Experiment Design to Obtain Unsteady Force and Moment Data on a Yawing Submarine Model - Sept. 2011

Problem: This problem is to determine (1) the desired values of fixed parameters and (2) the required sensitivity and uncertainties of the sensors or instruments of other measured variables for low uncertainty measurement of the unsteady side force and yawing moment on a DARPA 2 submarine model in the VPI&SU Stability Wind Tunnel.

Background: We can use the Dynamic-Plunge-Pitch-Roll (DyPPiR) Model Mount System to pitch a large sting-mounted model rapidly up, from 0 degrees to 30 degrees within 0.30 seconds. The DyPPiR is described at http://www.aoe.vt.edu/research/facilities/dyppir. Videos showing the motion of submarine, racecar, and aircraft models undergoing dynamic unsteady motions are available from this site for viewing. A carbon fiber and foam composite material submarine model that is L = 88 inches long and weighs 8 pounds has been constructed at Virginia Tech. Three strain gage load cells that measure only transferred side and normal forces (not moments) are used to connect the sting to the inside of the submarine model at these 3 locations. The strain gages are mounted on the loadcell flexures. These load cells have a linear relationship between the output voltage and the input load force and are not sensitive to the axial force. As shown in Figure 1, two loadcells (labeled “b” for “beta” and “g” for “gamma”) are mounted 5.75 inches apart in the front of the model at the same axial location and the third loadcell (labeled “d” for “delta”) is mounted in the stern of the model. This three loadcell design is used to make the model, sting, and loadcell system more stiff to motion than if only one loadcell were used. Miniature triaxial accelerometers, which measure all 3 components of acceleration, are located on the model close to the active flexures of the loadcells; for our design, we will assume that the loadcell flexures and the accelerometers are at the same locations. Note that these accelerometers measure components of the gravitational acceleration. Here we are concerned only with the component of the acceleration that is normal to the submarine axis.

Data Reduction Equations for the Side Force and Yawing Moment

When simulating a submarine yawing maneuver, the wind tunnel model is oriented with its sail on the side and yawing motions are in a vertical plane. When the model is at zero angle of attack ∀ to the approach flow, the y axis is in the vertical direction. The equation below is used to determine the aerodynamic side force F_y on the model:

$$m_{\text{mod}}\left(a_{y(cg)} - g\cdot\cos\alpha\right) = F_y - F_\beta - F_\gamma - F_\delta \qquad (1)$$

where F_β, F_γ, and F_δ are the forces measured by loadcells β, γ, and δ respectively, m_{mod} is the mass of the model and the loadcells to the flexures, and $a_{y(cg)}$ is the measured acceleration in the y direction at the center of gravity. Here g is the gravitational acceleration and ∀ is the angle that the model axis makes with the horizontal direction.

The acceleration at the center of gravity $a_{y(cg)}$ at any time can be determined from simultaneous 3 triaxial accelerometer measurements, assuming that the model is rigid. By knowing the point of rotation of the model, one can compute the angular acceleration of the model from the acceleration measurements and then $a_{y(cg)}$. Note that when the model is at rest in the wind tunnel, each axis of an accelerometer just measures the component of gravitational acceleration along that axis. Thus, in equation (1), when the model is not moving, as in a steady wind tunnel test, the left hand side of the equation is zero.

The aerodynamic yawing moment can be determined using the equation:

$$I_{rot}\dot{\omega} = M_{aero} - F_\beta \bar{x}_\beta - F_\gamma \bar{x}_\gamma - F_\delta \bar{x}_\delta \qquad (2)$$

where I_{rot} is the mass moment of inertia of the model about the point of rotation, $\dot{\omega}$ is the angular acceleration, M_{aero} is the aerodynamic moment produced by the flow about the point of rotation, and $\bar{x}_\beta, \bar{x}_\gamma$, and $\bar{x}_\delta$ are the distances between the flexure centers of loadcells β, γ, and δ and the point of rotation. The distances between the flexure centers of loadcells β, γ, and δ and the point of rotation, $\bar{x}_\beta, \bar{x}_\gamma$, and $\bar{x}_\delta$ should be positive for the defined body fixed coordinate system.

