FLOW SEPARATION AT THE INITIAL STAGE OF THE OBLIQUE WATER ENTRY OF A WEDGE

B.S. Yoon and Y.A. Semenov

School of Naval Architecture and Ocean Engineering University of Ulsan, Republic of Korea
E-mail: bsyoon@ulsan.ac.kr, semenov@a-teleport.com

ABSTRACT

The limit combination of the initial parameters corresponding to flow separation from the wedge vertex during the initial stage of the oblique impact of a wedge on a liquid half-space is investigated on the basis of an analytical solution of the problem. The liquid is assumed to be ideal and incompressible; gravity and surface tension effects are ignored. The flow generated by the impact is two-dimensional and potential. The analysis revealed a limit combination of the initial parameters at which the pressure along the whole length of one side of the wedge becomes less than the atmospheric pressure. Such a pressure distribution results in the ventilation of the wedge side, which starts from the contact point on the free surface and extends suddenly along the whole length of the wedge side, thus leading to flow separation from the wedge vertex.

I. INTRODUCTION

The problem of body penetration into fluids is topical in applications concerned with high-speed planing boats, seaplanes, half-submerged propellers, ships and offshore platforms designed to operate in a heavy sea [1].

Various initial parameters such as the direction of the entry velocity and the body orientation with respect to the free surface may correspond to different types of the flow morphology depending on a particular combination of these initial parameters. The present study is focused on one aspect of the water impact of wedge-shaped bodies, namely, on the onset of flow separation at the wedge vertex, which may occur due to an arbitrary wedge orientation and the horizontal component of the entry velocity.

The present study is focused on the effect that the horizontal component of the velocity exerts on the flow parameters during the initial stage of the water impact. The fluid is assumed to be ideal, weightless and with negligible surface tension effects. Two types of the flow depending on the position of flow separation are possible. For the first type studied in the present work, it is assumed that there is no flow separation at the wedge vertex, and therefore the velocity magnitude and pressure become infinite at the wedge vertex. Although infinite velocities in real flows do not occur, flow separation at the wedge vertex due to cavitation requires some physical conditions for the growth of cavitation nuclei contained in the real liquid. The dynamics of the cavitation nuclei is governed by the negative external pressure in the flow field and the time, and therefore the occurrence of cavitation at the wedge vertex depends on the pressure distribution along the wedge side and the flow velocity. It should also be noted that real wedge-shaped bodies have rounded edges. Even a small radius of the edge prevents the velocity from becoming infinite while affecting other flow parameters only slightly. In this study we assume that cavitation at the wedge vertex does not occur and flow separation depends on the flow characteristics enabling the ventilation of one wedge side. Such a type of the flow morphology is confirmed by experiments [2].

2. ANALYSIS OF THE FLOW PARAMETERS AT THE ONSET OF FLOW SEPARATION

An analytical solution for the asymmetric/oblique water entry of a wedge which does not assume flow separation from the wedge vertex has been derived in [3] by using an advanced hodograph method. A sketch of the flow and the definitions of the geometric parameters are shown in Fig. 1.

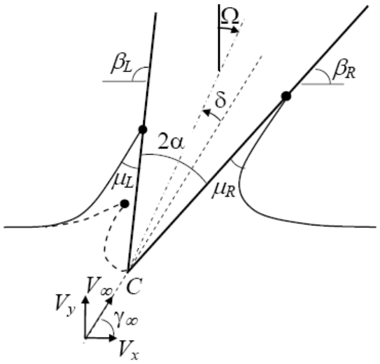

Figure 1. Sketch of water entry of a wedge

The pressure coefficient $p = (P - P_a)/(0.5\rho V_y^2)$ along the wedge sides is defined in terms of the vertical component V_y of the entry velocity. The force coefficients on the right and left wedge sides, C_{nR} and C_{nL}, are evaluated by integrating the pressure along the wedge sides

$$C_{\{nR,nL\}} = \frac{2}{\rho V_y^2 H} \int_0^{S_{\{O,B\}}} P_{\{R,L\}}(S)\,dS$$

where $H = V_y th$, $h = v_\infty \sin\gamma_\infty [\cot\beta_R + \cot\beta_L]$, v_∞ and γ_∞ are the magnitude and angle of the entry velocity; β_R and

β_L are the deadrise angles on the right and left wedge sides; S_O and S_B are the wetted lengths of the wedge sides.

2.1. Oblique entry of a wedge

In figure 2, streamline patterns for wedge angle $2\alpha = 5\pi/6$ are shown for three entry angles $\gamma_\infty = \pi/2, \quad 3\pi/4, \quad 8\pi/9$ and heel angle $\delta = \pi/2 - \gamma_\infty$, which provides the vertical orientation of the wedge with respect to the undisturbed free surface.

