Aerodynamics of a COVID-19 Drone

1. Background

The year is 2042, around two decades since the notorious psi variant of the COVID-19 virus first emerged and wreaked havoc around the world. Earth's population is sitting at less than 50 million people now, and humanity's first ever attempt at a unified global society under UN leadership has collapsed down to a handful of new nations and a dozen or so independent factions. This is a post-apocalyptic world where the COVID-19 pandemic never truly ended, and you are one of the few aerospace engineers left in a society where most people have taken up farming full-time to ensure sufficient food for their families.

But things are starting to look hopeful for you and your covert team of scientists and engineers. What started off as an initiative to recover and preserve human knowledge, has miraculously led to a scientific breakthrough in the development of an aerially deployable bio-agent that kills the psi variant. The end of the COVID-19 pandemic is finally in sight, and your job is to make a drone – i.e. an unpiloted aerial vehicle (UAV) – that can spray the bio-agent into the surrounding air. Thankfully, you still remember your aerodynamics knowledge from MECH-3640 as it was your favourite course at university before the world started to collapse.

With extremely limited resources available, the only practical way to build a working drone is to salvage old parts. To make matters worse, most pieces of technology have long been repurposed for basic human survival, but among the pile of junk left over, you find an old set of airplane wings (see Fig. 1). You have only one shot at making this drone work, so you decide to reverse engineer the wings by analysing their aerodynamic performance.

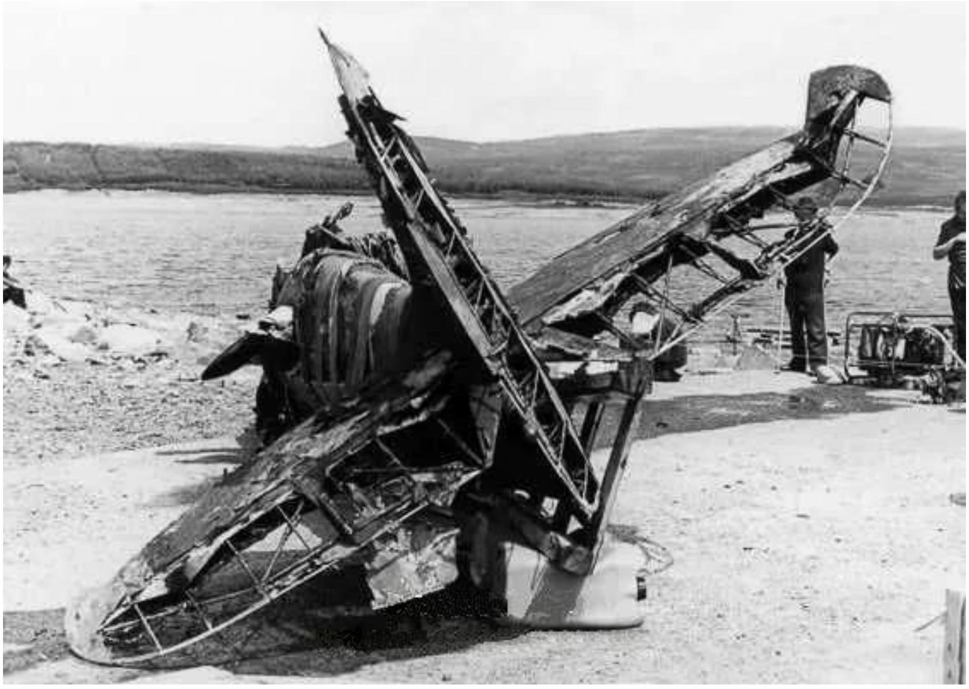

Fig. 1: Old set of airplane wings salvaged by your covert team
(for illustration purposes only).

2. Project Tasks

You have a series of tasks to complete and document as part of the analysis. Although you do not need to write a formal technical report, you should provide detailed explanations and/or steps of your work with full equations, figures and/or tables, where appropriate. Pay extra attention to ensuring that figures and/or tables are presented clearly and efficiently. The scope and schedule of this project are summarised below:

Focus	Analysis Approach	Due
Part I: Airfoil Aerodynamics	Analytical: Thin Airfoil Theory (TAT). Numerical: Vortex Panel Method (VPM) via XFLR5. Experimental: Wind tunnel experiments.	Nov 8 Upload to Canvas
Part II: Wing Aerodynamics	Analytical: Lifting Line Theory (LLT) by hand. Numerical: Lifting Line Theory (LLT) via XFLR5. Numerical: Vortex Lattice Method (VLM) via XFLR5.	

