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# On analytical models of vertical water entry of a symmetric body with separation and cavity initiation

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ABSTRACT

Two-dimensional water entry with separation is investigated through different analytical models. This study focuses on the transient force acting on the body when the jet root detaches from the body surface and a cavity starts to develop behind the body. Logvinovich (1972) suggested a separation model in order to estimate the transient force acting on a finite wedge entering water. This model is revisited, developed further and assessed through comparison with more recent works on flow separation. The concept of Fictitious Body Continuation combined with the Modified Logvinovich Model is also investigated to estimate the transient drag during the initial stage of cavity formation. This model accounts for the variation in speed of the body during the separation stage. Several case studies are presented in order to show the relevance of this model. These include separation from chines and separation from smooth bodies.

## 1. Introduction

Water impact is a widely studied hydrodynamic phenomenon which motivates the development of new Computational Fluid Dynamics (CFD) techniques [1], experiments [2] and analytical models [3]. This complex hydrodynamic phenomenon is of interest scientifically and due to its engineering applications in ship hydrodynamics (slamming, sloshing, wave impacts), ballistics (ricochet of projectiles), aerospace industry (ditching, re-entry of space capsules), biomechanics (animals running on water) and sports (acrobatic diving). During the early stage of water entry which is referred to as the water impact stage, the surface of the body in contact with the water (the wetted surface) expands very quickly and, as a result of the acceleration of the liquid from an initial state of rest, high hydrodynamic loads are exerted on the body. The water impact stage is characterised by the projection of splash jets and the presence of high pressures in small regions close to the jet roots. Later, as the body continues to penetrate the water, the wetted surface might stop expanding due to some reasons. Then the flow separates from the body surface and a cavity may start to form behind the body. Eventually, if the body continues to penetrate the water with sufficient speed, a tall cavity might develop above the descending body. This late stage, similar to an idealised infinite cavity flow, will be referred to as the cavity stage. In the absence of gravity the cavity behind the descending body continues to expand without limit, while maintaining an opening at the top. But gravity acts to slow down and eventually reverse the expansion of the cavity. Later in time the gravity closes the cavity either near the still water level or the cavity pinches off at some level above the body.

Extensive research has been dedicated to the water impact stage as it induces critical loads on structures subject to violent free-surface flows (see [4,3,1] for an overview). Many studies have also been dedicated to the cavity stage and the cavity collapse (see [5] as an example). By contrast, the early stage of cavity formation, starting when the jet root separates from the body surface, has been little studied so far. The present study focuses on this transition stage, which can also be referred to as the separation stage, following the impact stage and preceding the cavity stage (see Fig. 1). The beginning of the separation stage can also be defined as the instant when the wetted surface stops expanding. However, the duration of the transition stage cannot be precisely defined and, for this reason, it will be assumed to be of the same order as the duration of the entry stage. Although the maximum hydrodynamic loads occur during the impact stage, we also need to estimate the rate at which the loads decrease during the transition stage. This is needed to simulate the dynamic response of a structure undergoing an impact with separation, to estimate the deceleration of a body penetrating water or to estimate the lift on a planing hull close to the stern where separation occurs.

An important distinction shall be made between separation from chines (or knuckles) as occurs during the water entry of a finite wedge (Fig. 1(b)), and the separation of the free surface from a smooth body (e.g. circular cylinder, sphere). For a body with chines the separation occurs at the chines. But for a smooth body the water

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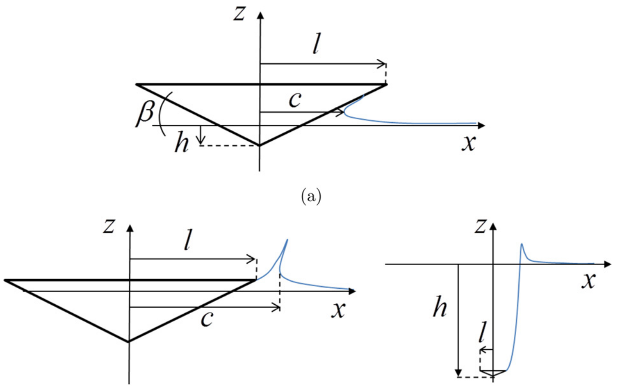

**Fig. 1.** Definitions of the different stages of water entry: (a) impact stage $c < l$, (b) separation stage $c > l$, and (c) cavity stage $h \gg l$.

surface separates at a free-boundary point on the body whose position is modelled according to criteria we discuss below in Section 3. In fact, for smooth bodies, the separation can start before the entire lower part of the body is in contact with the water [6].

