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A Fictitious Body Continuation model for the vertical water entry of 2D asymmetric bodies with flow separation

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1. Introduction

During the rapid water entry of an impermeable body, the induced flow may separate from the body surface. Flow separation can occur at chines or on smooth parts of the body where the deadrise angles become large. Then, a cavity flow forms behind the body and hydrodynamic loads usually start decreasing. It may be important to know how fast slamming pressure decays to predict the impact-induced transient response of a structure. Besides, for asymmetric bodies, flow separation may not happen at the same time on both sides of the body contour. Then there will be a transition stage where the evolution of the slamming loads will be governed by a competition between the local drop in pressure due to the flow separation and the ongoing expansion of the wetted area.

Tassin et al. (2014) [1], inspired by previous works [2, 3, 4, 5], investigated the 'Fictitious Body Continuation' (FBC) concept as an effective way to extend the use of Wagner-type models [6] after flow separation from the body. The principle of the FBC model is to extend the real body by a fictitious one so that Wagner's model can be applied to the composite real+fictitious body. In Tassin et al., the slamming pressure is computed by using the Modified Logvinovich Model (MLM), introduced by Korobkin (2004) [7]. The hydrodynamic load is obtained by integrating the pressure along the real part of the body only. By comparing the FBC estimates with experimental and CFD results, Tassin et al. found that a continuation with inclined flat plates can give a good agreement on the hydrodynamic loads during the early stage of cavity initiation. However, they only considered symmetric bodies: namely horizontal flate plate, wedges of different deadrise angles and circular cylinder.

The aim of the present study is to investigate whether the 'Fictitious Body Continuation' concept can be applied to more complex 2D asymmetric bodies. The expansion velocity of the Wagner wetted area is computed based on Scolan et al. (1999) [8], and the hydrodynamic pressure is estimated by using the MLM [7, 9].

2. Vertical water entry of a NACA foil as a case study

As a case study we consider the vertical water entry of a NACA 0028 [10] foil inclined at different angles. Before the first contact with the body, the fluid is at rest and is delimited by a flat free surface. For moderate inclination angles, θ, – with respect to the initial free surface – the foil contour is strongly asymmetric about the water entry vertical axis (see Fig. 1, left panel). The foil geometry leads to flow separation from a smooth body part at the leading edge and from a knuckle at the trailing edge. Beyond the separation points, the foil is continued by fictitious flat plates (Fig. 1, right panel), whose inclination angles are set to $\alpha_1 = 60°$ at the leading edge, and $\alpha_2 = 47°$ at the trailing edge; see §3 for a discussion on the chosen continuation angles.

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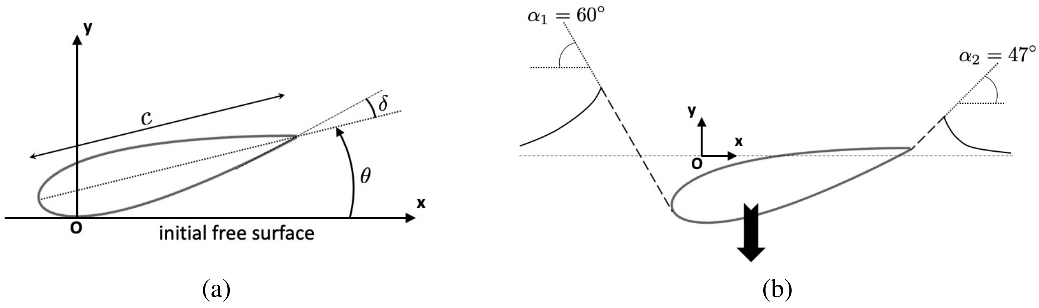

Figure 1: (a): Initial conditions of impact when the foil first touches the water. The initial free surface is assumed to be flat; θ is the inclination angle of the foil with respect to the initial free surface. The foil has a chord length c and its trailing edge has a half-opening angle δ. (b): Fictitious body continuation after flow separation from both sides of the foil. The foil is continued by two flat plates (dashed lines) of inclinations, $\alpha_1 = 60°$ on the left, and $\alpha_2 = 47°$ on the right.

