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# The Prediction of Porpoising Inception for Modern Planing Craft

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## *ABSTRACT*

*The purpose of this project was to study porpoising, one of the most common forms of dynamic instability found in planing boats. In descriptive terms, it is a coupled oscillation in pitch and heave that occurs in relatively calm water. These oscillations can be divergent in amplitude, leading to loss of control, injury to occupants or damage to the craft. The mechanics of porpoising have been studied sporadically from theoretical and experimental perspectives for many years. Studies by Perring (1933), Savitsky (1950 through 1976), Day and Haag (1952), Martin (1978), and others have shown that the inception of porpoising is influenced by displacement, center of gravity location, and various hull characteristics such as deadrise and beam. Until now, Day & Haag's thesis provided the only systematic test results concerning the porpoising stability limits of planing craft. Although the Day and Haag model tests were brilliantly executed and thoroughly reported, many users of these data are not aware of the size of the models tested. The average beam of the three tiny prismatic hulls was only 3.8 inches. As a starting point, these tests were re-created using a series of three hard-chined prismatic planing hullforms almost five times larger. The tests included hulls with higher deadrise angles, more typical of craft now employed for high-speed military purposes. Two models of actual full-scale craft, complete with performance-enhancing features including lifting strakes, trim tabs and variable drive angle were tested. These additions were found to have a profound effect upon the conditions at the inception of porpoising. Established planing hull analysis methods were augmented with techniques developed during the course of the study to provide a basis from which to design and outfit high-speed, heavily laden planing hulls with respect to porpoising stability.*

## INTRODUCTION

Planing craft are high-speed marine vehicles that derive most of their support from hydrodynamic pressures acting on their relatively flat, wide bottom surfaces. While the concept of planing was recognized in the late nineteenth century, the first practical application of the concept can be traced to the development of seaplane hulls during the beginning of the twentieth century. As power plants became light and powerful enough to propel a small to medium size boat past its "hump speed," defined by the generated wave patterns, into the planing speed regime, a whole new facet of marine transportation began. While the planing hull introduced the ability to operate at high speeds across the surface of the water, it can easily fall victim to dynamic instabilities, which have manifested themselves in both vertical and transverse responses. In mild cases, these instabilities can be a mere annoyance, but in the most extreme cases, they have led to catastrophic structural failure, to capsizing and to serious personal injury. One of the most common instabilities, known as "porpoising," is a vertical plane, coupled oscillation in pitch and heave which occurs in calm water, and can be divergent in magnitude. Porpoising inception and the craft parameters that influence it are the subjects of the research described in this report.

Planing craft have taken various forms, dependent upon the design speed and intended operational profile. The hull forms addressed in this paper are those designed for high-speed operation under moderate to heavy loading conditions. The typical bottom design for such craft include sharp corners at the chines and transom that ensure distinct water flow separation to minimize hull side flow attachment and to maximize dynamic lift. Without these sharp corners, the flow paths would separates from the hull. Just aft of this line is the stagnation line, the line at which the highest local pressures exist. When the local pressures are integrated over the bottom, the resultant center of dynamic pressure falls roughly around the ¼ chord point of the wetted surface. Remembering that the leading edge of the wetted length is shaped as a "V" when viewed from overhead, the angle at which the stagnation line is swept back is a function of the shape of the leading edge of the wetted surface.

An investigation into the cause of porpoising must analyze the response of the location of the center of pressure on the bottom of the boat as a function of a minute change in trim angle. If an equation could be written to describe this, the first derivative of this function with respect to trim angle would represent the magnitude of the moment produced in response to a minute trim change. The case in which the running trim angle is low yields a stable system because as the boat trims, the keel wetted length changes, but the wetted chine length does not change very much. Therefore, the position of the center of pressure changes only minimally. For the case in which the initial running trim angle is high, a trim change produces large changes in both the keel and chine wetted lengths, yielding a larger movement of the center of pressure. At some critical trim angle, the moment produced by the response of the movement of the center of pressure becomes greater than the moment that initially caused the disturbance. The disturbance can be as great as the boat impacting a wave, or as minute as the basic variations in turbulent fluid flow.