The zero value of the stream function is chosen to correspond to the splitting streamline containing the stagnation point. The density of streamlines increases with the magnitude of the velocity since the flux of the liquid between two nearest streamlines is constant. The streamline patterns clearly show an increase of the velocity near the root of the tip jets and a decrease of the velocity magnitude near the stagnation point, which is located on the wedge side with the smaller deadrise angle.

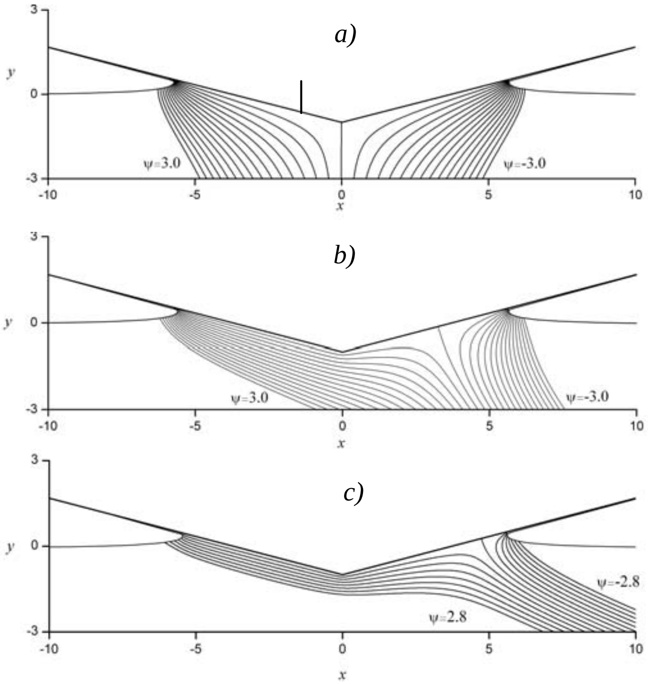

Figure 2. Streamline patterns for wedge angle $2\alpha = 5\pi/6$ and entry angles $\gamma_\infty = \pi/2, \quad 3\pi/4, \quad 8\pi/9$.

Fig. 2 shows that the stagnation point moves from the wedge vertex along the wedge side as the horizontal component of the velocity increases. At the same time, the location of the root of the tip jets is almost the same. Thus, the horizontal velocity does not affect the location of the root of the tip jets and hence the length of the wetted part of the wedge sides.

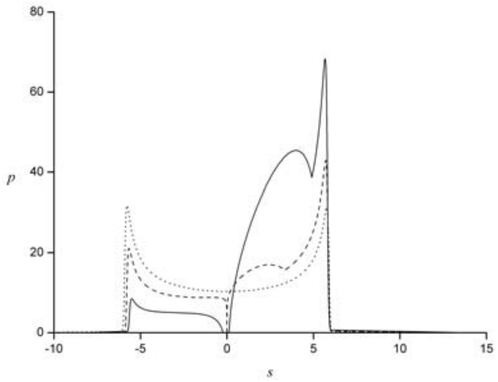

Figure 3. Pressure distributions along the wedge sides for cases (*a*) (dotted line), (*b*) (dashed line) and (*c*) (solid line) in figure 1.

The pressure distributions along the wedge sides for cases (*a*), (b) and (c) in Fig. 2 are shown in Fig. 3. The pressure distribution exhibits specific behavior at the point corresponding to the stagnation points in Fig. 2. Such behavior has been predicted in [3] for the cases of the vertical entry of asymmetric wedges and in [4] for the oblique entry of a flat plate.

For the case of the oblique entry of a wedge, the pressure distribution is similar to that for a flat plate at small deadrise angles and at larger values of the horizontal component of the velocity. This similarity reveals the significant contribution of the horizontal component of the velocity to the pressure distribution along the wedge sides.

The cusp point in the pressure distribution along the wedge sides has been explained in [3] and [4]. Since for steady flows $dp/ds = 0$ at the stagnation point, this effect occurs due to flow unsteadiness. For the case of oblique entry, the larger increase in the pressure peak near the tip jet occurs due to the x-component of the entry velocity causing more liquid to enter the tip jet. Thus, the larger the slamming effect in the pressure distribution due to the x-component of the entry velocity, the more pronounced the effect of two maxima in the pressure distribution. In Fig. 3 the larger pressure maximum corresponds to the slamming effect studied in detail in [5] for the water entry of symmetric wedges. In Fig. 3, the location of the pressure peak on the wedge side is almost the same for different entry angles, which agrees with the above discussion of the location of the roots of the tip jets in Fig. 2.

Note that the similar problem of impact between a liquid wedge and a solid wall has been considered in [6] using the advanced hodograph method and in [7] using the boundary element method with an analytical solution for the jet based on the shallow water approximation. The results presented in [7] do not exhibit the specific behavior of the pressure distribution for the case of oblique impact.

