ASYMMETRY AND HORIZONTAL VELOCITY DURING WATER IMPACT

Carolyn Judge, Armin Troesch

Department of Naval Architecture and Marine Engineering
University of Michigan, Ann Arbor

High-speed planing boats are widely popular but little is understood about their stability at high speeds. Many of these craft are known to experience unexpected behavior at operational speeds. Research at the University of Michigan intending to understand dynamic instability has used a water impact model to determine the flow over a cross-section of the hull. The impact model takes a two-dimensional section of the hull and predicts how the flow moves over the bottom as the hull section enters the water. By using a low order strip theory and viewing the planing hull as a series of cross-sections at different points of impact (near the bow the hull is just starting to enter the water while near the transom the hull has mostly entered the water), this model determines the transverse flow characteristics over the entire hull. The resulting boundary value problem can be numerically solved using a two-dimensional vortex distribution.

At the last IWWWFB conference, the authors discussed Xu's model for asymmetric impact along with the governing equations and problem formulation for symmetric impact with horizontal velocity [1]. The present work begins with a brief review of Xu's work and the motivation for understanding horizontal velocity during impact. The solutions to the governing equations are then presented as well as results for both symmetric and asymmetric impact with horizontal velocity.

Xu [3] developed a model for asymmetric impact which was built on Vorus's [2] work. Vorus's model allowed for arbitrary sectional contour impact, reordering the variables in the first order in a physically consistent manner. Xu described two types of impact due to asymmetry. Type A flow, Figure 1, was when there was small asymmetry and the water moved out towards the chine on both sides of the keel. Type B flow, Figure 2, occurred when there was large asymmetry and the flow separated from the hull at the keel on one side.

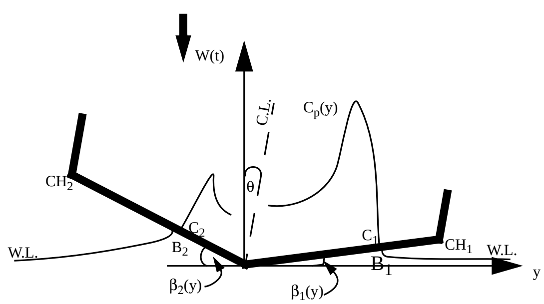

Figure 1: Type A Flow

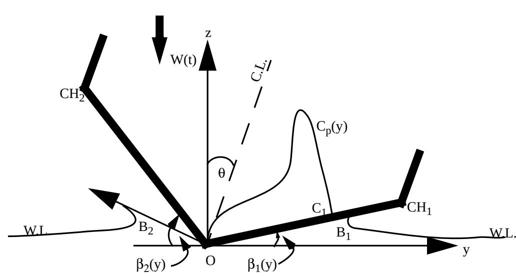

Figure 2: Type B Flow

Xu determined the onset of Type B flow by calculating the initial positions of the zero-pressure points (C_1 and C_2) for different values of θ $\{\theta = \frac{1}{2}(\beta_2 - \beta_1)\}$. As θ increases, C_2 moves closer towards the keel.

When C_2 reaches the keel, the flow becomes Type B. The limiting angle of β_2 versus the corresponding β_1 is plotted in Figure 3 and suggests that the critical value of β_2 is relatively insensitive to β_1.

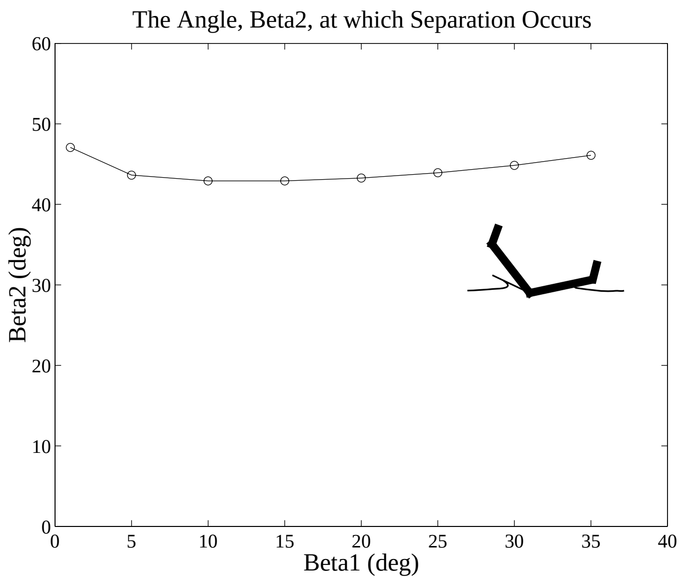

Figure 3: For each β_1 , the value of β_2 which causes Type B flow due to vertical impact

Horizontal velocity, as well as asymmetry, is very important when considering transverse plane motions. In order to predict stability in the transverse plane, horizontal velocity during impact needs to be taken into consideration. Consider a symmetric impact with horizontal velocity, Figure 4. When roll is constrained, this type of impact will produce Type A and Type B flows. Using the solutions to the governing equations shown here, the ratio of horizontal to vertical impact velocity required for Type B flow can be calculated. In addition, the results for an asymmetric impact with horizontal velocity can be determined.

