Lab-Exercise Manual
AE4115 Experimental Simulations

Propulsion-Integration Testing on a Complete Aircraft Model

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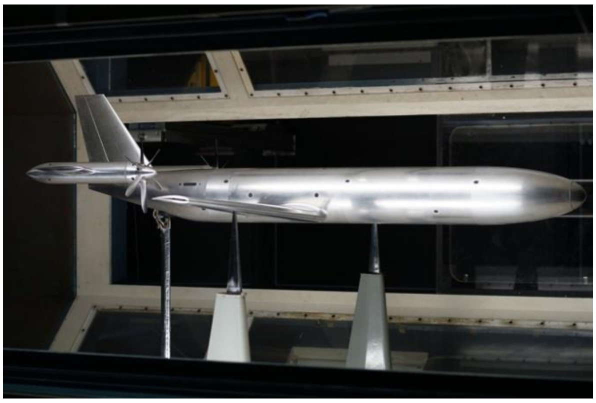

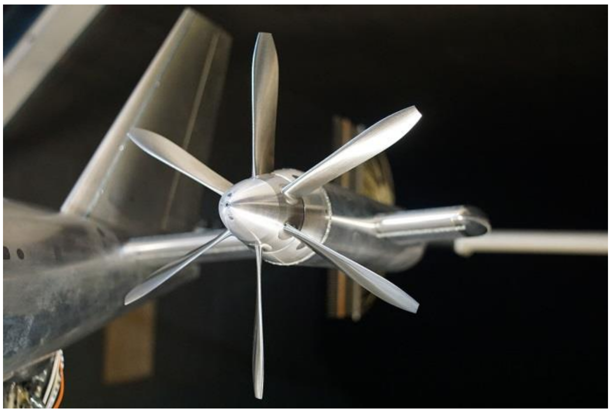

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1 Introduction

Growing concerns about the environmental impact of aviation combined with ever growing passenger numbers motivate the development of more efficient and quiet aircraft. Over the past decades, the largest advances in aircraft performance have been accomplished by improving the efficiency of the propulsion system. For air-breathing engines in isolation, the propulsive efficiency η_p at a given thrust T and flight velocity V_∞ can be increased by giving a smaller velocity increment ΔV to a larger mass flow $\dot{m}$. This can be seen from equations (1.1) and (1.2), and corresponds to an increase in effective by-pass ratio of the engine.

$$\eta_p = \frac{2}{2 + \Delta V / V_\infty} \tag{1.1}$$

$$T = \dot{m} \Delta V \tag{1.2}$$

An increase in by-pass ratio naturally corresponds to an increase in engine diameter (at constant thrust). With increasing engine size, the interactions between the propulsion system and the airframe become stronger. Therefore, accounting for propulsion integration becomes increasingly important during design and development to achieve optimal aircraft performance.

An extreme example of a propulsor with a high by-pass ratio is the propeller. By eliminating the engine shroud, such as installed around turbofan engines, the engine diameter can be increased further without introducing weight and drag penalties. Consequently, propellers are inherently more efficient than turbofan engines. However, this comes at the cost of even more complex interactions between the propulsion system and the rest of the airframe. Besides, noise becomes an issue due to the absence of the engine shroud. Clearly, for propeller-driven aircraft, propulsion integration is a critical aspect. Note that this becomes even more important for the complex electric aircraft configurations proposed nowadays (distributed propulsion, vertical takeoff and landing capabilities, etc.).

Constraints on the propeller's diameter and blade tip Mach number limit the maximum size of propeller-driven aircraft. Therefore, propellers are typically suited for aircraft designed for short-haul missions. By optimally integrating the propellers with the airframe, improved aerodynamic and acoustic efficiency can be achieved. In this lab exercise, we will consider an aircraft configuration with a propeller mounted to each side of the horizontal tailplane. Previous work by Goldsmith[1] identified this configuration as the most efficient solution for regional aircraft with propellers. A notional sketch is provided in Figure 1.

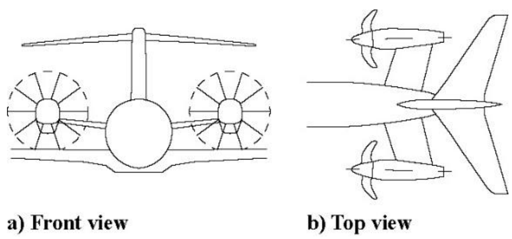


Figure 1: Notional sketch of aircraft configuration with horizontal-tailplane-mounted propellers. Based on Ref. [1].

