Department of Ocean Engineering
Massachusetts Institute of Technology

13.021 Marine Hydrodynamics I, Fall 2003

Laboratory Assignment A

Flow Past a 3-D Hydrofoil

To be performed at the Marine Hydrodynamics Laboratory Variable Pressure Water Tunnel, Room 3-269, at the times you have signed up for. Reports are to be done ***individually*** *and are due by Friday, December 5, 2003.*

Introduction This lab will characterize the performance of a 3-D hydrofoil including the lift and drag of the foils vs. angle of attack. A team trying to set the world speed record for a sailboat provided the foil being tested. They need to achieve a speed in excess of 45 knots. The sailboat uses four hydrofoils to lift the boat out of the water and thereby reduces its drag. The limiting factor for the speed that these hydrofoils can achieve is set by the cavitation limit of the hydrofoil. Your job is to measure the general lift and drag performance of the foil and determine the cavitation inception performance at a particular lift coefficient.

Specifically you will:

- Determine the Lift and drag of the foil as a function of angle of attack.
- Measure the total pressure profile across the wake of the foil at z/S =0.58 (foil mid-span) with foil set to Angle of attack of 5 degrees
- Observe the cavitation inception point of the foil when set to an Angle of attack of 5 degrees

The hydrofoil is mounted to a rudder dynamometer that is instrumented to measure lift and drag. The lift and drag data collected can be reduced to standard lift coefficient and drag coefficient plots vs. angle of attack.

Also velocity data around a closed contour at z/S=0.58 will be provided to you. By combining the sectional velocity and pressure data you will compute the sectional forces at z/S=0.5 and AOA=5 degrees using the following methods:

- Momentum integration
- Energy flux method to determine drag
- Circulation and Kutta-Joukowski (Lift)

Lastly, the cavitation number at inception for the foil at a particular angle of attack can be determined from observing the tunnel pressure at which cavitation is first observed on the foil.

Pre-Lab Preparations The following pre-lab preparations are to be done by the group **before** arriving at the lab, and a copy your write-up of the pre-lab assignment must be passed in upon arrival at the lab. The questions posed in the pre-lab will help prepare you for the lab so you will better understand the measurements you will make during the 2-hour lab session. In other words time spent on the pre-lab will save you a lot of extra effort both during and after the lab.

1) Read through the entire lab *carefully* so you have a clear idea of what needs to be accomplished. Prepare an action plan including data sheets you think you may need and expected results for each measurement portion of the lab. Include a copy of these preparatory sheets and graphs with your pre-lab write-up.

2) The hydrofoil being tested has a NACA 2410 section profile. The 2-D sectional force data for this foil is provided in Figure 1. From this data determine the sectional lift and drag given the following foil information:
    - Density of water =997kg/m^3
    - Angle of attack= 5 degrees
    - Flow speed 5 m/s
    - Section chord length: 84mm