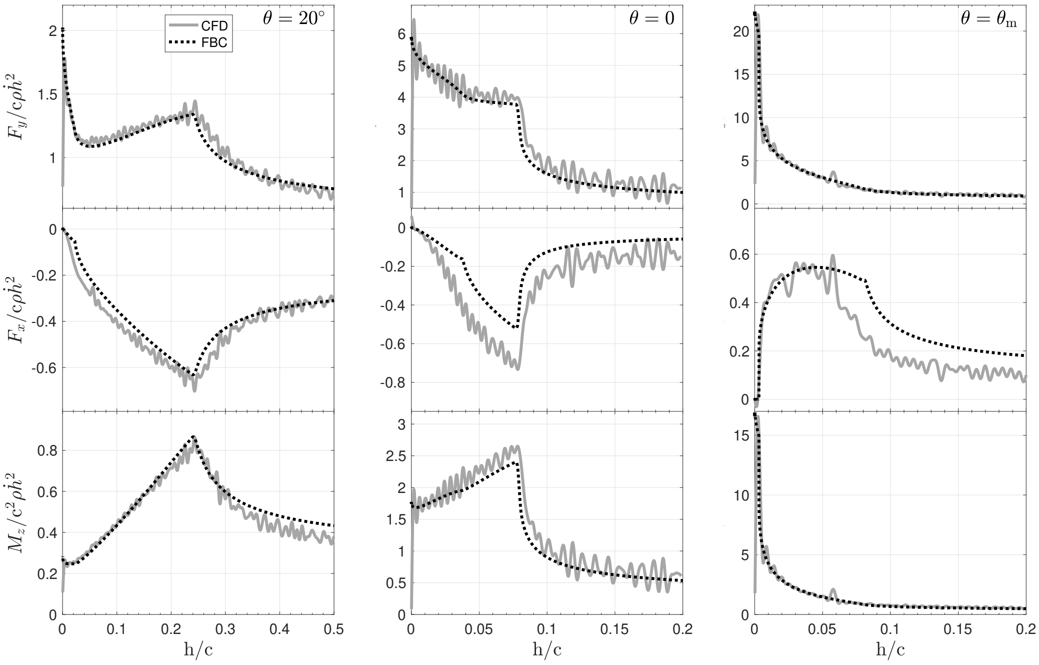

Figure 2: Vertical water entry of a NACA 0028 foil at constant velocity. CFD and FBC results are shown respectively as grey solid lines and black dotted lines. From top to bottom: force components and moment, F_y, F_x, M_z, as a function of the penetration depth h. These quantities are nondimensionalized by using the entry velocity $\dot{h}$, the fluid density ρ, and the foil chord length c. From left to right: calculations are shown for different inclination angles, $\theta = 20°$ (left), $\theta = 0$ (middle), $\theta = \theta_m$ (right). $\theta_m = -14.5°$ is the inclination angle at which the FBC model predicts maximum instant value for $F_y/c\rho\dot{h}^2$ (at the beginning of the impact).

Figs. 2-3 show the evolution of the two hydrodynamic force components F_x, F_y, and of the moment M_z (computed at the leading edge) acting on the foil during vertical water entry at constant velocity, for 5 different inclination angles: $\theta = -28.1°$; $-18.1°$; $-14.5°$; $0°$; $20°$. The FBC predictions are compared with CFD simulations carried out with the finite-element software ABAQUS/Explicit (version 2017). Flow separation events can be easily identified for the FBC model as they induce breaks in the force-displacement curves. The same breaks can also be identified in CFD results at the same penetration depths, although they are somewhat smoothened. For all inclination angles, both models show a good agreement on separation times.