2.2. Flow separation conditions

A combination of the wedge orientation and the direction of the entry velocity may form conditions, $\pi - \gamma_\infty < \beta_L$, for which the liquid at infinity is running away from the left side of the wedge. For such initial parameters, flow separation from the wedge vertex may occur, which changes the flow topology and requires another mathematical formulation of the problem. In that case only one side of the wedge interacts with the liquid, and the resulting flow corresponds to the water entry of a flat plate. The initial separation-ventilation of the flow has been studied in [2] experimentally and theoretically using the method of two-dimensional vortex distributions. In that work, the dependence $\gamma_\infty^* = \gamma_\infty(\Omega)$ has been obtained for a wedge of angle $2\alpha = 106^0$ in the transient regime between the wedge and the flat plate water entry flows.

A flow separation criterion based on the consideration of the normal forces acting on the wedge sides has been proposed in [3] for the case of the vertical water entry of asymmetric wedges. According to the criterion, flow separation occurs if the total force on the wedge sides becomes equal to zero. Note that this criterion has been formulated assuming that the pressure along the free surface P_a can be ignored. This assumption is acceptable for a very high entry velocity providing $-P_a/(0.5\rho V_y^2) \approx 0$. However, entry velocities may have relatively low values in the naval context when studying slamming or high-speed planing hulls. The present study enables one to verify the proposed criterion for the case of oblique entry accounting for the atmospheric pressure on the free surface.

Fig. 4, shows the force coefficients on the left side of the wedge versus the entry angle $\gamma_\infty - \pi/2$ for wedge angle $2\alpha = 106^0$ and different wedge orientations. For small values of $\gamma_\infty - \pi/2$, provided that the entry velocity is nearly perpendicular to the free surface, the force coefficients vary about linearly with the entry angle γ_∞ . At some value of $\gamma_\infty - \pi/2$, the coefficient of the normal force C_{nL} becomes negative and then decreases further. Negative values of the force coefficient on the left side of the wedge without cavitation development may occur if the average pressure, $\overline{P}$, on the wedge side satisfies the condition $P_c < \overline{P} < P_a$ where P_c is the vapor pressure. The upper limit of γ_∞ is dictated by the convergence of the iterative solution process.

The streamline pattern corresponding to the limit angle of the entry velocity γ_∞^* is shown in Fig. 5. It can be seen that the streamlines come uniformly to the free surface on the left side. This means that the velocity in this part of the free surface is only slightly different from the entry velocity $v_\infty e^{i\gamma_\infty}$. There is some elevation of the free surface caused by the mass of liquid coming from the right side of the wedge.

The pressure distributions along the wedge sides corresponding to the limit angle of the entry velocity γ_∞^* for three cases of the wedge orientation are shown in Fig. 6.

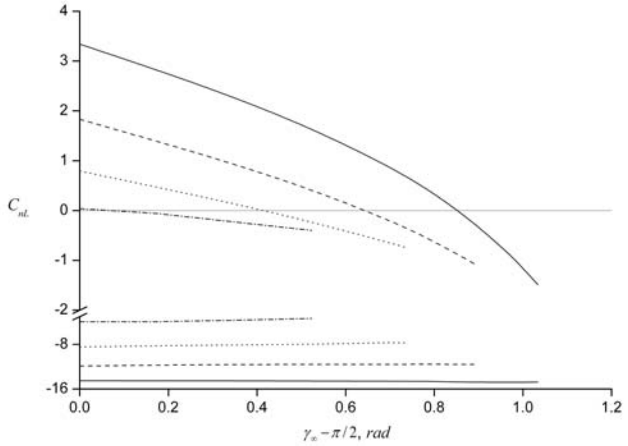

Figure 4. Effect of the entry angle γ_∞ on the non-dimensional coefficients of the normal force on the left side of a $2\alpha = 106^0$ wedge. The heel angle varies providing the wedge orientation $\Omega = 0^0$ (solid line), $\Omega = 10^0$ (dashed line), $\Omega = 20^0$ (dotted line) and $\Omega = 30^0$ (dash-dotted line). The lower part of the graph shows the force coefficients corresponding to zero pressure $P = 0$ along the wedge side, $P_a = 0.1 MPa$ and vertical component of the entry velocity $V_y = 3.81 m/\sec$ (the experimental conditions in [2]).