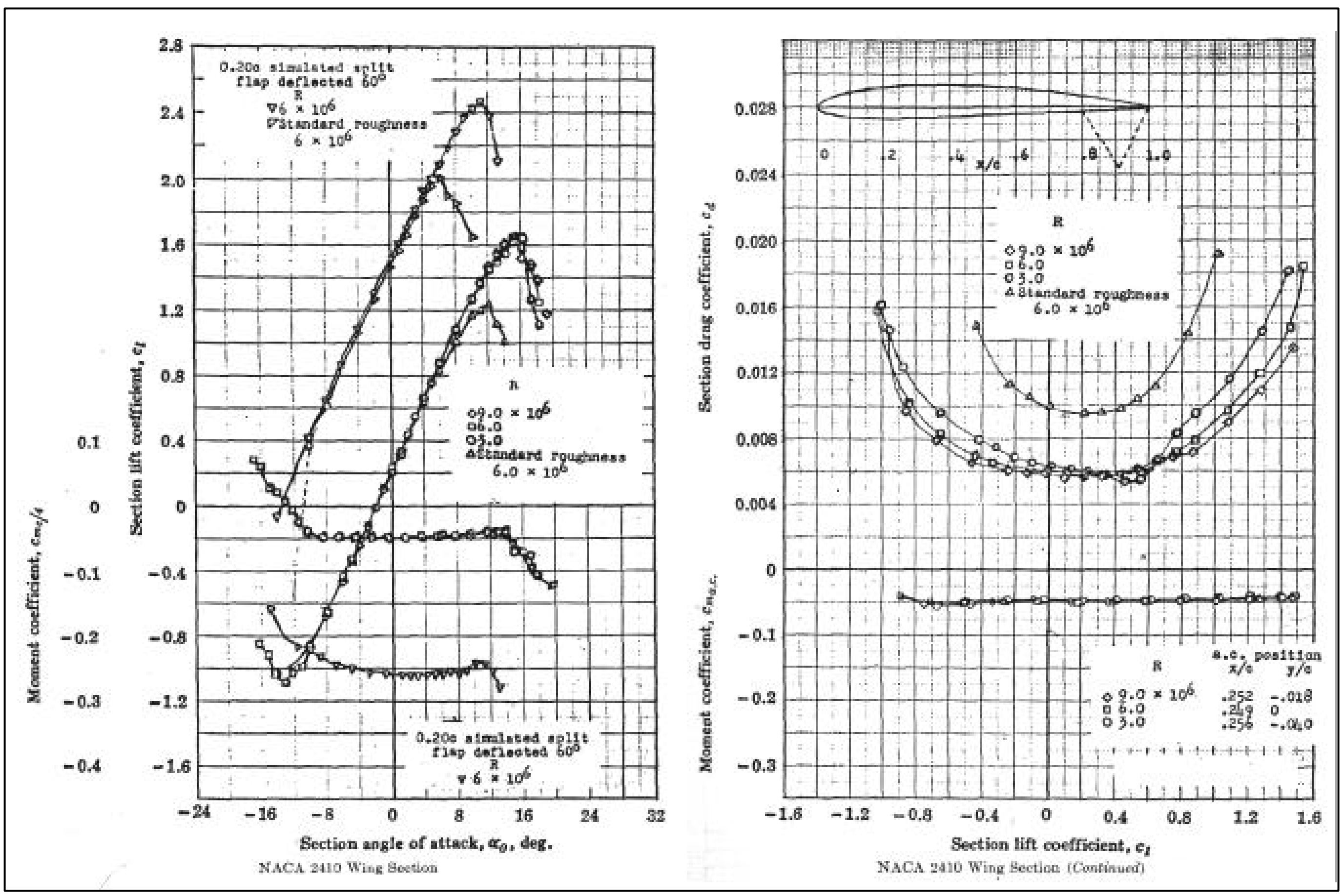

Figure 1: NACA 2410 sectional performance data
(From Abbot and Von Donnoff , Theory of Wing Sections)

3) Figure 2 below shows a contour in the fluid around a foil where the pressure and velocity around the foil have been measured or can be inferred from Bernoulli's relation. For this example assume Bernoulli's equation is valid everywhere.
   i. Determine the pressure and velocities everywhere around the contour.
   ii. Perform a momentum integration to determine the sectional lift and drag for the foil in terms of U_∞. Also compute the sectional lift and drag coefficient assuming that the body has a chord length $\ell = 1.0$.
   iii. Compute the circulation around the contour and determine the lift using Kutta-Joukowski's law.

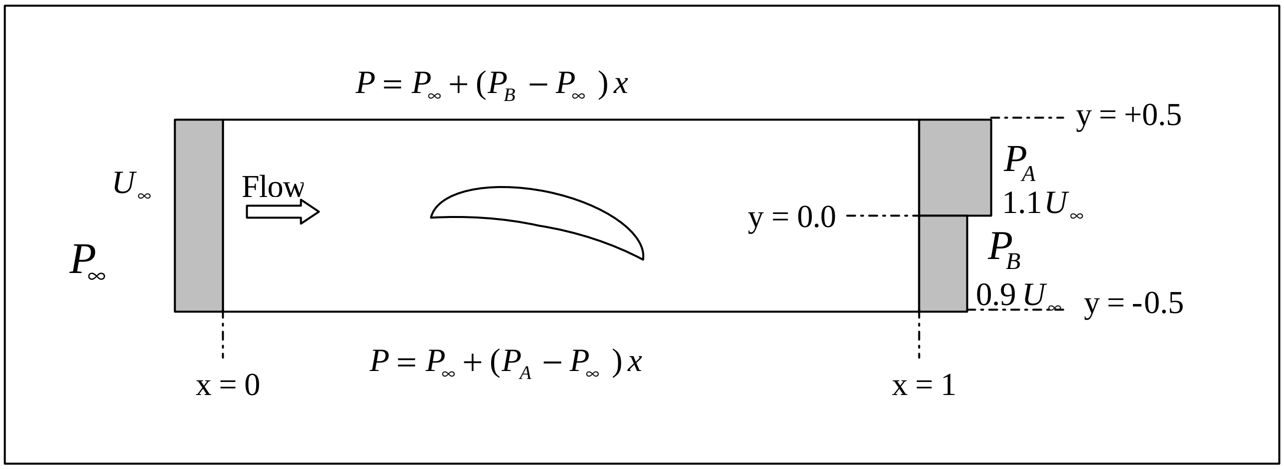

Figure 2: Contour data for pre-lab (3).