Marking Distribution	
Part I: Airfoil Aerodynamics	79 pts
Part II: Wing Aerodynamics	80 pts
Presentation	10 pts
Total	**169 pts**

Part I: Airfoil Aerodynamics

1. From visual inspection, you have a hunch that the salvaged wings are designed from a NACA-type airfoil. Determine the 4-digit NACA number of the recovered wing by cutting a 2D section of the wing, tracing it out, and measuring its dimensions. The airfoil is already traced out for you in Fig. 2. [4pts]

2. For the airfoil in Question 1, use TAT to calculate the following:

   a) The zero-lift angle of attack ($\alpha_{L=0}$). [4pts]

   b) The moment coefficient about the quarter chord ($C_{m,c/4}$). [4pts]

   c) The location of the centre of pressure (x_{cp}). [2pts]

   d) The location of the aerodynamic centre (x_{ac}). [1pt]

   Hint: The equation for the camber line of a 4-digit NACA airfoil is given by:

$$z = \begin{cases} \dfrac{m}{p^2}\left(2px - \dfrac{x^2}{c}\right) & 0 \le x \le pc \\ \dfrac{m}{(1-p)^2}\left((1-2p)c + 2px - \dfrac{x^2}{c}\right) & pc \le x \le c \end{cases}$$

   where z is the camber (measured perpendicular to the chord), x is the chord-wise coordinate, m is the maximum camber ($100m$ is the first digit in the 4-digit NACA designation), and p is the location of maximum camber measured from the leading edge ($10p$ is the second digit in the 4-digit NACA designation).

3. For the airfoil in Question 1, plot the lift curve (C_l vs α) and the drag polar (C_d vs C_l) using three different approaches:

   a) <u>Analytical</u>: TAT. [2pts]

   b) <u>Experimental</u>: Wind tunnel experiments, for which tuft-visualisation videos and force measurement data will be uploaded to Canvas after the lab sessions on October 23–24. [6pts]

   c) <u>Numerical</u>: VPM as implemented in XFLR5 with viscosity models, using a Reynolds number equivalent to that of the wind tunnel experiments. [2pts]

   Compare the results from the three approaches, identifying any trends, similarities, and differences, and explaining them using scientific and/or physical arguments. [8pts]

4. Describe the strengths and weaknesses of each of the three different approaches (analytical, experimental, and numerical). [6pts]

5. Let's explore the effects of airfoil thickness. Using the airfoil in Question 1 as your baseline, consider five additional airfoils with the same camber line but different thicknesses: (i) one with 3% less thickness, (ii) one with 6% less thickness, (iii) one with 3% more thickness, (iv) one with 6% more thickness, and (v) one with 9% more thickness. These thickness values are expressed in terms of the chord length.

   a) Make a table listing the 4-digit NACA number of all six airfoils (one from Question 1 + five new ones). [1pt]

   b) For these six airfoils, plot the lift curve (C_l vs α) and the drag polar (C_d vs C_l) using the three approaches in Question 3. [4pts]

   c) Repeat (b) but for flow that has been tripped artificially on the upper and lower surfaces of the airfoils at $x = 0.05c$ to increase the effective Reynolds number (this will be discussed in more detail during Tutorial 7). [4pts]

   Examine the results, identifying any trends, similarities, and differences, and explaining them using scientific and/or physical arguments. You may use screenshots of the tuft-visualisation videos to strengthen your arguments. [14pts]

6. Let's explore the effects of airfoil camber. Using the airfoil in Question 1 as your baseline, consider two additional airfoils: (i) one with 1% less camber, and (ii) one with 1% more camber. These camber values are expressed in terms of the chord length.

   a) Make a table listing the 4-digit NACA number of all three airfoils (one from Question 1 + two new ones). [1pt]

   b) For these three airfoils, plot the lift curve (C_l vs α) and the drag polar (C_d vs C_l) using the three approaches in Question 3. [6pts]

   Examine the results, identifying any trends, similarities, and difference, and explaining them using scientific and/or physical arguments. You may use screenshots of the tuft-visualisation videos to strengthen your arguments. [10pts]