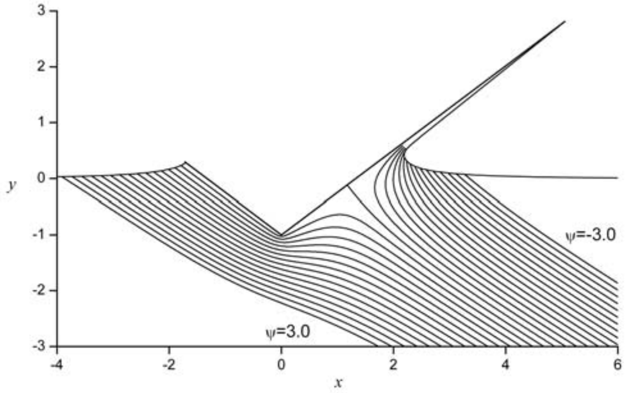

Figure 5. Streamline patterns corresponding to the onset of ventilation of the left side of the wedge: $2\alpha = 106^0$, $\Omega = 0^0$, $\gamma_\infty^* = 59.2^0$

For all these cases the pressure along the left side, $s < 0$, monotonically decreases when going from the contact point to the wedge vertex. From the results presented in Fig. 3 it can be seen that the pressure peak caused by the slamming effect on the left side of the wedge decreases with increasing entry angle and completely disappears at the limit value $\gamma_\infty = \gamma_\infty^*$ shown in Fig. 6. The pressure distribution along the whole wedge side without pressure maxima at the root of the tip jet provides physical conditions for the ventilation of the left side of the wedge starting from the contact point of the free surface and the wedge side. Thus, the disappearance of the pressure maxima near the root of the tip jet, which is caused by the slamming effect, and the negative pressure coefficient corresponding to $P < P_a$ lead to sudden ventilation along the whole wedge side and, consequently, to flow separation from the wedge vertex.

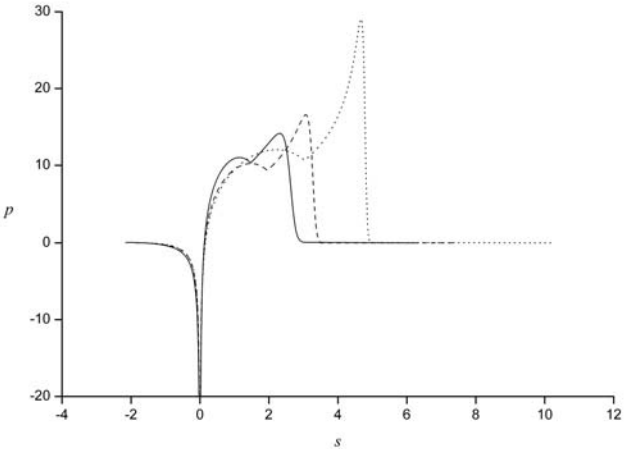

Figure 6. Pressure distributions along the wedge sides ($s < 0$ for the left side and $s > 0$ for the right side) corresponding to the onset of ventilation of the left side of the wedge for three angles of rotation: $\Omega = 0^0$, $\gamma_\infty^* = 59.2^0$ (solid line); $\Omega = 10^0$, $\gamma_\infty^* = 51.0^0$ (dashed line); $\Omega = 20^0$, $\gamma_\infty^* = 41.0^0$ (dotted line)

3. CONCLUSIONS

The initial stage of the oblique impact of a wedge on a liquid half-space has been investigated with the aim to determine the onset of flow separation from the wedge vertex as a function of the initial parameters determining the wedge orientation and the direction of the entry velocity. The study is based on an analytical solution of the problem, which made it possible to investigate a wide range of the initial parameters including the limit conditions for the existence of the solution of the problem.

The effect of the horizontal component of the entry velocity on the flow parameters has been studied for various initial entry velocities and wedge orientations with respect to the free surface. For small deadrise angles and large entry angles, the self-similar solution gives a pressure distribution along the wedge side with the larger incidence angle which has two maxima and a local minimum between them located at the stagnation point Such behavior of the pressure distribution is similar to that obtained for the water entry of a flat plate [4], and it is caused by the slamming effect near the root of the tip jet. The larger the horizontal component of the entry velocity, the larger the slamming pressure peak and the more visible the effect of the pressure minimum at the stagnation point. At the same time, it is found that the horizontal component of the entry velocity affects neither the location of the pressure peak on the wedge side nor the location of the roots of the tip jets and thus the wetted length of the wedge sides.

For the maximal value of the horizontal component of the entry velocity at which the convergence of the solution can be obtained, the flow characteristics on the wedge side with the smaller incidence angle also become independent of the wedge orientation: the velocity along the free surface intersecting with this wedge side becomes close to the entry velocity; the pressure distribution along the wedge side also becomes the same for different wedge rotations and is monotonic without any pressure increase near the root of the tip jet; the length of the tip jet tends to zero as illustrated in Fig. 5. Besides, the pressure coefficient becomes negative along the whole length of the wedge side, thus providing conditions for ventilation and, consequently, for flow separation from the wedge vertex.

4. REFERENCES

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