4) What parameters are needed to measure the cavitation number for a 3-D hydrofoil? With the foil at positive angle of attack where on the foil do you expect to first observe cavitation? Explain.

Laboratory Assignment

Description of Apparatus

Figure 3 is a schematic of the foil as mounted in the tunnel test section. Relevant dimensions for the foil are provided in Figure 3.The 3D hydrofoil has been mounted to a rudder dynamometer that is inserted into the water tunnel. The rudder dynamometer force gauges measure lift drag and foil moment using strain gauge element type forces gauges. The signals are fed into a strain gauge amplifier then to a computer data acquisition system where the force data is collected in electronic form. The forces gauges have been calibrated by applying known weights to each gauge. The calibration data will be provided to convert the measured output of the force gauge (volts) into force units.

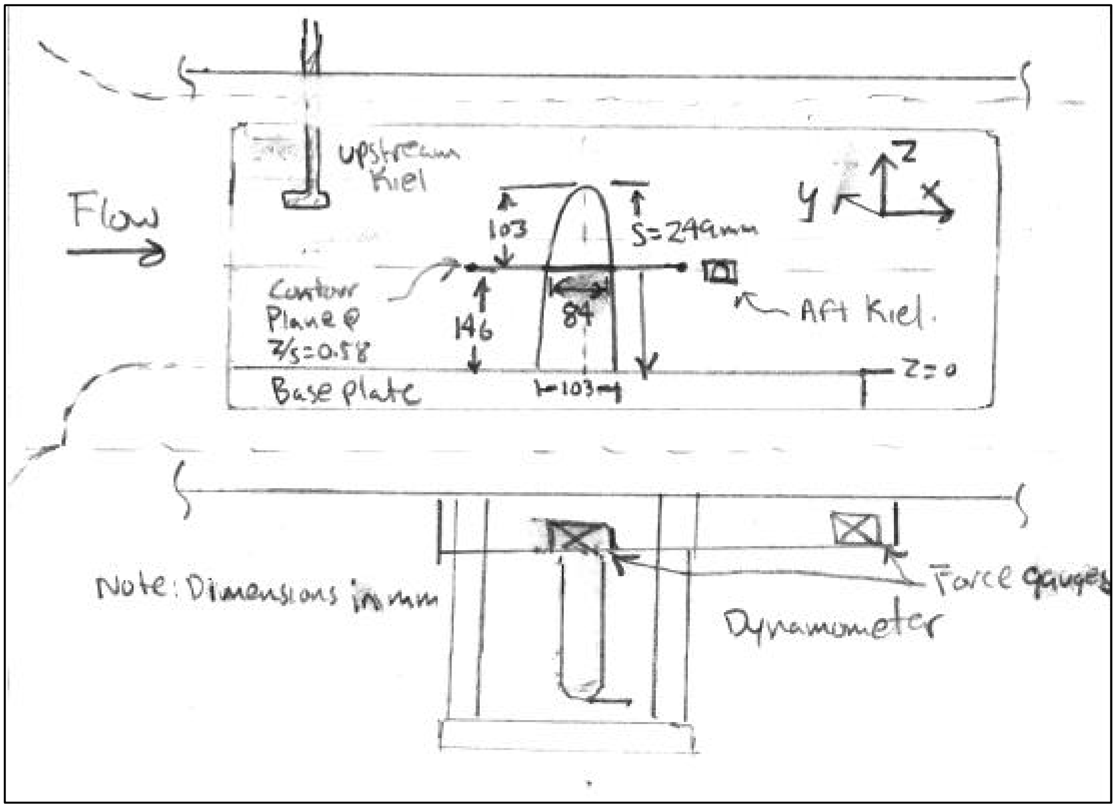

Figure 3: Schematic of Foil setup in propeller test section

As well a pair of Kiel probes (which measure total pressure) have been mounted in the water tunnel. The first is fixed in a position upstream of the foil and is the reference total pressure. Assume that the inflow velocity and total pressure are uniform upstream of the foil. The second Kiel probe is mounted aft of the foil and at the foil span z/S=0.58. This height is also the same height that the velocity contour data was collected and these data will be used to determine sectional forces at this span location. This aft Kiel probe can be traversed across the tunnel to determine the total pressure profile aft in the wake of the foil at this section. Thus by measuring the difference in the forward Kiel probe and the aft Kiel probe one can measure the change in total pressure from upstream to downstream. Remember if there were no losses we would measure no change in this pressure. Thus this measurement is a direct measure of the loss due to the viscous effects on the foil section.