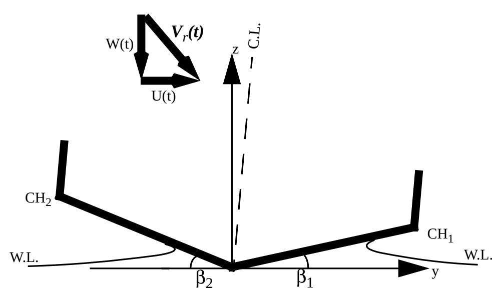

Figure 4: Symmetric Impact with Horizontal Velocity

The model for determining the locations of the zero-pressure points for the initial conditions is defined by the dynamic boundary conditions, the kinematic boundary condition (or kutta conditions), and the displacement continuity condition. The initial conditions are determined for flat-sided contours with constant impact velocity. The dynamic boundary condition is the zero pressure requirement outside the zero-pressure points and gives the velocities of the jet roots.

$$Y_{B1t} = \frac{\tilde{V}_s^2(b_1) - V_n^2(b_1) - V_s^2(b_1)}{2(\tilde{V}_s(b_1) - V_s(b_1))}$$

$$Y_{B2t} = \frac{\tilde{V}_s^2(-b_2) - V_n^2(-b_2) - V_s^2(-b_2)}{2(\tilde{V}_s(-b_2) - V_s(-b_2))}$$

Y_{b1t} and Y_{b2t} are the jet velocities and $\tilde{V}_s$ and V_s are the total (fall plus perturbation) and fall velocities, respectively, in the tangential direction and V_n is the fall velocity in the normal direction. The jet-spray roots and zero-pressure point locations are non dimensionalized by the right-hand side zero-pressure point and are b_1, b_2, 1, and c_2, respectively. The kinematic boundary condition requires zero normal velocity on the hull. This leads to the kutta conditions which must be satisfied at the zero-pressure points, C_1 and C_2, to guarantee velocity continuity.

$$\frac{1}{2\pi}\int_1^{b_1}\frac{\gamma_s(s)}{\chi(s)(s+c_2)(s-1)}ds-\frac{1}{2\pi}\int_{-b_2}^{-c_2}\frac{\gamma_s(s)}{\chi(s)(s+c_2)(s-1)}ds = \frac{1}{\pi}\int_{-c_2}^{1}\frac{\cos\tilde{\beta}(V_n\cos\beta)}{\chi(s)(s+c_2)(s-1)}ds$$

$$\frac{1}{2\pi}\int_1^{b_1}\frac{\gamma_s(s)s}{\chi(s)(s+c_2)(s-1)}ds-\frac{1}{2\pi}\int_{-b_2}^{-c_2}\frac{\gamma_s(s)s}{\chi(s)(s+c_2)(s-1)}ds = \frac{1}{\pi}\int_{-c_2}^{1}\frac{\cos\tilde{\beta}(V_n\cos\beta)s}{\chi(s)(s+c_2)(s-1)}ds+\frac{1}{2\pi}\left[\int_1^{b_1}\gamma(s)ds+\int_{-b_2}^{-c_2}\gamma(s)ds\right]$$

where $\tilde{\beta}(\xi) = \operatorname{atan}(\sin\beta)$, $\chi(\xi) = \frac{\kappa(\xi)}{\sqrt{(\xi+c_2)(1-\xi)}}$ and for constant deadrise, $\kappa(\xi) = \left|\frac{1-\xi}{\xi}\right|^{\frac{\tilde{\beta}_1}{\pi}}\left|\frac{\xi+c_2}{\xi}\right|^{\frac{\tilde{\beta}_2}{\pi}}$.

The displacement continuity condition is a conservation of mass requirement. It requires that the displacement of the cylinder and the free surface contours combine to be a continuous nontrivial function of y to the second order. The displacement continuity condition must be satisfied at the jet-spray root locations, B_1 and B_2.

$$\int_{-c_2^*}^{1}\frac{\cos\tilde{\beta}(V_n^*\cos\beta)}{\chi^*(s)(s+c_2^*)(1-s)}ds = \int_{-c_2^*}^{1}\frac{\cos\tilde{\beta}H_c(s)}{\chi^*(s)(s+c_2^*)(1-s)}ds$$

$$\int_{-c_2^*}^{1}\frac{\cos\tilde{\beta}(V_n^*\cos\beta)}{\chi^*(s)(1-s)}ds-\int_{-c_2^*}^{1}\frac{\cos\tilde{\beta}H_c(s)}{\chi^*(s)(1-s)}ds = \int_{-c_2^*}^{1}\frac{\cos\tilde{\beta}(V_n^*\cos\beta)}{\chi^*(s)(s+c_2^*)}ds-\int_{-c_2^*}^{1}\frac{\cos\tilde{\beta}H_c(s)}{\chi^*(s)(s+c_2^*)}ds$$

where c_2^* is the ratio of the left-hand jet-spray root location to the right-hand jet-spray root location, $\chi^*(\xi)$ is $\chi(\xi)$ with c_2^* plugged in for c_2 and $V_n^* = \int_0^t V_n d\tau$.