[1] Goldsmith, I. M., "A Study to Define the Research and Technology Requirements for Advanced Turbo/Propfan Transport Aircraft," NASA CR-166138, 1981.

The interactions between the propellers and the airframe can be divided into upstream and downstream effects. When installed in a tractor configuration (propeller ahead of engine, such as in Figure 1), the downstream effect corresponds to a modification of the airframe performance due to the propeller, and vice versa for the upstream effect. The downstream effect is caused by the variations in axial and tangential velocity in the propeller slipstream, that modify the inflow conditions to the downstream element (wing, tailplane, or pylon). The upstream effect is due to blockage and upwash in the propeller plane caused by the downstream element (wing, tailplane, or pylon). A detailed discussion of the aerodynamic interference effects between propellers and wings is provided by Veldhuis[2].

The interference between propellers and aerodynamic surfaces is highly complex due to the unsteady and viscous phenomena involved. Therefore, numerical simulations of complete aircraft configurations with fully-resolved propellers are computationally expensive. For performance studies at airplane level, which typically involve a large range of operating conditions of interest, the use of numerical simulations is therefore not feasible. In such case, experimental simulations are an effective means to obtain an extensive data set in a relatively short amount of time. Besides, the experimental data can be used to validate numerical simulations that may be performed to obtain additional information for a few selected test cases. However, also the experimental approach has its limitations. These limitations will be explored in the present lab exercise.

[2] Veldhuis, L. L. M., "Propeller-Wing Aerodynamic Interference," PhD thesis, Delft University of Technology, 2005.

2 Objectives

The objective of the lab exercise is to gain insight into the:

- Possibilities of and limitations to obtaining experimental data from wind-tunnel tests to describe aircraft behavior in free flight
- Choices of experimental simulation techniques required for simulation of free flight
- Power integration effects on aircraft performance
- Dominant noise sources of a propeller aircraft, and the relationship between noise generation and aerodynamic performance
- Correction procedures of wind-tunnel data, and the significance of corrections to properly describe the aerodynamic performance and stability of an aircraft model in wind-tunnel tests
- Successful definition of an effective test plan to satisfy predefined measurement objectives

The body of the lab exercise consists of an experimental investigation of the behavior of a propeller-powered aircraft. It includes balance measurements for aerodynamic performance and unsteady pressure measurements with microphones for noise description. The measurement data will need to be used to determine the aircraft characteristics, the influence of the wind-tunnel walls on the aerodynamic performance with and without power effects, and the main acoustic characteristics of the aircraft.

Before performing the lab exercise, it is important to read carefully the present manual, and evaluate the material on correction methods provided in the lectures and references.

3 Procedure

The practical assignment consists of 5 steps:

1. Group enrolment
2. Definition of test plan and writing of pre-test report
3. Discussion of pre-test report and possible update of test plan
4. Execution of wind-tunnel test
5. Processing and analysis of data and writing of post-test report

3.1 Step 1: Group Enrolment

The work is performed in groups of at most 4 students. The entire exercise is performed with this group, except for the final assessment, which is based on an oral examination. Group enrolment will be done through the Brightspace environment in the first two weeks of the course. The choice of group defines the date and time of the wind-tunnel test slot and the corresponding measurement assignment.

3.2 Step 2: Definition of Test Plan and Writing of Pre-Test Report

A custom-made test plan is required to achieve the goal of the selected measurement assignment within the allotted time for the experiment. It is the responsibility of the group to come up with such a test plan. This entails a selection of measurement quantities of interest, variables of interest, and the definition of a test matrix. The requirements for the pre-test report are discussed in Section 7.1. The deadline for submission of the pre-test report is stated in Chapter 9.

3.3 Step 3: Discussion of Pre-Test Report and Possible Update of Test Plan

The pre-test report is discussed with the lab-exercise supervisor before the wind-tunnel test. The supervisor will provide feedback on the pre-test report, and possibly identify the need for changes to the test plan and/or test matrix. In that case, these will need to be updated before the wind-tunnel test. A pass grade for the pre-test report is a mandatory condition for admission to the wind-tunnel test

3.4 Step 4: Execution of Wind-Tunnel Test

The approved test plan will be used to perform the wind-tunnel test. After an instruction on the operating procedures of the wind tunnel, the group will execute its own test matrix. Assistance will be available to operate the propellers and make necessary adjustments to the model.

