# Low Speed Flow Past a High Aspect Ratio Swept Wing

Academic Supervisor: Prof. Oliver Buxton

2024/25

## 1 Introduction

This lab assesses your understanding of the application of panel methods to predicting the flow over a finite aspect ratio swept wing. You will compare the output of a panel code to experimental data collected from a wing model placed within a wind tunnel. The model is a swept uniformly tapered half wing with straight leading and trailing edges. Its dimensions are as follows:

| **Dimension** | **Value** |
|---|---:|
| Semi-span $s$ | 600 mm |
| Root chord $c_0$ | 225 mm |
| Tip chord $c(s)$ | 95 mm |
| Leading edge sweep $\Lambda_{LE}$ | 36.9° |
| Linear twist from root to tip | -1.5° |
| Constant aerofoil cross section | 17% thick GA(W)1[3] |

Each tapped section is connected to one channel of the multi-tube manometers. Each manometer is also connected to the two tappings on the pitot tube upstream of the tube. The density of the fluid in each manometer is $866 \mathrm{kg\,m^{-3}}$.

This lab will be assessed orally 1.5 hours after the practical session finishes. Prior to the lab you are required to download and unzip the archived files from the lab's Blackboard page. These files include

- Panel source code and executable files (`panel_code/`)
- Specific data output from the panel code (`output_data/`)
- An Excel spreadsheet into which you are expected to enter your experimentally acquired data during the lab (`data.xlsx`)
- A MATLAB script to perform the required data processing (`data_processing.m`)

You will also be required to perform some preliminary work, documented in §2. Please read this lab handout carefully and in full before undertaking any of the preliminary work.

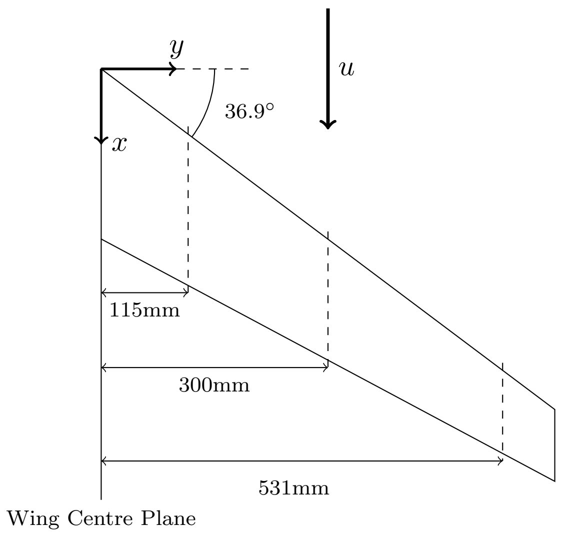


**Figure 1:** The wing has 3 pressure tapped sections at $y = 115$ (red), 300 (yellow) and 531 (green)

# 2 Preliminary Work

Before the timetabled lab session you are required to perform some preliminary work. This preliminary work is **compulsory** for each student and will form part of the oral assessment. Failure to do it will affect your final mark.

- You are required to run the panel code with various discretisations for discussion in the oral assessment. **Please read §4 where this preliminary work will be discussed in more detail.**
- Calculate the wind speed, and the reading on the manometer in mm of manometer liquid, required to give a Reynolds number of $4 \times 10^5$ based on the root chord
- In the experiment the temperature of the wind tunnel and atmospheric pressure will be different to the values used for the previous calculation, so the wind speed will need to be recalculated once atmospheric conditions are known. These values can be directly added to the spreadsheet `data.xlsx` which you should download to your laptop and bring to the lab.
- Consult the relevant sections in the references in the bibliography for discussion in the oral assessment.