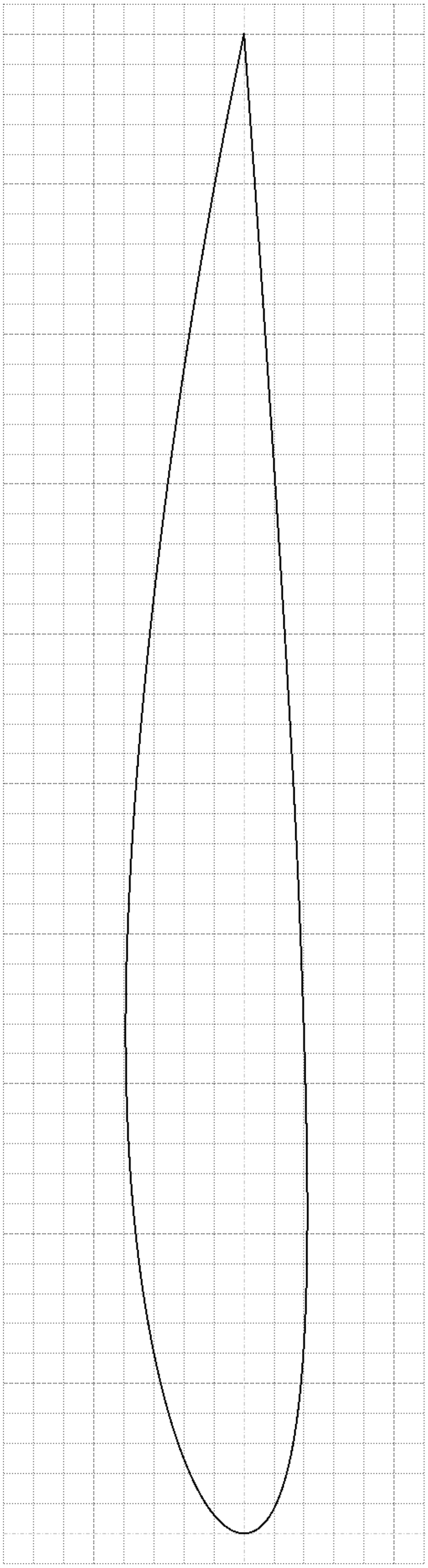

Fig. 2: Airfoil section at the wing root.

Part II: Wing Aerodynamics

1. While you were busy analysing the airfoil, your team members scanned the wing planform, as shown in Fig. 3 (a high-resolution image has been uploaded to Canvas: `Planform.png`). Using the scale provided in the image, determine the following:

   a) Wingspan. [1pt]

   b) Wing area. [1pt]

   Hint: You may wish to draw additional sections near the wing tips to measure the wing area more accurately.

   c) Aspect ratio. [1pt]

   d) Chord length at the six spanwise stations, where station 1 is the wing root. [1pt]

   e) Angle of incidence at the six spanwise stations. [1pt]

   Hint: The angle of incidence is the angle between the chord line and the longitudinal axis of the aircraft.

2. Analytical LLT: As a gross approximation, assume that the drone's wing is **perfectly elliptical and untwisted**. Using LLT and your measurements from Question 1, calculate the following based on the need for level flight at a cruising speed of 140 km/h, an altitude of 2,000 meters, and an aircraft weight of 5.7 kN.

   a) Wing lift coefficient. [2pts]

   b) Induced drag coefficient. [2pts]

   c) Induced angle of attack. [2pts]

   d) Geometric angle of attack. [2pts]

   Hint: You can find standard atmospheric air properties in the Appendix.

3. Numerical LLT: Let's model the wing more accurately, **no longer assuming that it is perfectly elliptical and untwisted**. Using the numerical LLT scheme in XFLR5 and your measurements from Question 1, plot C_L vs α on one graph and C_{D_i} vs α on another. For the same flight conditions and aircraft weight as in Question 2, what is the angle of attack required to maintain level flight? [6pts]

   Hint: For a twisted wing, the angle of attack is typically measured at the wing root.

   Warning: The 'angle of attack' reported by XFLR5 may need to be corrected by an offset. This is because the 'angle of attack' reported by XFLR5 is sometimes (erroneously) taken relative to the longitudinal axis of the aircraft, rather than the chord line at the wing root.

