analysis. The accuracy of the formulae would determine the potential accuracy of the method, and whether the effects of the trim tabs could be accounted for. Development of this complex spreadsheet was begun using Excel 97, because of the ease with which Macro routines could be created and edited using Visual Basic. Excel's very flexible graphing options would also later allow automatic visual representation of the results. As work progressed on the spreadsheet, Excel's true power was recognized, as it had the ability to make iterative calculations to determine the effect of multiple force additions upon an equilibrium system. The spreadsheet tolerated near-circular references, whereby certain parameters were calculated based upon other parameters that they affected. An example would be causing a slight change to the vertical keel depth, which causes changes in the wetted area, lifting coefficients, and drag, which in turn affects the required thrust, and the lifting forces and moments applied by the propulsive thrust. An equilibrium solution must exist, and the spreadsheet iterates until all forces are balanced, and returns a moment error based upon the critical trim angle for porpoising. Provisions were made in the spreadsheet program for inputting the properties of the hull bottom as discussed earlier, and cells were allocated for the input of loading, propulsive and trim tab parameters.

Formulae for the equilibrium planing conditions were taken from Savitsky's 1964 and 1976 papers, and incorporated into the spreadsheet. An analysis of these formulae indicated that there were several unknowns present, for which there could exist many equilibrium solutions. Equation (1) would serve to eliminate one unknown, the trim angle, and make a solution possible. The logic behind the present solution was to use Equation (1) to predict the critical porpoising trim as a function of speed, placing the hull right on the porpoising inception boundary at evenly spaced speed increments across the applicable speed range. The major unknown remaining was the planing depth of the keel at the transom for each speed increment. The solution was setup by referencing the equations for wetted surface area, lifting coefficients, drag and moments to this planing depth. The necessary dependence of the equations result in the spider web-like flow chart at the end of the section, Figure 19, which graphically represents the operation of the spreadsheet. Excel's Goal Seek function was used to obtain a solution for an individual case. It was set up using one column of the spreadsheet to rectify all forces into the vertical plane, and sum them. This resulted in a "vertical force error," which was then used by the Goal Seek function to adjust the planing depth. When engaged, and viewed on a slow enough computer system, it was possible to actually see the vertical force error oscillate about zero, until it finally converged exactly on zero, yielding the equilibrium condition.

Excel's Macro functions were used to create a routine that would execute the Goal Seek function over the entire speed range. A velocity resolution of $C_V$=0.25 was used for the solution. The initial results for a sample configuration were presented in the form of a moment error, because of the initial assumption of the critical running trim angle. If the boat would naturally tend to operate at a higher trim angle than the critical angle, it would be unstable with respect to porpoising, and conversely, if it were a stable condition, it would tend toward a running trim angle lower than the critical trim angle. A logic command was used to convert an unstable condition to the negative moment required to reach stability, and for a stable case, the required moment was set to zero. The spreadsheet automatically re-dimensionalized all parameters for final viewing. Any point on Figure 20A faster than 16.5 ft/sec will result in an unstable system, because a negative moment is required to bring the model below its critical trim angle. The required effective horsepower could also be determined for the operating conditions, and the values generated for the bare hull resistance were generally quite close to those measured in previous, unrelated tests. It is necessary to understand that this solution method can only be used as an actual performance predictor at the critical porpoising point trim angle for a given speed, as these are the only points for which the moment error is zero, and actually represent a real point on the hull's performance envelope.

Knowing the required moment to stabilize the boat would be useful, but not nearly as easy to understand as if the program could be designed to calculate the required trim tab deflections based on their compound effect on stability. To do this, another Macro program was devised which automatically iterated through tab deflections from 0 to 19 degrees, and used logic functions to select the critical points from the moment curve produced by each iteration. This presented some difficulty because of the ability to return to stability while increasing speed at a constant trim tab deflection. This was overcome, and the spreadsheet was designed to automatically assemble a plot of the tab deflection required to achieve a given speed, an example of which is shown in Figure 20B. The correlation is easily seen between the two plots, because the point of initial instability for trim tabs set to zero degrees deflection on Figure 20A is at the same speed as the point plotted on 20B. Hence, Figure 20B is merely a cumulation of the critical points from Figure 20A for each trim tab deflection, with a fifth order trendline automatically faired through the points.