| Station | Green | Yellow | Red |
|---|---|---|---|
| $x/c$ | Tapping | Tapping | Tapping |
| Lower Surface<br>0.90 | 1 | 1 | 1 |
| 0.80 | 2 | 2 | 2 |
| 0.70 | - | 3 | 3 |
| 0.60 | 3 | 4 | 4 |
| 0.50 | - | 5 | - |
| 0.40 | - | - | - |
| 0.30 | 4 | 6 | 5 |
| 0.20 | - | 7 | 6 |
| 0.15 | 5 | 8 | 7 |
| 0.10 | 6 | 9 | 8 |
| 0.05 | 7 | 10 | 9 |
| 0.025 | - | 11 | 10 |
| 0.0125 | - | - | 11 |
| 0.00 | 8 | 12 | 12 |
| Upper Surface<br>0.0125 | 9 | - | 13 |
| 0.025 | - | 13 | 14 |
| 0.05 | 10 | 14 | 15 |
| 0.10 | 11 | 15 | 16 |
| 0.15 | 12 | 16 | 17 |
| 0.20 | - | 17 | 18 |
| 0.30 | 13 | 18 | 19 |
| 0.40 | - | - | - |
| 0.50 | - | 19 | - |
| 0.60 | 14 | 20 | 20 |
| 0.70 | - | 21 | 21 |
| 0.80 | 15 | 22 | 22 |
| 0.90 | - | 23 | 23 |

**Table 1:** Table of the chord-wise positions of the pressure tappings at each of the three stations. The pressure tappings will be split over two multitube manometers, both of which will be connected to an upstream pitot tube

# 3 Experimental Procedure

N.B. each individual student is awarded a mark for their carry out of the lab during the practical work. All data should be recorded in the appropriate place in the `data.xlsx` spreadsheet, which should have been downloaded to your laptop and brought to the lab session.

### 3.1 Detailed Pressure Readings

1. Set the wing at a nominal incidence of 0°at the root to the free stream
2. Set the wind tunnel speed according to the value calculated in §2
3. Record the manometer readings
4. Repeat the pressure measurements (steps 1 to 3) for two other incidences, to be assigned to your group by the demonstrator at the start of the laboratory
5. Note that the angle of incidence is changed using a stepper motor. You are advised to change the angle of attack gradually in order to avoid motor stall

### 3.2 Stalling

1. Set the wing back to a nominal incidence of 0°
2. With the wind tunnel running at the same speed as used in §3.1 gradually begin to increase the incidence
3. Using both the attached wool tufts and the pressure distributions from the manometer record the incidence at which each of the 3 sections stall
4. At the stall angles make sketches of the qualitative shape of the pressure distribution for each of the sections, detailed measurements are not required

## 4 Objectives of the Data Processing Methodologies

During the course of the experiment you will record pressure distributions on the wing at zero incidence and two other incidence angles, $\alpha$. Each lab group will conduct the experiment for different incidences which are included in the `labgroup_incidences.xlsx` spreadsheet on the lab's Blackboard page. You are required to compare these experimentally obtained results against the output of a 3D panel code, which is implemented in FORTRAN. Instructions are given on how to run the panel code in the appendix. When you unzip the zipped file from the lab's Blackboard directory you will find a number of data files in the folder `output_data/` that contain the panel code's output pressure coefficient, $C_p$, distributions as a function of the chord-wise position, $x/c$, at all three sections in the range $0° \leq \alpha \leq 16°$.[1] These values

[1] Please refer to the Outputs section of the Appendix of this handout for an explanation of the various data files.

are calculated from a discretisation of 16 chord-wise panels on each side of the aerofoil and 9 span-wise panels per semi-span.

> **Preliminary work from §2:** Take a suitable incidence (i.e. one of the incidences allocated to your group) and run the panel code with coarser and finer discretisation than that described above. Vary the number of panels in the spanwise direction and on each side of the aerofoil. You will then be quizzed on your understanding of the effects of altering the resolution of the panel code on its ability to predict the $C_p$ distribution at the three sections of the wing during the oral assessment. See the appendix for further details on how to run the panel code.

You will be assessed orally 1.5 hours after the lab session finishes. The objectives of the oral assessment are as follows:

1. Identify (and explain) the influence of sweep and finite aspect ratio on the sectional-lift-coefficient slope of a swept wing. With reference to the assumptions made in a panel code, identify where and why the inviscid panel code solution is a good approximation to reality and where and why the inviscid solution is not a good approximation to reality.