Several studies report the influence of the impacting speed and the properties of the body surface (wettability, roughness) on the cavity formation [7,8], and on the location of the separation points (or line) on a smooth surface which delimit the wetted area when it stops expanding [9,6]. Experiments and modelling on the water entry of spheres by Duez et al. [10] have shown that the critical velocity of cavity formation as a function of the wettability of the surface can be predicted, but separation from smooth bodies is still an open problem which would require us to take into account the interaction between air and water. The prediction of the location of the separation line seems particularly challenging. For practical applications, different attempts have been made to model separation using potential flow theory. Sun [11] simulated the water entry of a circular cylinder using a fully nonlinear boundary element method (BEM) in which the position of the "separation point" was determined by enforcing a condition of positive pressure on the wetted surface. Battistin and Iafrati [12] also observed (in their numerical simulations) negative pressures in the neighborhood of the jet root when it approaches the maximum breadth of a circular cylinder. Negative pressures are likely to occur during oblique impacts [13,14] and vertical impacts with deceleration [15–17], which might show the limitations of the criterion of positive pressure used by Sun [11] for more general cases. Most of the models dedicated to flow separation from chines include a Kutta type condition at the separation point [18,19], which keeps the flow tangential to the body surface and avoids a pressure singularity at the separation point. Reinhard et al. [14] and Reinhard [19] also used a Brillouin–Villat type condition in order to determine the position of the separation point on a smooth surface during oblique impact at high horizontal speed.

In the present paper, we investigate a model which was proposed by Logvinovich [20] in order to estimate the force during the transient stage of separation for finite wedges and cones. This model is based on the assumption that the entry speed is high enough so that gravity can be neglected during the impact stage and the transition stage. Its main idea is to use a Wagner type model, even during the separation stage with contact points being fictitious and placed beyond the chine. This fictitious contact point might be seen as the position of the jet root when it leaves the body. The position of this fictitious contact point is determined by enforcing a zero-pressure condition at the chine. A similar approach seems to have been used by Algarín and Tascón [21] in order to model the two-dimensional water entry of an asymmetric body with chines. Fairlie-Clarke and Tveitnes [22] proposed a model for the wedge water entry with separation. This model is based on the momentum theory and an assumption that the added mass of the wedge keeps on increasing during the separation stage. The latter assumption has some similarities with the idea of Logvinovich of a fictitious contact point which goes beyond the chine of the wedge. Logvinovich suggested a criterion for the determination of the position of the fictitious contact point whereas the approach of Fairlie-Clarke and Tveitnes [22] requires one to identify the evolution of the added mass after separation from experiments or numerical simulations. The purpose of the present work is to assess the accuracy of the Logvinovich model, to develop it further and to modify it by using recent numerical results. The results of the Logvinovich model are first compared to recent numerical results for wedges with deadrise angles of 10°, 20° and 30°. An extension of the model has also been implemented, based on a suggestion of Logvinovich to take into account the deadrise angle of the wedge. But its results are shown to be worse than those of the original model. Based on further comparisons between the original model and the results of Iafrati and Korobkin [23,24], we show that the model fails to reproduce the water entry of a flat plate and therefore the model should not be expected to give accurate results for wedge entries. By using these observations, we suggest a correction of the Logvinovich model. We also introduce an analytical model which presents similarities with the Logvinovich model. This model is based on the concept of Fictitious Body Continuation (FBC) and the Modified Logvinovich Model (MLM). It is shown that this new model can be used to describe water entry with separation and varying speed. Contrary to the suggestion of Fairlie-Clarke and Tveitnes [22], the contribution of the acceleration of the body to the force is calculated by assuming that the added mass does not increase after the separation. Finally, the FBC approach is applied to smooth body separation.

The paper is arranged as follows. Section 2 introduces the Logvinovich model of separation in its extended form, taking into account the deadrise angle of the wedge. The concept of Fictitious Body Continuation is discussed in Section 3. Conclusions are drawn in Section 4.

## 2. Logvinovich model of wedge entry with separation

In this section, we investigate the model of wedge water entry with separation proposed by Logvinovich [20], in order to assess its accuracy. For this purpose, an extension of the model suggested in [20] is derived and compared to the original model from [20]. Some characteristic features of the model are shown through the study of the flat-plate water entry and comparison with theoretical and numerical approaches by Iafrati and Korobkin [24]. The limitations of the original model are clearly highlighted and a correction of the model is proposed by using the observations made for the flat-plate water entry.

### 2.1. Extension of the Logvinovich model of separation by taking into account the deadrise angle of the wedge

Logvinovich [20] studied in detail the water entry problem without separation. He made substantial effort to improve the original Wagner model of water impact [25,26] and discussed different ways of taking into account nonlinear terms for the computation of the hydrodynamic pressure. We shall recall that the Wagner model of water impact (without separation) is based on the so-called flat plate approximation which assumes that the velocity potential in the fluid domain ($z < 0$), $\varphi$, is the solution of the following linear boundary value problem:

$$\varphi_{xx} + \varphi_{zz} = 0 \qquad (z < 0), \tag{1a}$$