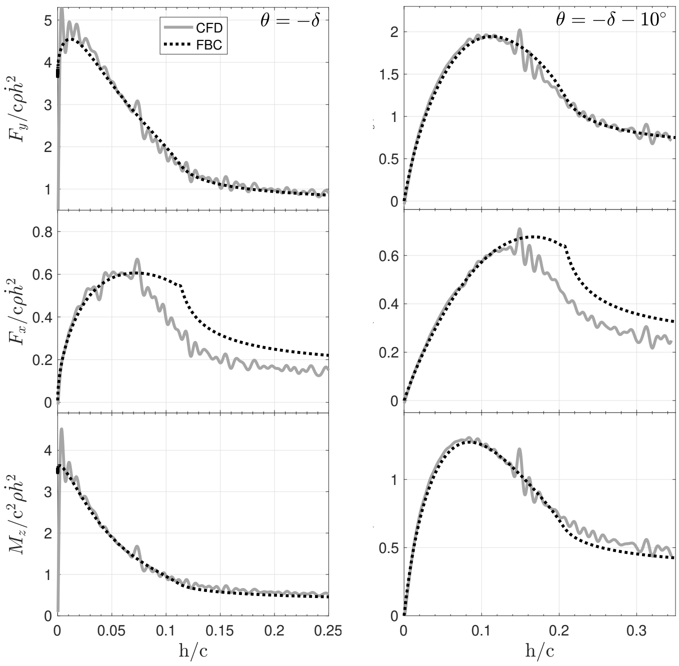

Figure 3: Same as Fig. 2 for two other inclination angles: $\theta = -\delta$ (left) and $\theta = -\delta - 10^\circ$ (right). $\delta \simeq 18.1^\circ$ is the half opening angle of the foil trailing edge. For $\theta = -\delta$ the trailing edge contour is tangent to the initial free surface.

The FBC and CFD models agree very well also in terms of vertical force F_y and moment M_z, for all considered inclination angles. The agreement is less satisfactory regarding the horizontal force component F_x (except for $\theta = 20^\circ$). We note, however, that the magnitude of F_x is significantly smaller than the magnitude of F_y for the considered range of inclination angles. F_x is a second-order quantity whose main contributions are due to the pressure peaks close to the contact points between the body contour and the fluid free surface, where the deadrise angles are the largest. The MLM is known to provide very good estimates of global loads, but it tends to overestimate the pressure peaks when the local deadrise angles become significant [11]. This explains the larger disagreement between FBC and CFD models regarding F_x. However, for practical use, it is not an issue as long as F_x remains moderately smaller than F_y, which is the case for all considered inclination angles.

3. Discussion

Within the FBC approach, one important question to address is whether there exists a simple and generic fictitious body shape that can properly mimic flow separation regarding slamming loads. In the present study, the real body contour is continued by fictitious flat plates, whose inclination angles α_1 and α_2 need to be chosen *a priori*. Comparisons with experiments or self-sufficient models (e.g. CFD simulations) can provide some 'heuristic' knowledge of suitable continuation angles. This question was partly investigated by Tassin et al. (2014), for a few symmetric body shapes. They found as 'best' continuation angles, $\alpha_{\text{fp}} = 47^\circ$ for a horizontal flat-plate, $\alpha_{\text{cl}} = 60^\circ$ for a circular cylinder, and α ranging from 45° to 55° for wedges with different deadrise angles.

The present work suggests that best continuation angles may weakly depend on the exact shape of the real body contour. We have considered a foil geometry as a benchmark for the FBC model, setting the continuation angles to $\alpha_1 = \alpha_{\text{cl}}$ for flow separation at the smooth leading edge, and $\alpha_2 = \alpha_{\text{fp}}$ at the sharp trailing edge. Through comparisons with CFD simulations, the FBC model has been found to provide good estimates of the slamming loads for a broad range of inclination angles ($-30^\circ < \theta < 20^\circ$); this, without any change in the values of α_1 and α_2. Consequently, one could wonder whether α_{fp} and α_{cl} – for flow separation at a chine and from a smooth body part respectively – can be used as generic continuation angles for a broad family of body shapes. Comparative studies for other asymmetric bodies would be useful to better delimit the generic feature of continuation angles.

Acknowledgements

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