2. Observe and comment on the stalling behaviour of a swept wing and explain why this behaviour is/is not well modelled in the 3D panel code. Discuss how the sweep, taper and twist influence the stall behaviour.

3. Discuss the effects of altering the resolution of the panel code on its ability to predict the $C_p$ distribution at the three sections of the wing. Note the time required for computation and discuss what could the optimal number of panels in terms of time and accuracy of computation.

The MATLAB script `data_processing.m` has been specifically designed to read the Excel spreadsheet `data.xlsx`, which you will have populated during the lab, and produce the graphs that you need to meet these objectives.

## 5 The Oral Assessment

The oral assessment will take place 1.5 hours after the lab has finished. You will be assessed in groups of 3/4 students for a period of 12 minutes (in a 15-minutes time slot). You must work together as a group to address all the objectives of §4. A group mark is awarded therefore it is recommended that smaller groups of students focus on tackling one objective per group to maximise efficiency. However, each student is expected to have an understanding of all three objectives. The discussion of each objective carries the same weight of marks. This discussion should then be combined into a short Powerpoint presentation (10 minutes maximum) discussing the three objectives of §4 in turn with all of the relevant plots, presented neatly and clearly. The marker will then question you (c. 2 minutes) based on the contents of your brief presentation. However, the marker is free to ask questions from an objective that was not presented by a student to check the overall level of understanding. Different weightings to the group mark can be awarded to different students based on the student's performance in the oral examination assessed by the marker if a clear difference in the level of understanding is observed. The final 3 minutes will be reserved for feedback from the marker. This will take place after the assessment has concluded.

1. To meet the first objective you must consider the $C_p$ distribution, as a function of $x/c$, for each section (i.e. red, yellow or green). These are then integrated over the chord in order to to obtain a sectional lift coefficient $C'_L$ as a function of $\alpha$. Compare these plots to the equivalent experimental plots. Thereafter, select a section (i.e. red, yellow or green) and incidence where the match between the results of the panel code and the experiment are close to one another. Plot $C_p$ against $x/c$ at this section for the particular incidence of interest. Next, select a section and incidence where the results of the panel code and the experiment diverge from one another and plot $C_p$ against $x/c$. Explain why you have chosen these two sections and incidences and why the experiments and panel code output do/don't agree.

2. The second objective concerns the stalling behaviour of the wing. The wing uses twist and taper in order to mitigate against some of the adverse stalling characteristics of a swept wing. Comment on the stalling behaviour of the aerofoil making use of sketches of the wool tufts at the various sections on the wing. At what incidence does the wing stall at the three sections? Comment on the stall incidence that you observe experimentally in comparison to the stall angle that is documented for the infinite wing in [3], you will find [2, 1] helpful when formulating your answer. Explain whether the panel code is able to accurately predict the stalling behaviour of the wing.

3. The third objective concerns assessing the effects of altering the resolution of the panel code on its ability to predict the $C_p$ distribution (at the various wing sections). What is the minimum resolution that is required for a converged solution? Take note of the run times for the various discretisations that you run. Is there an optimal number of panels? Is the problem more sensitive to spanwise or chordwise resolution? Is there a way to reduce the optimal number of panels?

## References

[1] CW Harper and RL Maki. A review of the stall characteristics of swept wings. *NASA Technical Report*, NASA-TN-D-2373, 1964.

[2] RC Lock. The aerodynamic design of swept winged aircraft at transonic and supersonic speeds. *Journal of the Royal Aeronautical Society*, 67:325–337, 1963.

[3] RJ McGhee and WD Beasley. Low-speed aerodynamic characteristics of a 17-percent-thick airfoil section designed for general aviation applications. *NASA Technical Report*, NASA-TN-D-7428, 1973.

# A Computational Method

A combined vortex ring and source panel method is used to compute the inviscid, incompressible and irrotational flow past a three dimensional swept wing. A surface mesh generator must be employed prior to the use of the panel code. The panel source code and mesh generator used here are called `combo.f` and `geowing.f` respectively.

In order to simplify the work on the panel code, executable (.exe) files will be provided on Blackboard. However, the students are free to start from the original code, compile it and run it themselves in FORTRAN. When altering the number of panels used, it is suggested to start from a small number and then increase it until the maximum number of panels the code can handle is found.

