(\varphi_\xi^2 + \varphi_\eta^2\right) = 0 \quad \text{on } h(\xi,\eta) = 0\\
&-(\xi h_\xi + \eta h_\eta) + (h_\xi\varphi_\xi + h_\eta\varphi_\eta) = 0 \quad \text{on } h(\xi,\eta) = 0\\
&\varphi \to 0 \qquad \text{as } \xi^2 + \eta^2 \to \infty
\end{aligned}
$$

where Ω is fluid domain, $h(\xi,\eta) = 0$ is the equation of the free surface and ν is the unit normal to the boundary, which is oriented inward the fluid domain.

As discussed in Iafrati and Korobkin (2004), the free surface conditions are strongly simplified by introducing a modified velocity potential defined as

$$S = \varphi - \frac{1}{2}\rho^2 \quad \rho = \sqrt{\xi^2 + \eta^2}$$

in terms of which the kinematic and dynamic boundary conditions become

$$S_n = 0 \quad S_{tau} = \pm\sqrt{-2S} \ , \tag{2}$$

respectively. In the above equation, τ denote the arclength along the free surface, which grows moving toward the positive ξ-axis. It can be shown that the sign in front of the dynamic boundary condition is always negative on the part of the free surface which is ahead of the leading edge whereas it change from negative to positive when moving along the free surface from $\xi = -\infty$ up to the trailing edge.

Additional conditions are enforced at the trailing edge of the plate, according to which the free surface is always attached at the edge of the plate and leaves the plate tangentially. These conditions are similar to the ones used for the plate entry problem (Iafrati and Korobkin, 2004; Iafrati, 2007). The conditions are expressed as:

$$h(1, -V/U) = 0 \quad h_\eta = -h_\xi \tan\gamma \ .$$

The first condition is enforced by assigning that the vertex of the first free surface panel one is at the trailing edge of the plate. The condition that the free surface leaves the plate tangentially is enforced by varying the point along the free surface where the sign in the dynamic boundary condition changes from negative to positive (see Iafrati and Korobkin, 2004).

In order to reduce the computational effort needed for the description of the solution within the thin jet layer, the thinnest part of the jet is described by a simplified shallow water model, similar to that used in Korobkin and Iafrati (2006).

In Fig. 5 the free surface profiles obtained at the same plate incidence, $\gamma = 10$ deg, and different horizontal velocity components $U = 30, 40$ and 50 m/s, are shown. Due to the different values of the ratio V/U, the plate is positioned at different heights. In terms of the non-dimensional variables, the root of the jet moves forward when reducing the horizontal velocity component. Note that, because of the difference in U, this does not reflect what occurs in physical variables. Behind the trailing edge of the plate there is a wake region and the free surface forms a corner with the angle between the two sides of the free surface of about 60 degrees.

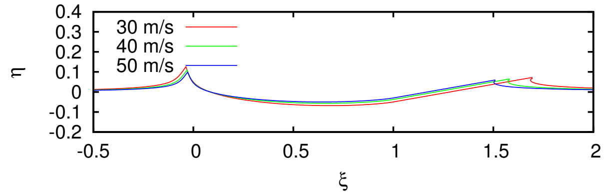

Figure 5: Free surface shapes obtained for a plate incidence $\gamma = 10$ at different horizontal velocities. For the sake of the clarity, on the right hand side of the plate, the thinnest part of the jet, described by the shallow water model, is not depicted.

The solutions for the thinnest part of the jet, described by the shallow water model, are plotted in Fig. 6. According to the definition of the self-similar variables, the position of a point in the self-similar plane gives an indication of the velocity of that point in the physical plane being $u = \xi U$ and $v = \eta U$. From the results presented it is found that the position of the tip is $\xi_T = 3.33, 3.11, 2.97$ for $U = 30, 40$ and 50 m/s, respectively. Hence, for the three cases in Fig. 6 the horizontal velocity of the tip is about 100, 124.4 and 148.5 m/s.

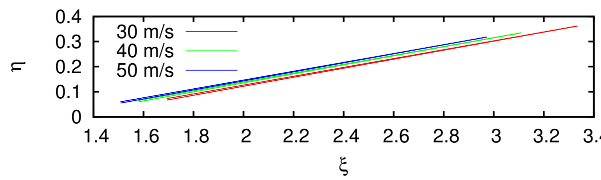

Figure 6: Free surface shapes of the jet regions obtained for a plate incidence $\gamma = 10$ at different horizontal velocities.

The most interesting aspect in terms of applications concerns the pressure distributions. For the three cases discussed above, the distributions of the self-similar pressure $\psi = p/(\varrho U^2)$, ϱ being the liquid density, are shown in Fig. 7.