We can also vary the ambient pressure in the tunnel to induce cavitation effects on the foil. The ambient pressure in the tunnel is recorded using a mercury manometer attached to the tunnel, which measure ambient pressure at the test section centerline.

Test Procedure

Water tunnel staff will provide instructions for operating the Water Tunnel and associated data collection equipment. Follow their instructions.

The lab personnel will show you how to start the tunnel and bring up the flow speed in the tunnel to the test speed of 5 m/s. By keeping the RPM of the drive impeller fixed will ensure that the tunnel velocity is held at 5 m/s.

The data acquisition system will record the average force signals by sampling 10000 samples over 10 seconds and averaging the result. These averages will be output to the screen and can be saved in a file. One person in your group should be appointed to run the data acquisition software.

Forces vs. Angle of Attack

Lab personnel will show someone in the group how to manually vary the angle of attack of the foil on the dynamometer. There will also be a gauge on the shaft of the foil to determine the angle of attack (AOA) for the foil. Starting at AOA = 0 deg. Collect force data at various AOA's (both positive and negative). Be sure to vary the angle enough to observe stall (the point where lift decreases for increased AOA). You'll want 15 to 20 points of AOA. (Hint: look at figure 1 to estimate the AOA range you might need to cover).

Sectional Data at AOA=5 deg z/S=0.58

Set the AOA to +5 degrees and set the tunnel speed to 5 m/s. Lab personnel will show someone in your group how to move the traverse(and aft Kiel probe) to various cross-stream (Y) positions. Collect Kiel probe pressure data at various y-location across the wake at z/S=0.58 using the data acquisition software (one channel is set to measure Kiel pressure). Be sure to read of the Y-position for each pressure point collected and collect data from y=+50mm to y=-50mm (note y=0 is the foil axis). Collect 20 or so points across the wake.

Cavitation observations

With the tunnel speed set to 5 m/s and the AOA = +5 degrees, lower the tunnel pressure as instructed by lab personnel. Watch for cavitiation on the foil as the tunnel pressure lowers. When cavitation first appears record the tunnel ambient pressure on the tunnel mercury manometer. Also observe (and sketch) where you first see cavitation appear on the foil.

<u>Additional data provided</u>
Because of safety issues of using the Laser Doppler Velocimetry system, velocity data collected using this system around the foil section z/S=0.58 will be provided for you. The tunnel speed was set to 5 m/s for this data and the aft cut of this contour is at the same stream wise (X) location as the aft Kiel probe. (Thus you now have both velocity and pressure across the wake.

Post Lab Analysis (To Be Done Individually and Due December 5, 2003)

In your lab report, the final results you present must be in non-dimensional form. Tables and graphical plots should be used.

The lab report should include your pre-lab preparation, the specific procedure of your groups experiment, data analysis and discussion of results. Also a one-page report on the other experiment you observed should be attached to the end.

The following results should be analyzed and discussed in you lab report:

1) Calculations and graphs of lift coefficient and drag coefficient vs. AOF presented in a way similar to Figure 1.
2) Calculate the sectional forces at the z/S=0.58 location using the contour data provided and the pressure data collected with the following methods:
   i. Direct momentum integration of both lift and drag. (Note you will need to determine the pressure on the contour in regions where it has not been directly measured). What relationship can you invoke to estimate this pressure? Justify.
   ii. Compute the circulation around the contour and apply Kutta-Joukowski's force law to obtain the [lift] [drag] [lift and drag].
   iii. Using the total pressure data across the wake, use the energy flux method to determine the drag (or loss) of the foil section. In the energy flux method, the change of internal energy of the fluid passing through the contour $(\Delta E = -\Delta P_{tot})$ is related to the work done by the drag force D: $D\,U_\infty = \int \Delta E\, u(y)\, dy$. Therefore the drag force is: $D = \dfrac{-\int \Delta P_{tot}\, u(y)\, dy}{U_\infty}$.
   U_∞ is the free stream velocity, y is the cross-stream direction of the Kiel probe wake cut, ΔP_{tot} is the recorded total pressure change between the upstream Kiel probe and the downstream Kiel probe at a particular y location.
   iv. Discuss any differences in determining the forces between the momentum integration results and the other methods.
3) Compute the cavitation number for the foil at AOA=5 deg and present this result. Discuss your cavitation observation on the foil including sketches where appropriate. If this foil operates on the sailboat at a depth of 1 meter, estimate how fast this foil can go at this AOA before it cavitates.

Note that the numerical integration performed in (2) can be done using simple trapezoidal rule techniques.

Besides the specific data analysis and discussions requested above you are encouraged to discuss other relevant hydrodynamics that you have learned form the experiment. The lab report should be written in a professional manner. It needs to be both complete and concise.