3.5 Step 5: Processing and Analysis of Data and Writing of Post-Test Report

Following the experiment, the measurement data are to be processed, analyzed, and discussed in a post-test report. The requirements for the post-test report are discussed in Section 7.2. The deadline for submission of the post-test report is stated in Chapter 9. The final oral examination of the AE4115 course will include a defense of the post-test report of the lab exercise.

4 Experimental Setup

4.1 Wind-Tunnel Facility

The experiments are performed in the Low-Turbulence Tunnel (LTT) at Delft University of Technology (see Figure 2). This low-speed closed-return wind tunnel features a closed-wall test section with a cross-section of 1.80 x 1.25 m (see Figure 3). The maximum velocity in the test section is about 120 m/s; typically, tests are performed in the velocity range of 30 < V_∞ < 100 m/s. At these freestream velocities, the turbulence level is below 0.1% (bandpass filtered between 2 and 5000 Hz). This high flow quality is a result of the large contraction ratio of 17.8. The wind tunnel is not acoustically treated, and thus the acoustic measurements will be affected by reflections in the hard-walled test section. The test section is slightly divergent to reduce the longitudinal pressure gradient. As a result, buoyancy can be ignored.

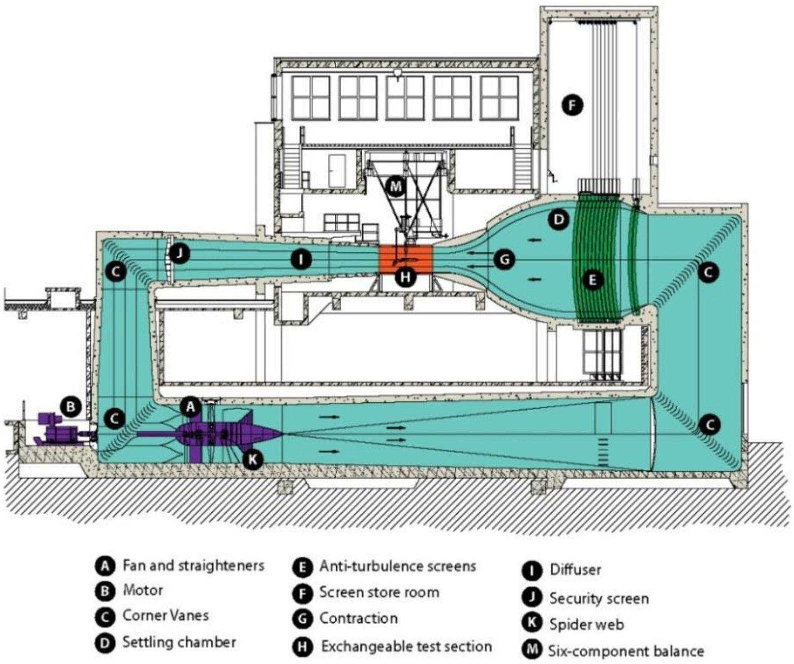


Figure 2: Schematic drawing of Delft University of Technology's Low-Turbulence Tunnel.[3] Image credit: Momchil Dimchev.

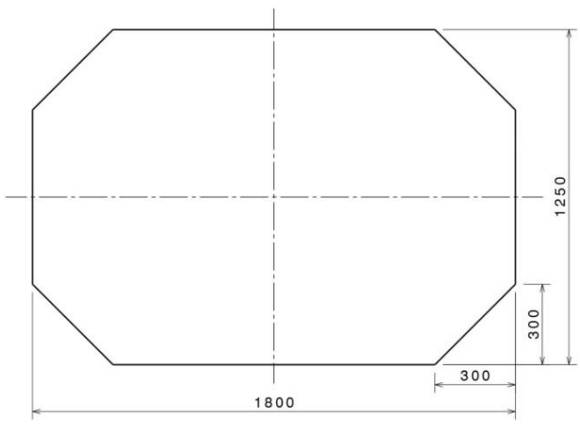


Figure 3: Cross-section of wind-tunnel test section. Dimensions in millimeters.

[3] The 'spider web' refers to a construction of tubes installed downstream of the fan. Its function is to obtain a uniform velocity distribution in the test section.

4.2 Model

All tests are performed with the aircraft model shown in Figure 4 and Figure 5. The model is connected to the external balance (Section 4.3) through three support struts. The angle of attack can be varied by moving the aft support strut, while the angle of sideslip can be set through a synchronous rotation of the balance system and the turntable in the top part of the test section. Since the balance is located above the test section, the aircraft model is installed upside down.