The mass of the model and the loadcells to the flexures can be determined in the following way. First, the model and sting are oriented vertically so that the weight of the model does not cause any side load on the loadcells. Then the electronics for each loadcell is zeroed or nulled so that there is no voltage output. Next, the sting and model are positioned horizontally in the wind tunnel and the output voltage from each loadcell is recorded. The sum of the measured weights from each loadcell is the weight of the entire model and hardware to the instrumented midpoint of each flexure:

$$Weight = m_{\text{mod}} g = F_\beta + F_\gamma + F_\delta \qquad (3)$$

Solving a static moment equation about the point of rotation can be used to determine the location of the center of gravity:

$$(Weight)\bar{x}_{cg} = F_\beta \bar{x}_\beta + F_\gamma \bar{x}_\gamma + F_\delta \bar{x}_\delta \qquad (4)$$

Once the weight and center of gravity of the model have been determined, it is usual to adjust the loadcell electronics voltage output to zero when the model is horizontal in the wind tunnel. Thus, the weight of the model does not contribute to the loadcell voltage output. For steady wind tunnel tests (no moving model), equation (1) reduces to:

$$F_z = F_\beta + F_\gamma + F_\delta \qquad (5)$$

and equation (2) reduces to:

$$M_{aero} = F_\beta \bar{x}_\beta + F_\gamma \bar{x}_\gamma + F_\delta \bar{x}_\delta \qquad (6)$$

In the case of model motion but no flow, these “tare“ runs have no M_{aero} and can be used to solve equation (2) for the mass moment of inertia I_{rot}. The angular acceleration about the point of rotation $\dot{\omega}$ in equation (2) can be determined from the accelerometer measurements. Once the mass moment of inertia is known, equation (2) can be used for a moving model and flow to calculate the M_{aero}.

Assignments:

(1) For unsteady tests to obtain the lowest uncertainty side force and yawing moment measurements, what would be the ideal mass and moment of inertia of the model?

(2) Given the attached steady flow data (Figures 2a and 2b) for the side force $C_y = F_y/qL^2$ and yawing moment $C_n = M_{aero}/qL^3$ coefficients on a fully appended DARPA 2 submarine model. Here "q" is the undisturbed upstream free-stream dynamic pressure. Note that these moment data are about the "moment reference point" shown in Figure 1. Determine the load range of each of the β, γ, and δ loadcells, if we desire an 8 volt output for angle of sideslip of $\alpha = 26^o$ with a 100fps flow at 77 ^{o}F in Blacksburg (elevation 2100 feet). Assume that $F_\beta = F_\gamma$.

(3) Using the "Method of Equal Effects", determine the required experimental uncertainty of each loadcell measurement and each value of the moment arms for <u>steady</u> measurements, when the desired uncertainty for the side force coefficient C_y and the yawing moment coefficient C_n is +/-0.0003.

(4) Using the "Method of Equal Effects", determine the required experimental uncertainty of each loadcell measurement, the required experimental uncertainty of each value of the moment arms, and the required experimental uncertainty of each accelerometer measurement for <u>constant angular velocity motions about the z axis</u>, when the desired uncertainty for the side force coefficient C_y and the yawing moment coefficient C_n is +/-0.0003. Do you need to know the moment of inertia about the point of rotation and its uncertainty before the "Method of Equal Effects" can be used?