4. Let's compare the C_{D_i} values found under the assumptions of Question 2 (an elliptical untwisted wing) and Question 3 (an elliptical-like twisted wing).

   a) Calculate the percentage difference in C_{D_i}. [2pts]

   b) Calculate the span efficiency factor (e) and the induced drag factor (δ) for the two cases. [2pts]

   c) Comment on the advantages of using analytical methods in engineering design. [3pts]

5. Let's explore the effects of wing taper ratio. Consider ten tapered wings with different taper ratios (ranging from λ = 0.1 to 1.0), but with the same wing area and aspect ratio as the wing from Question 1. Assume that these tapered wings are all untwisted.

   a) Determine the chord length at the wing root (c_{root}) and that at the wing tip (c_{tip}) for each of the ten tapered wings, completing the table below: [2pts]

Taper Ratio (λ)	c_{root}	c_{tip}
0.1		
0.2		
0.3		
0.4		
0.5		
0.6		
0.7		
0.8		
0.9		
1.0		

   b) Using the numerical LLT scheme in XFLR5, plot the induced drag factor against the taper ratio (δ vs λ) for the ten tapered wings where $\alpha = 5°$. Use the free-stream properties from Question 2. [4pts]

   c) Discuss the results from part (b), proposing an optimal taper ratio and commenting on the wing's elliptical shape. [4pts]

6. Let's explore the effects of wing aspect ratio. Consider four tapered wings with different aspect ratios (ranging from $AR = 2$ to 8), having the same wing area as found in Question 1 and having the optimal taper ratio you proposed in Question 5c. Assume that these tapered wings are all untwisted.

   a) Complete the table below: [2pts]

Aspect Ratio (AR)	**Wingspan (b)**	c_{root}	c_{tip}
2			
4			
6			
8			

   b) Using the numerical LLT scheme in XFLR5, plot the lift curve (C_L vs α) and the drag polar (C_L vs C_D) for the four tapered wings. Use a free-stream velocity of 140 km/h and a flight altitude of 2,000 meters. [3pts]

   Note: In Part I, you were asked to plot the drag polar as the drag coefficient versus the lift coefficient. Here you are asked to plot the drag polar as the lift coefficient versus the drag coefficient. Both forms are valid and used in aerodynamics.

   c) Examine the results from part (b), identifying any trends and features, and explaining them using scientific and/or physical arguments. How can these results help you design an aircraft? [10pts]

   d) Plot the drag polar again, but using the induced drag coefficient (C_{D_i}) instead of the total drag coefficient (C_D), i.e. plot C_L vs C_{D_i}. Compare this to the drag polar from part (b), identifying any trends, similarities and differences, and explaining them using scientific and/or physical arguments. [5pts]

   e) For the wing with $AR = 2$, run an analysis using the numerical VLM scheme in XFLR5, and then plot C_L vs α. Compare these results with those obtained using the numerical LLT scheme in XFLR5, commenting on any trends, similarities and differences. For this particular wing, which method (VLM or LLT) do you trust more, and why? [4pts]

7. Plot the lift curve (C_L vs α) for the following on one graph:

   a) The airfoil using TAT (Part I: Question 3a). [1pt]

   b) The airfoil using experimental measurements in a wind tunnel (Part I: Question 3b). [1pt]

   c) The wing (untwisted) using the numerical LLT scheme in XFLR5. [1pt]

d) The wing (twisted) using the numerical LLT scheme in XFLR5 (Part II: Question 3). [1pt]

e) The optimally tapered wing (untwisted) using the numerical LLT scheme in XFLR5 (Part II: Question 5). [1pt]

f) The rectangular wing ($\lambda = 1.0$, untwisted) using the numerical LLT scheme in XFLR5 (Part II: Question 5). [1pt]

g) The optimally tapered wing (untwisted) with $AR = 4$ using the numerical LLT scheme in XFLR5 (Part II: Question 6). [1pt]

h) The optimally tapered wing (untwisted) with $AR = 8$ using the numerical LLT scheme in XFLR5 (Part II: Question 6). [1pt]

Compare the results obtained, identifying any trends, similarities and differences, and explaining them using scientific and/or physical arguments. [12pts]