The results for a symmetric impact with horizontal velocity are shown in Figure 5. The ratio of horizontal to vertical impact velocity required for Type B flow is greatly dependent on deadrise angle. For low deadrise angles, the horizontal velocity must be much greater than the vertical velocity for separation to occur. However, as the deadrise angle increases the necessary ratio reduces rapidly at first and then begins to flatten out.

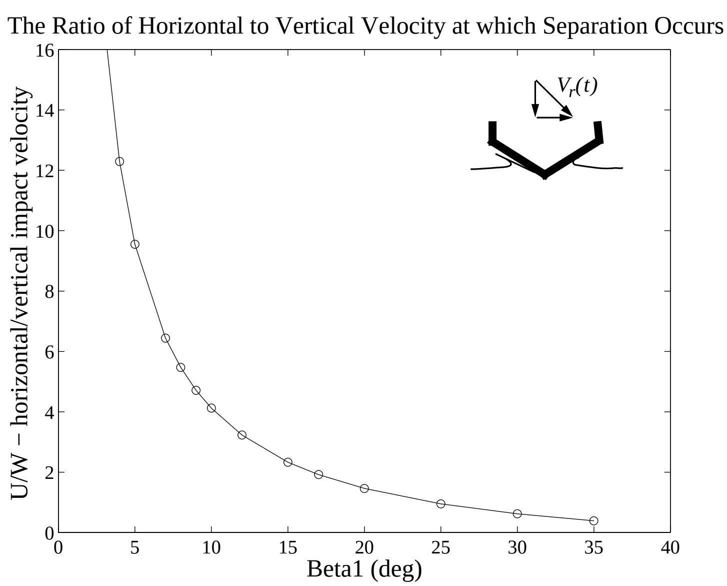

Figure 5: U / W required for Type B flow for symmetric hulls of varying deadrise angles

In understanding transverse stability of planing hulls, the interaction of asymmetry and horizontal velocity is important. For a given ratio of horizontal to vertical velocity, the angle β_2 required for separation can be determined. In Figure 6 the limiting angle of β_2 versus the corresponding β_1 is plotted for different ratios of horizontal to vertical velocity. For each of the different ratios, the dependence of β_2 on β_1 for initiation of Type B flow is small. The increase in horizontal velocity decreases the value of β_2 required for separation. Therefore, the more a planing boat is heeled over, the less horizontal velocity is required to get separation off the keel. Likewise, the larger the horizontal velocity, the smaller θ needs to be for Type B flow.

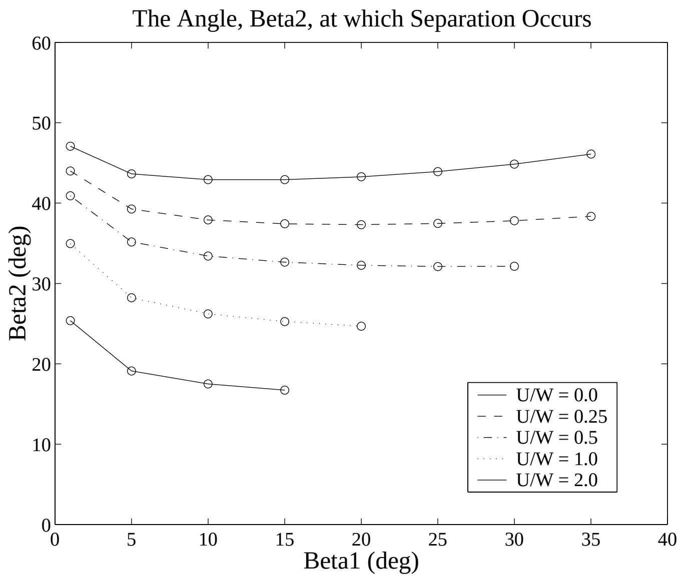

Figure 6: β_2 for Type B flow with corresponding β_1 for varying U / W

The results of an impact model that included both asymmetry and horizontal velocity could be incorporated into a nonlinear motion simulator in order to provide an analytical transverse stability tool. The results would allow for a dynamic righting arm curve to be developed for high speed planing craft. Horizontal velocity is a significant component of transverse planing stability and therefore needs to be addressed. That is the goal of developing the model presented here.

Acknowledgment

This research has been supported by the Department of Defense, Office of Naval Research and the Link Foundation. The authors would also like to thank Lixin Xu for his hypergeometric function software and discussions on his model and problem derivation.

References

[1] Judge, C., Xu, L., and Troesch, A.W. 1999 Water impact model with horizontal velocity. *14th International Workshop on Water Waves and Floating Bodies*. Port Huron, MI

[2] Vorus, W.S. 1996 A flat cylinder theory for vessel impact and steady planing resistance. *Journal of Ship Research*, **40**, 2

[3] Xu, L. 1998 A theory of asymmetrical vessel impact and steady planing. *Ph.D dissertation*, Department of Naval Architecture and Marine Engineering, University of Michigan, Ann Arbor

[4] Xu, L., Troesch, A.W., and Vorus, W.S. 1998 Asymmetric Vessel Impact and Planing Hydrodynamics, *Journal of Ship Research*, **42**, 3