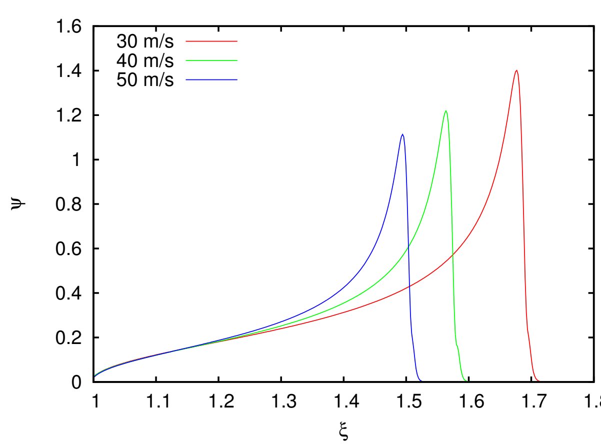

Figure 7: Pressure distributions for a plate incidence $\gamma = 10$ at different horizontal velocities.

It is seen that the non-dimensional pressure diminishes when increasing the horizontal velocity, with the peak values located at $\psi_p = 1.40, 1.22$ and 1.11 for $U = 30, 40$ and 50 m/s. However, the physical value of the pressure grows due to the quadratic term U^2.

In Fig. 8 and 9, the role played by the incidence of the plate on the free surface configuration and on the pressure distribution is shown for the case with $U = 30$ m/s. The results indicate that, when reducing the incidence of the plate, there is an increase of the wetted length as well as an increase in the intensity of the pressure peak.

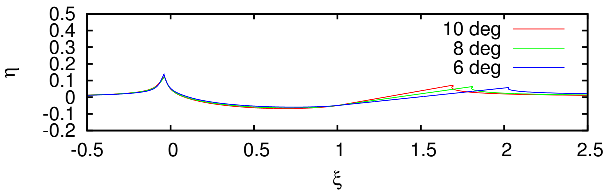

Figure 8: Free surface shape for $U = 30$ m/s, and different values of the plate incidence.

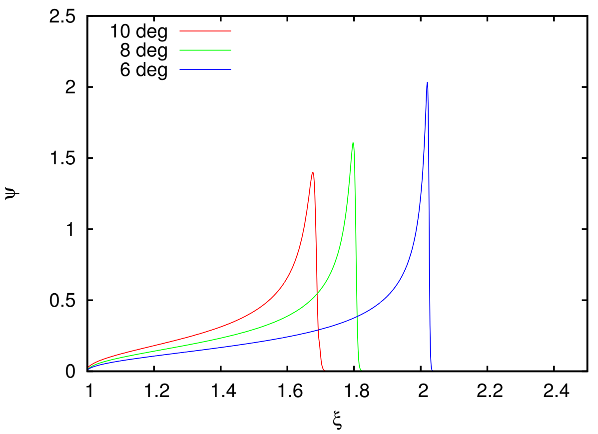

Figure 9: Pressure distributions for $U = 30$ m/s, and different values of the plate incidence.

The analysis of the solution is still in process and a much deeper discussion on the dependences will be presented at the Workshop. Hopefully, comparisons with experimental results will be established as well.

4. ACKNOWLEDGMENTS

This work has been partially funded by the Flagship Project RITMARE - The Italian Research for the Sea - coordinated by the Italian National Research Council and funded by the Italian Ministry of Education, University and Research within the National Research Program 2011-2013." Part of the work has been done in the framework of the SMAES-FP7 project (Grant Agreement N. 266172).

5. REFERENCES

H. Climent, L. Benitez, F. Rosich, F. Rueda and N. Pentecote (2006) *Aircraft Ditching Numerical Simulation*, 25th International Congress of the Aeronautical Sciences, Hamburg, Germany.

O.M. Faltinsen and Y.A. Semenov (2008) *Nonlinear problem of flat-plate entry into an incompressible liquid*, J. Fluid Mech. 611, 151-173.

A. Iafrati and Korobkin (2004) *Initial stage of flat plate impact onto liquid free surface*, Phys. Fluids 16, 2214-2227.

A. Iafrati and Korobkin (2005) *Self-similar solutions for porous/perforated wedge entry problem*, 20th IWWWFB, Longyearbyen, Norway.

A. Iafrati (2007) *Free surface flow generated by the water impact of a flat plate*, Proc. 9th Int. Conf. Num. Ship Hydrod., Ann Arbor (MI), USA.

C. Judge, A. Troesch and M. Perlin (2004) *Initial water impact of a wedge at vertical and oblique angles*, J. Engng. Math., 48, 279-303.

A. Korobkin and A. Iafrati Numerical study of jet flow generated by impact on weakly compressible liquid*, Phys. Fluids 18, 032108.*

R.F. Smiley (1951) An experimental study of water-pressure distributions during landings and planing of a heavily loaded rectangular flat-plate model *NACA TN 2453.*