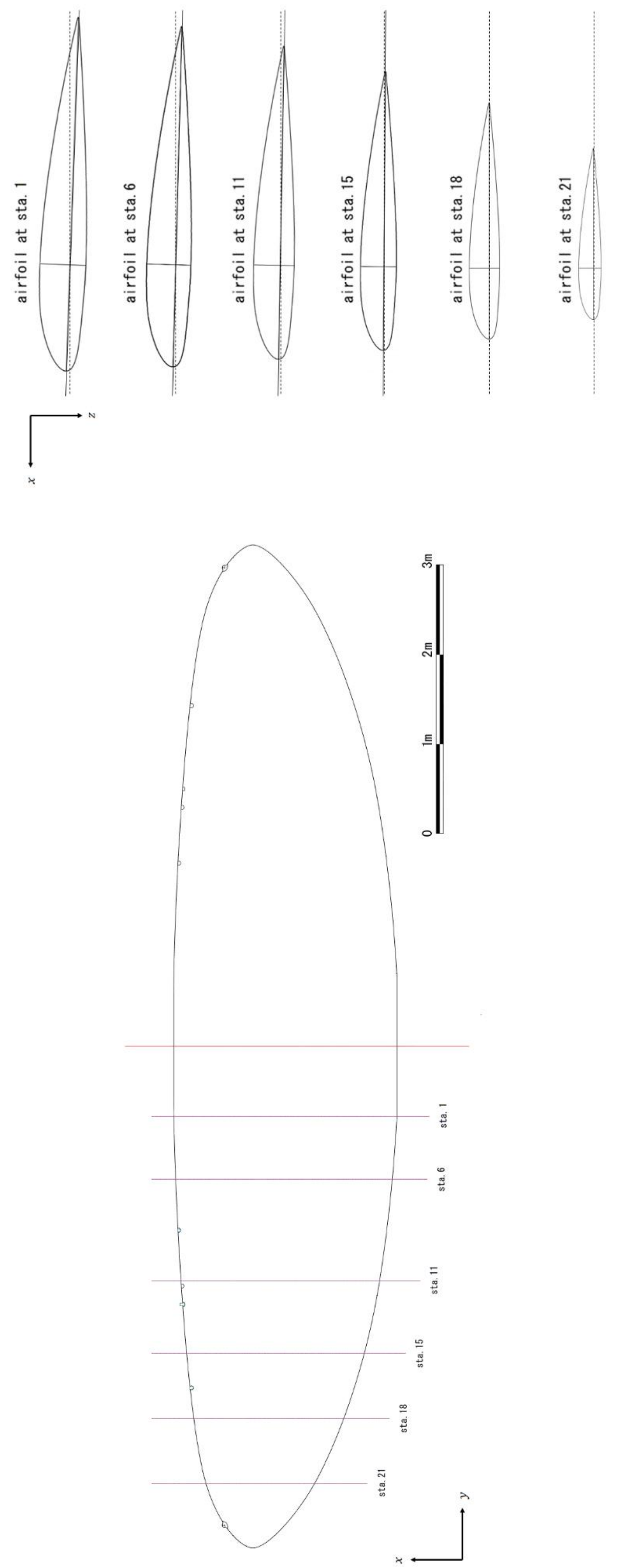

Fig. 3: Planform of the wing (see Canvas for a high-resolution image: `Planform.png`).

Appendix

Altitude h_G, m	Altitude h, m	Temperature T, K	Pressure p, N/m^2	Density ρ, kg/m^3
0	0	288.16	1.01325 + 5	1.2250 + 0
100	100	287.51	1.0013	1.2133
200	200	286.86	9.8945 + 4	1.2071
300	300	286.21	9.7773	1.1901
400	400	285.56	9.6611	1.1787
500	500	284.91	9.5461	1.1673
600	600	284.26	9.4322	1.1560
700	700	283.61	9.3194	1.1448
800	800	282.96	9.2077	1.1337
900	900	282.31	9.0971	1.1226
1,000	1,000	281.66	8.9876 + 4	1.1117 + 0
1,100	1,100	281.01	8.8792	1.1008
1,200	1,200	280.36	8.7718	1.0900
1,300	1,300	279.71	8.6655	1.0793
1,400	1,400	279.06	8.5602	1.0687
1,500	1,500	278.41	8.4560	1.0581
1,600	1,600	277.76	8.3527	1.0476
1,700	1,700	277.11	8.2506	1.0373
1,800	1,799	276.46	8.1494	1.0269
1,900	1,899	275.81	8.0493	1.0167
2,000	1,999	275.16	7.9501 + 4	1.0066 + 0
2,100	2,099	274.51	7.8520	9.9649 − 1
2,200	2,199	273.86	7.7548	9.8649
2,300	2,299	273.22	7.6586	9.7657
2,400	2,399	272.57	7.5634	9.6673
2,500	2,499	271.92	7.4692	9.5696
2,600	2,599	271.27	7.3759	9.4727
2,700	2,699	270.62	7.2835	9.3765
2,800	2,799	269.97	7.1921	9.2811
2,900	2,899	269.32	7.1016	9.1865
3,000	2,999	268.67	7.0121 + 4	9.0926 − 1
3,100	3,098	268.02	6.9235	8.9994
3,200	3,198	267.37	6.8357	8.9070
3,300	3,298	266.72	6.7489	8.8153
3,400	3,398	266.07	6.6630	8.7243
3,500	3,498	265.42	6.5780	8.6341
3,600	3,598	264.77	6.4939	8.5445
3,700	3,698	264.12	6.4106	8.4557
3,800	3,798	263.47	6.3282	8.3676
3,900	3,898	262.83	6.2467	8.2802
4,000	3,997	262.18	6.1660 + 4	8.1935 − 1
4,100	4,097	261.53	6.0862	8.1075
4,200	4,197	260.88	6.0072	8.0222
4,300	4,297	260.23	5.9290	7.9376
4,400	4,397	259.58	5.8517	7.8536
4,500	4,497	258.93	5.7752	7.7704
4,600	4,597	258.28	5.6995	7.6878
4,700	4,697	257.63	5.6247	7.6059
4,800	4,796	256.98	5.5506	7.5247
4,900	4,896	256.33	5.4773	7.4442