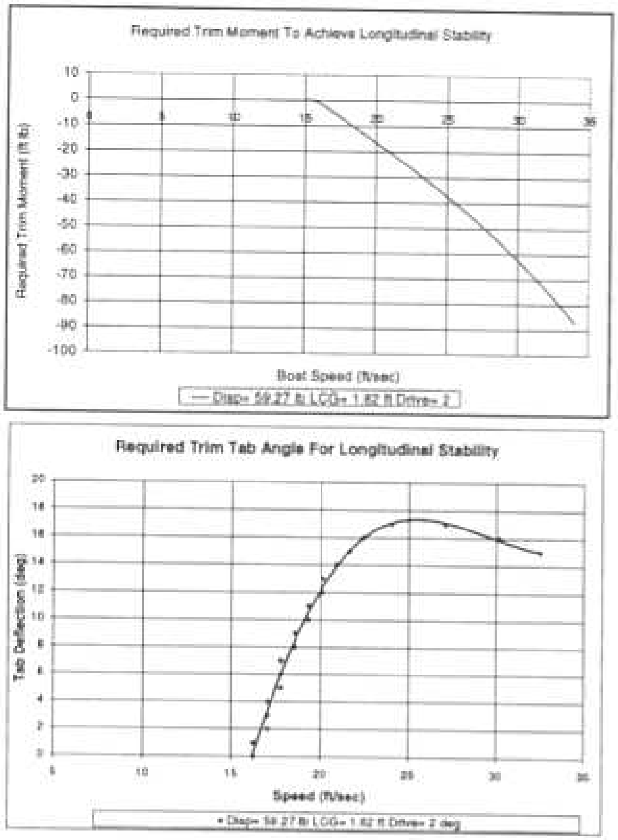

Figure 20A and 20B – Sample Output from Predictive Spreadsheet

## CONCLUSIONS

The present work, testing and analysis has offered a fresh look at the porpoising properties of "V-hulled" planing boats. The Day & Haag porpoising limits were confirmed using significantly larger models. These results provide confirmation that porpoising is a geometric, pressure related phenomenon. While viscous forces influence the magnitude and direction of the hull resistance force, they do not play a major role in the inception of porpoising. An empirical formula was developed to predict the critical porpoising trim angle. In addition, it was determined that at the porpoising inception limit for a given speed, the critical porpoising trim angle was such that the ratio of hydrodynamically derived support to residual hydrostatic support was very closely preserved regardless of loading or deadrise angle.

During the testing of scale hullforms, it was found that, for purposes of porpoising analysis, the amount of lift provided by running strakes could be quantified by determining the model's porpoising limit. As loading increased, the hull naturally rode deeper in the water, invoking lift from different combinations of running strakes, depending on their shape, transverse location and longitudinal termination point. For a given loading, an effective lifting deadrise angle was determined.

The bulk of testing was performed on scale hulls with adjustable trim tabs. It was found that, once an effective deadrise angle had been established for a given load condition based on the conditions at porpoising with no tab deflection, the critical porpoising trim angle could be determined by using the previously determined formula, subtracting the trim tab lift from the hull's weight. This was done on the assumption that in order to maintain equilibrium, any lift generated by the trim tabs reduces the weight the hull must support. The relatively large magnitude of the lifting forces provided by the tabs did in fact have a profound effect upon the critical trim angle.

To quantify the performance of low-aspect ratio trim tabs, a series of tests was run with a trim tab instrumented to measure the lift being generated. The results of these tests were very logical and several very important relationships were established. First, the magnitude of the lift generated by the trim tabs, once the model was fully planing, was independent of trim angle and any pitching motions. Porpoising motions did not affect the generated lift either, according to the time histories generated by the dynamometry. In addition, the lift generated was a function of the square of the speed, yielding a constant lift coefficient for all fully planing speeds. As predicted by Jones' formula, the lift curve was linear, meaning that the amount of lift generated was linearly related to trim tab deflection for deflections up to 18 degrees. Finally, the slope of this lift curve was within two percent of the slope predicted by Jones' formula, when aspect ratio was taken to be the span of the tab at the one-quarter chord point divided by the chord for the low aspect ratio, tapered trim tabs.

The above lessons and formulas were integrated into an automated prediction method based upon Savitsky's techniques. The computerized solution operated by first predicting the critical trim angle based on the boat parameters, then basing all calculations on this value and an estimate of keel planing depth. The computer then performs iterations by varying the planing depth, calculating forces and moments, and readjusting the trim angle to match the new conditions. Finally, an equilibrium solution is converged upon. Moments were summed to determine whether or not the boat would tend to operate at a higher or lower trim angle than the assumed critical angle, and a determination of stability made at intervals across the planing speed spectrum. The program was set up to collect the critical points for each trim tab deflection, then present them as a plot of required trim tab angle to achieve stability.