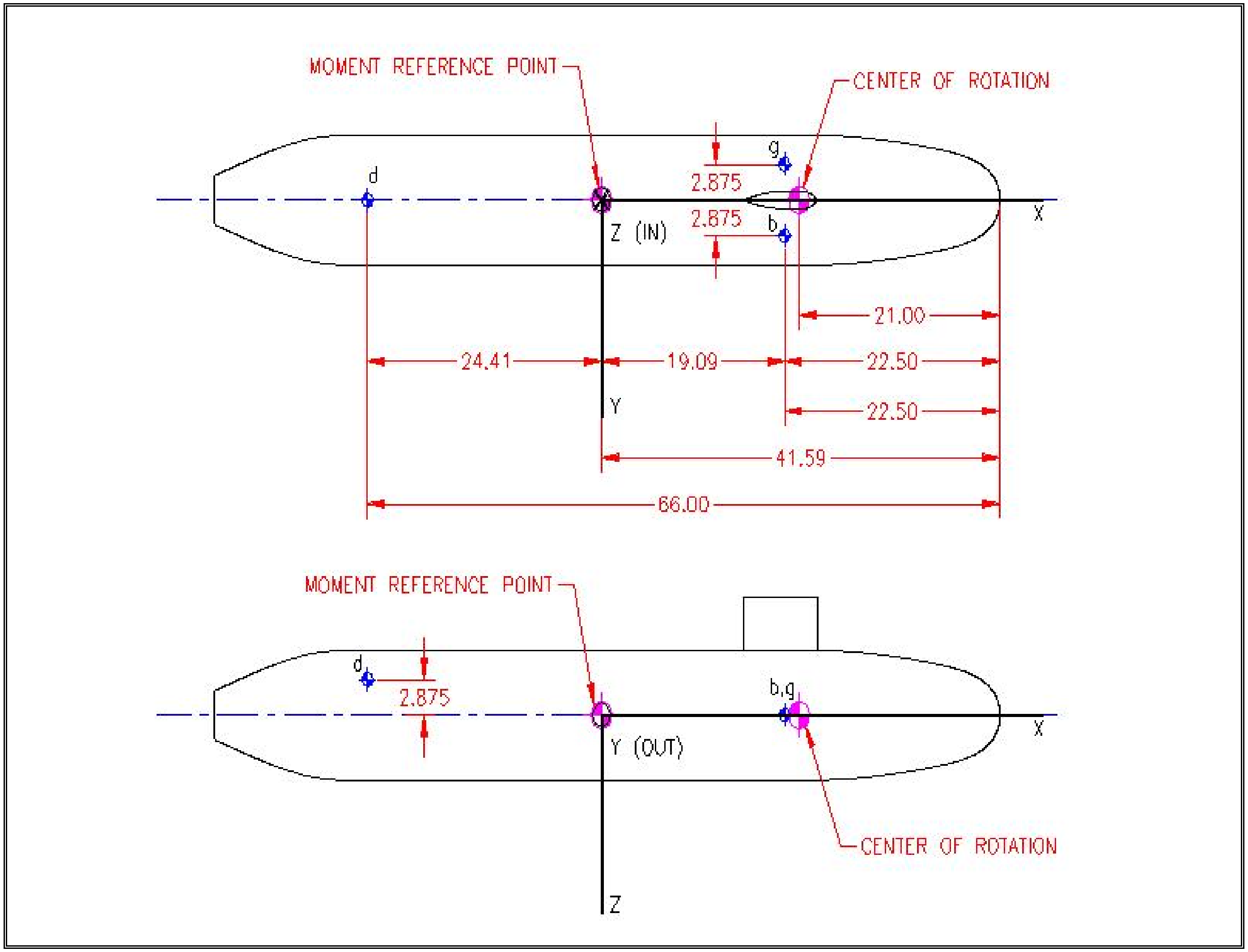

Figure 1: Side and Top view of Virginia Tech's DARPA2L Model

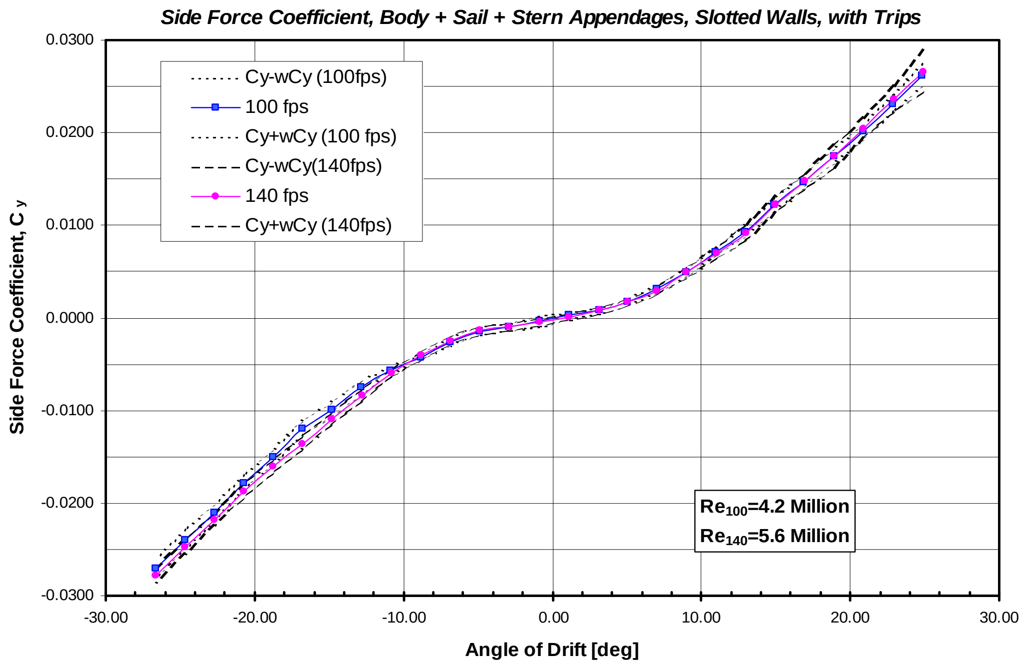

Figure 2a: Steady Side Force