Table A-1 Standard Atmosphere, SI Units

Wind Tunnel Lab

Name: **Group:** **Date:**

1. Introduction

In this lab, you will conduct a wind tunnel experiment to collect lift and drag data from an airfoil. Each group will be responsible for one of the airfoils analysed in the course project.

Gp	Airfoil	Description
1	A	Baseline airfoil
2	B	3% thinner
3	C	6% thinner
4	D	3% thicker
5	E	6% thicker
6	F	9% thicker
7	G	1% less camber

Gp	Airfoil	Description
8	H	1% more camber
9	A	Baseline airfoil, tripped flow
10	B	3% thinner, tripped flow
11	C	6% thinner, tripped flow
12	D	3% thicker, tripped flow
13	E	6% thicker, tripped flow
14	F	9% thicker, tripped flow

By now, you should understand some of the key differences between a 2D airfoil and a 3D wing. From the lectures, we have established that the lift force of an airfoil and that of a wing can be expressed as Equations 1 and 2, respectively:

$$L' = \frac{1}{2} C_l \rho V_\infty^2 c \qquad \text{Eq. 1}$$

$$L = \frac{1}{2} C_L \rho V_\infty^2 S \qquad \text{Eq. 2}$$

In the above equations, c is the chord length of the airfoil, while S is the total area of the wing. So how do aerodynamicists conduct experiments in the real world to determine the performance of an airfoil, which is inherently 2D? By using an extruded airfoil as a test model that spans the entire wind tunnel (i.e. wall-to-wall), we can essentially eliminate the effects of wingtip vortices and induced drag, rendering the test model as a pseudo-2D airfoil. In other words, in this specific case, we can assume that the two lift coefficients are equal:

$$C_l = C_L \qquad \text{Eq. 3}$$

You will conduct experiments as a group and share the collected data (lift and drag forces) with the entire class. However, you will analyse the data individually, and report the results as part of the course project.

2. Experimental Setup

The experiment is performed in the small wind tunnel at the Aerodynamics and Acoustics Facility (AAF) at the Hong Kong University of Science and Technology. The wind tunnel is open-loop, with a test section whose dimensions are 243 × 50 × 40 cm ($L \times W \times H$), producing a maximum air speed of 27 m/s. A rendering of the test section is shown in Fig. 1 and a simplified schematic of the setup is shown in Fig. 2. The extruded airfoils are machined out of aluminium and have a chord of 100 mm and a span of 395 mm. For your experiments, the free-stream velocity is set to 23 m/s.