The method presents the designer of high-speed offshore planing boats the ability to assess porpoising stability quickly, and determine whether or not he has chosen large enough trim tabs to suit his hull and center of gravity location. The one shortcoming of this method as developed thus far is that while provision was made for selecting the propulsive force location and angle of application, the effects of actual non-axial propeller forces are not addressed. Predictions were reasonably accurate for towed models, but it cannot be used for a full scale hull until a method is added to it to predict the vertical plane propeller forces generated by various combinations of pitch, rake, and blade and hub design. These forces can be very large for surface piercing propellers. At present there is no known source of such force data in open literature. Preparation is underway to conduct radio-controlled free running stability tests with the $\lambda=7$ scale hullform. This model is fitted with the same trim tabs used in the towing tank testing, and their deflection is adjustable via radio-control. In addition, the drive trim angle and propeller shaft height of its two outboard engines can be set prior to each run. Electronic radio-telemetry will be used to record the model speed and running trim angle. The effects on propeller forces will be analyzed, and the capability for conducting research at much higher speeds than in the towing tank will be available.

With the increasing importance of littoral warfare to the U.S. Navy, high-speed patrol/interdiction craft will become more numerous and more capable. Performance prediction in the design stage will become more necessary for both performance enhancement and affordability. While the traditionally empirical, prototype, test-and-fix approach will continue to be used by the recreational boat and offshore racing boat design communities, a validated, scientifically based prediction tool will prove to be more cost-effective and reliable for the military and commercial high speed craft designs. As sophisticated computation capabilities continue to become available to smaller organizations and individuals, such a tool, when fully validated through full-scale correlation, will hopefully become as widely used and respected as the Day & Haag predictor.

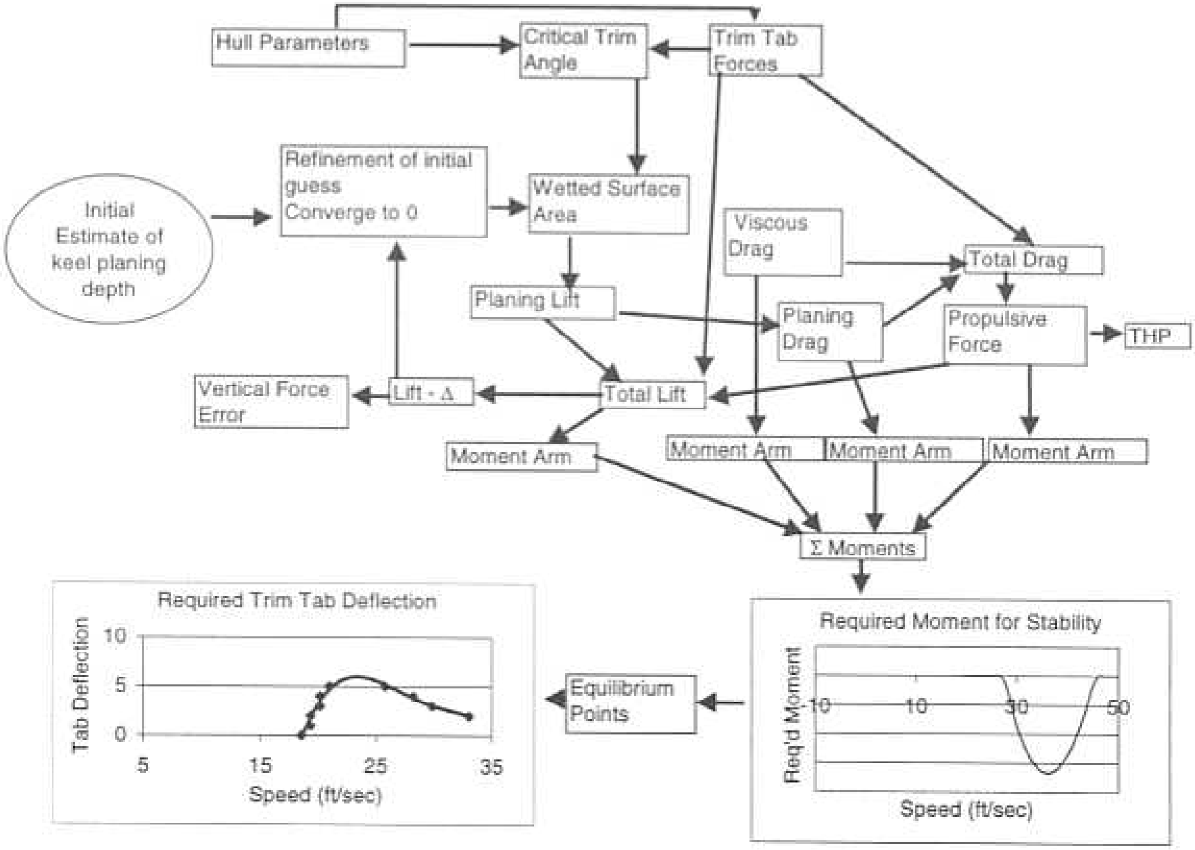

Figure 19 – Spreadsheet Solution Method Flowchart