Coefficient, Full Body Configuration with Sail on Side

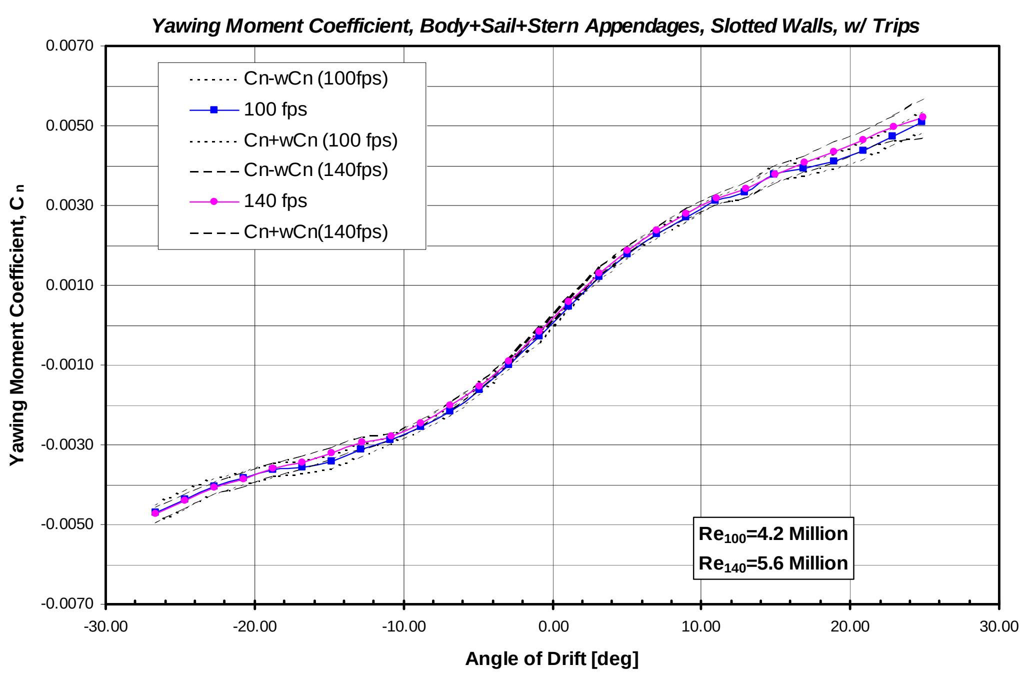

Figure 2b: Steady Yawing Moment Coefficient, Full Body Configuration with Sail on Side