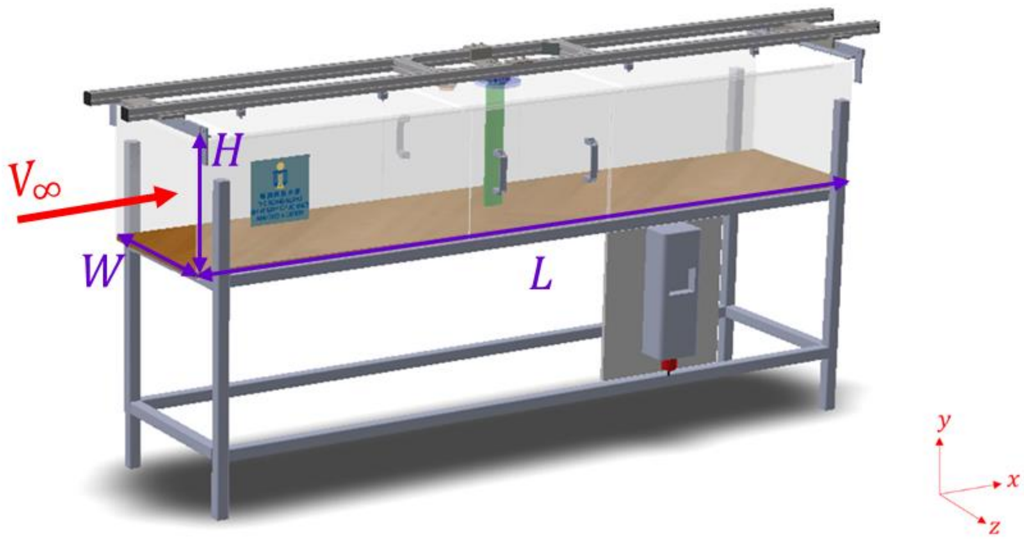

Fig. 1: Rendering of the wind tunnel with an extruded airfoil (green, centre) mounted from the ceiling of the test section.

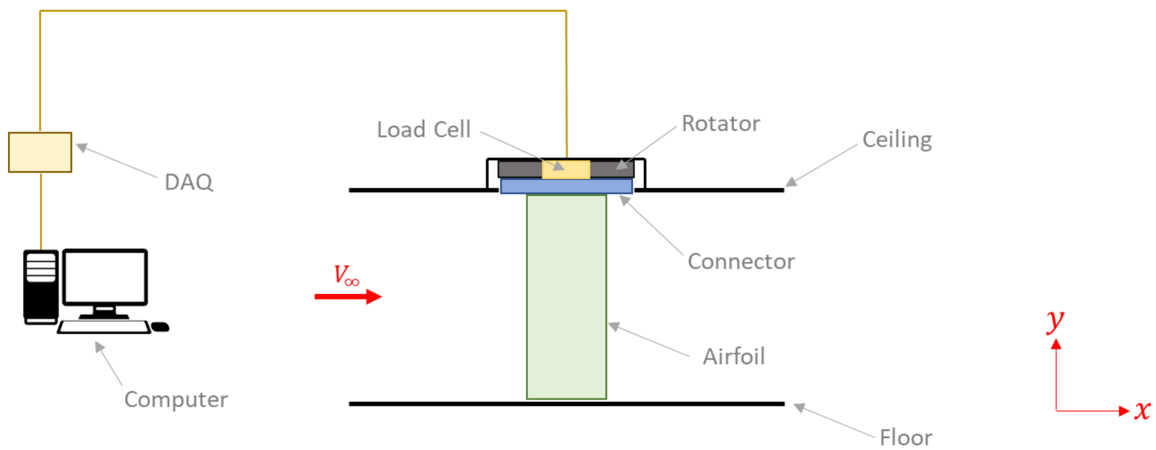

Fig. 2: Schematic of the setup.

3. Experimental Procedure

Follow the procedure listed below. The wind tunnel **must be shut down** before you do any work in the test section.

1) Assemble the test rig.
2) Check that the connector is not touching the wind tunnel walls (floor or ceiling).
3) Calibrate the load cell, which is used to measure the lift and drag forces.
4) Turn on the wind tunnel and adjust the flow speed to 23 m/s.
5) Digitize the load cell measurements: 40,000 samples @ 20,000 Hz.
6) Change the angle of attack and repeat steps 2 to 6.
7) Turn off the wind tunnel and disassemble the test rig.

4. Results

Calculate the time-averaged lift and drag forces at every angle of attack.

Airfoil:	Air Temperature:	Air Pressure:
Samples:	Sample Rate:	

Angle of Attack (°)	Lift (N)	Drag (N)	Angle of Attack (°)	Lift (N)	Drag (N)
-4			13		
-2			14		
0			15		
2			16		
4			17		
6			18		
8			19		
9			20		
10			21		
11			22		
12			23		

5. Tuft Visualisation

Attach the tufts as instructed and observe their behaviour as the angle of attack is increased.