When a single, instantaneous disturbance is applied, the virtual center of forces, similar in concept to the center of gravity, but accounting for all internal masses and all external forces except pressure, moves slightly. The virtual center of forces is an imaginary point about which trimming moments due to propulsive forces (thrust and vertical force), appendage forces (lift and drag), and hull friction forces are summed and the resultant is assumed to act. The response of the center of pressure for the unstable case is seen to move ahead of the virtual center of forces, causing an overcompensation in trim. For simplicity's sake, the center of forces is taken to remain constant after the disturbance, when actually it could move slightly as a function of trim angle. For a stable case, a disturbance results in movement of the center of pressure just sufficient to reach a new state of equilibrium. The disturbance may cause a few oscillations, but the boat quickly settles back to its original attitude.

To date, the porpoising of planing hulls has been analyzed empirically from an external point of view. A study into the actual cause of porpoising is therefore warranted. Remembering that the lift on a planing surface is comprised of two parts, both hydrodynamic and hydrostatic, their interaction is the logical starting point for such an analysis. The long-standing equations used to predict the lift developed by deadrise planing surfaces are theoretically based, with empirical coefficients from test data.

$$C_{L_o} = \tau^{1.1}\left(0.0120 * \lambda^{\frac{1}{2}} + \frac{0.0055 * \lambda^{\frac{5}{2}}}{C_v^{\,2}}\right) \qquad (3)$$

Equation (3), originally developed by Sottorf in 1933, then modified by Savitsky in 1954, predicts the lift coefficient based upon λ, the mean non-dimensional wetted length and the speed coefficient of the planing surface, not to be confused with the symbol λ when used to refer to geometric scale ratio. The two terms inside parentheses represent the two components of lift, the first being hydrodynamic and the second hydrostatic. Logically, as wetted length increases, the lift coefficient increases at a lesser rate due to the decreased aspect ratio. The hydrostatic lift term is based on the submerged volume and decreases as speed increases. Note that unlike modern airfoil theory, which uses the planform surface area to non-dimensionalize the lifting force, planing hull analysis utilizes the beam squared as the non-dimensionalizing parameter, as shown by:

$$C_{L_o} = \frac{L_n}{\frac{1}{2} * \rho * V^2 * b^2} \qquad (4)$$

$C_{Lo}$ is the lift coefficient generated by a flat plate, or a hull with zero deadrise angle. To predict the reduction in lift experienced by a deadrise surface relative to a flat surface, the following, equation has been used, where β is in degrees. $C_{L\beta}$ is also called the required lift coefficient. Note that when $\beta = 0$, $C_{L\beta} = C_{Lo}$.

$$C_{L_{req}} = C_{L\beta} = C_{Lo} - 0.0065 * \beta * C_{Lo}^{\;0.6} \qquad \beta \geq 0 \qquad (5)$$

The analysis was carried forward from the development of the critical porpoising trim angle to determine the individual effects of the hydrodynamic and hydrostatic components of lift. A computer program was developed which would utilize Equation (1) to predict the critical porpoising trim angle at increments across the speed range for a given deadrise and loading for an imaginary deadrise planing surface. The program then determined the theoretical $C_{L\beta}$ and $C_{Lo}$ based on those parameters. An iterative solution method was used which would determine $C_{Lo}$ since it appears in Equation (5) twice. Equation (3) was then implemented, and a similar iterative solution method was set up to determine λ. The mean wetted length now known, the individual components could be determined, and their individual contribution to lift analyzed.

It was found that when the trim angle was constrained across the speed range to the critical porpoising angle, the percentage of lift generated hydrodynamically increased with increasing speed, while the remainder, the hydrostatic lift, decreased as speed increased. This analysis proved fruitful when it was found that the relative percentages of these components remained virtually constant over various combinations of deadrise and displacement from $C_V = 2.5$ to $C_V = 5$. The maximum error between different cases in this range was two percent while $C_\Delta$ was varied from 0.25 to 0.57 and deadrise from 15 to 25 degrees. On the basis of this observation, a curve was generated which appears in Figure 1. It is important to note that as either displacement or deadrise changes, the critical trim angle changes noticeably. However, at the critical angle, the percentage of contribution of each component remained near the curve. Remembering that Equation (1) was developed empirically, as were the previously developed planing equations, a two-percent error could be expected. When trim angle was varied from the critical trim angle, a relatively large change in the lift component ratios was observed. A trim angle increase tends to invoke more hydrodynamic support as less hull length is wetted and angle of attack increases. Conversely, a trim decrease causes more lift to be provided by hydrostatic means as wetted length increases and angle of attack decreases.