### Obtaining the codes

All the necessary files may be downloaded from Blackboard, including the input files required for this exercise. These should be copied to your home directory or a suitable subdirectory.

Windows executables (pre-compiled files) are included in the downloaded folder from blackboard. To run them simply type the name of the relevant .exe file and hit enter. There is a file called 'libgfortran' this must be in the same directory when you run the code to get it to work. If you wish to run on Linux or Mac it necessary to compile the FORTRAN code again. Firstly you will need the FORTRAN compiler. On Ubuntu based systems this can be installed with the command `sudo apt-get install build-essentials gfortran`. On Mac you should download the package manage mac-ports from their website, once installed use the command `sudo port install gfortran`. Compiling the code is then done with the two commands:

```
gfortran geowing.f -o geowing
gfortran combo.f -o combo
```

### Mesh Generator

The mesh generator executable `geowing` requires the file '`aerofoil.dat` to be in the same directory as execution but requires no input arguments to run. The aerofoil file consists of a list of data points which describe the 17% thick GA(W)1 section. This file does not need to be and should not be edited. The code will then ask for a series of user inputs:

1. Type `n` followed by the enter key. This indicates the code will load the `aerofoil.dat` file
2. It will then ask for the cord-wise discreatisation, input a number
3. It will then ask for the root cord, input `0.225`
4. It will then ask for the semi-span, input `0.6`
5. It will then ask for the taper ratio, input `0.42`
6. It will then ask if the wing is swept, input `sweep`
7. It will then ask for the leading edge angle, input `36.9`
8. It will then ask for the dihedral angle, input `0`
9. It will then ask for the twist angle, input `-1.5`
10. It will then ask for the root incidence angle, input `0`
11. It will then ask for the span-wise resolution, input a number

The number of chord-wise panels on each side of the aerofoil and the number of span-wise panels per semi-span should not exceed 30 and 20 respectively. The mesh generator will make a larger mesh but the panel code can only take up to 1200 panels. Therefore the total number of panels should not exceed 1200. Note, a resolution of 20x12 produces almost exactly 1200 panels.

### Panel Code

The panel code executable `combo` requires 4 input files to be passed as run-time arguments: `mesh.dat`, `auxiliary.dat`, `stream.dat` and `sect_inp`. Therefore execution of this code on Linux or Mac looks like

```
./combo mesh.dat auxiliary.dat stream.dat sect_inp
```

and

```
combo.exe mesh.dat auxiliary.dat stream.dat sect_inp
```

on Windows.

1. The first two files specify the wing and panel geometries and are outputs of the mesh generator. These do not require alteration.

2. The file `stream.dat` specifies the free stream conditions. This file should be edited and the relevant free stream velocity, pitch angle, yaw angle and density inserted in that order. SI units and degrees for angles should be used. Note that the yaw angle should be zero.

3. The file `sect_inp` controls the output of chord-wise pressure distributions. This must also be edited such that the number of sectional outputs followed by the span-wise location of each of these sections is specified. The specified sections should be coincident with those of the experiment.

Once the input files have been edited the code may be run using the executable. No command line inputs are required whilst running this code. Depending on the number of panels used and the speed and memory of the machine the code may take up to 5 minutes or longer to run. Note on some machines the code may signal a divide by zero error occurred. This does not affect the output.

## Outputs

The number of output files depends on the number of sections specified in `sect_inp`. Each sectional pressure distribution is written to a file whose name is of the form `sect_001`. N.B. `sect_001` corresponds to the red section of the wing, `sect_002` corresponds to the yellow section and `sect_003` corresponds to the green section. There are two other output files; `span_load` and `force.dat`.

1. The sectional files `sect_001` contain chord-wise pressure distributions, where the distance from the leading edge is given as a proportion of the local chord

2. The `span_load` file contains a span-wise loading distribution. The span-wise coordinate has been normalised with respect to the semi-span

3. The file `force.dat` contains a summary of the overall forces and coefficients on the wing. It is not necessary for the laboratory exercise and has only been included for interest