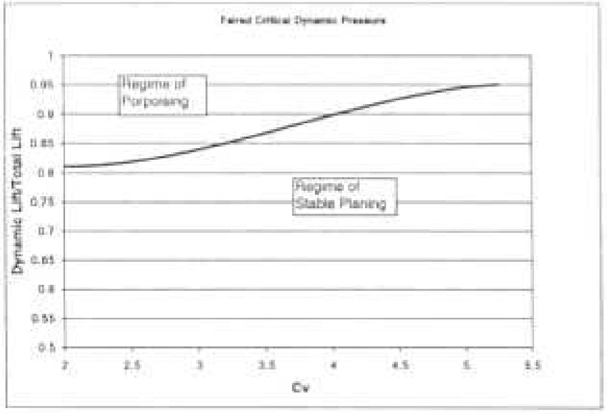

Figure 1 – Percentage of Lift Dynamically Generated at Porpoising Inception

The above mechanism suggests that there exists some natural limit defining how much dynamic lift a hull will generate at a given speed. Once this limit is exceeded, the trim angle will fall, resulting in more support being provided hydrostatically. Porpoising results when a significant overshoot in this lift transfer occurs and the oscillation continues. Assume, for simplicity, that a prismatic planing hull at speed has the shape of a right triangle with the still water as the hypotenuse and the transom and bottom as the mutually perpendicular sides. The hydrodynamic lift component is assumed to act at three-quarters of the mean wetted length forward of the transom, or the one-quarter chord point, an assumption derived from aerodynamic practices. The hydrostatic support for a triangular prism is based solely on the submerged geometry, and is one-third the mean wetted length forward of the transom.

## TESTING PART I

The purpose of the first series of towing tank experiments was to reproduce the tests performed by Day & Haag in 1952, and to ensure that the results were applicable to model boats of a larger scale. The U.S. Naval Academy's Prismatic Planing Series hulls were used. The series consisted of three models. The overall beam was 18 inches, and the chine beam was 17.5 inches for each. Each model had a different deadrise angle, the shallowest being 15 degrees, the middle 20 degrees and the deepest was 25 degrees. Each boat had the same 5 inch high hullside, and an identical chine plan. The overall depth of the 25 degree model was over 2 inches greater than the 15 degree deadrise model giving a much fuller appearance. Figure 2 shows all three models together from astern.

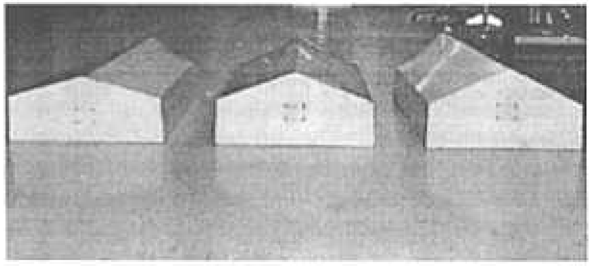

Figure 2 – NAHL Prismatic Planing Series, $\beta = 15, 20$ and 25 degrees

The models were refinished specifically for this testing program. Each was painstakingly epoxy-filled, sanded and painted standard model testing yellow by Mr. William Beaver of the U.S. Naval Academy's Technical Support Division. The primary purpose for this work was to ensure that each model had a fair surface, and that all corners were sharp and free of imperfections which might hinder flow separation, causing inaccurate results at some speeds.

The testing was conducted in the U.S. Naval Academy Hydromechanics Laboratory. The 380' tank offers one of the longest testing lengths for high-speed work available at an undergraduate institution. The tank cross section measures 26' wide and 16' deep. The resulting cross sectional area, $A_{tank}$ must be large enough relative to the maximum sectional area of the model, $A_{model}$, such that the model hydrodynamics are not influenced by the proximity of solid boundaries. For all model testing conducted for this project, ${}^{A_{model}}/_{A_{tank}} < {}^{1}/_{1300}$ which is well below the empirically established criterion of ${}^{1}/_{200}$ considered adequate to prevent blockage and