Figure 4: Aircraft model installed in test section of Delft University of Technology's Low-Turbulence Tunnel (front view). Image credit: Reynard de Vries.

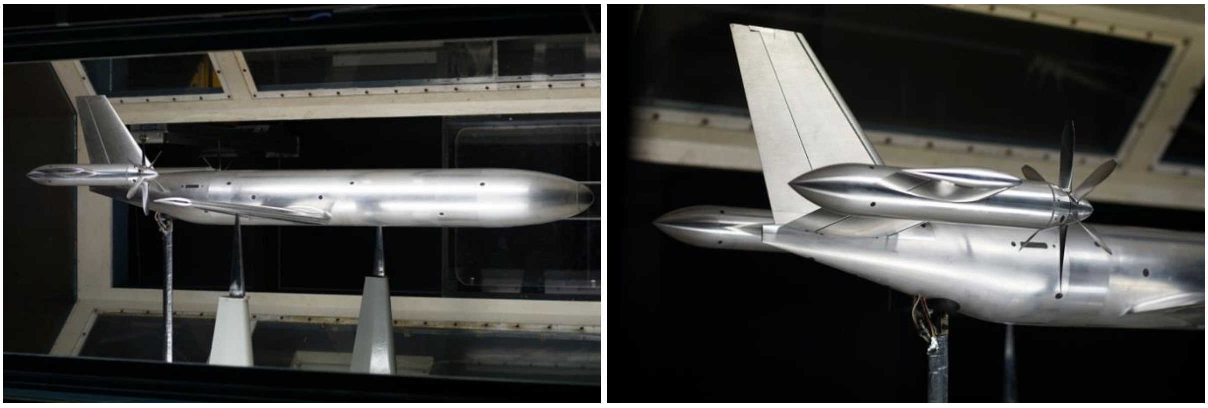


Figure 5: Photographs of aircraft model with horizontal-tailplane-mounted propellers; images flipped for convenience. Image credit: Nando van Arnhem.

The model features a fuselage, wing, removable vertical tailplane, and removable horizontal tailplane with integrated nacelles and removable propellers. The specifics of the different components are discussed below; detailed geometry specifications and technical drawings of the model are presented in Appendix A.

The unswept wing has a span of 1.397 m and aspect ratio of 8.91. The effects of ailerons can be evaluated by using the plain flaps integrated into the tip sections of the wing. A separate high-lift flap can be installed on the wing to simulate the aircraft behavior under high-lift conditions. The flap can be deflected at any desired angle, but needs to be installed manually, requiring a wind-tunnel downtime of about 30 minutes. Therefore, the flap will not be used during the practical.

The horizontal tailplane features an integrated nacelle on each side of the aircraft, with the nacelle centerline positioned at 70% of the tailplane's semispan. Each nacelle houses an electric motor with maximum power output of 2.5 kW. Plain flaps are available to simulate the effects of an elevator. The elevator surfaces are split and are installed on both sides of the nacelles, and the deflection angle can be set to any desired value in the range of −25 to +25 degrees. Positive elevator deflection is defined as deflection that leads to an additional nose-down pitching moment, i.e. down on the actual aircraft, hence up in the wind tunnel because the model is mounted upside down.

The vertical tailplane features a plain flap that acts as a rudder. The rudder deflection can be set to any desired angle in the range of −20 to +20 degrees. Positive rudder deflection is defined as rudder deflection that leads to a positive sideforce contribution.

Transition is forced on the wing, horizontal tailplane, vertical tailplane, fuselage, and nacelles. On the wing, trip strips are positioned at 5% of the local chord on the upper side and 10% of the local chord on the lower side. On the tailplanes, the trip strips are positioned at 5% of the chord on both upper and lower sides.

The aircraft model can be equipped with two six-bladed propellers with a diameter of 0.2032 m. The pitch angle of the blades is set to 45 deg at $r/R = 0.7$. To minimize wind-tunnel downtime during the tests, this setting will be fixed for all experiments. The propellers are installed in a tractor configuration on the nacelles that are integrated into the horizontal tailplane. The propellers will be operated by the lab supervisor, who will control and set the rotational speed to the value you will provide. Three propellers are available: two right-handed propellers (rotating in clockwise direction as seen from the back) and one left-handed propeller. Since the rotation direction of the electric motors can be changed easily, the different propeller models can be used to study the effects of propeller rotation direction. Three configurations can be considered:

1. co-rotating configuration with both propellers rotating in the same direction
2. counter-rotating configuration with inboard-up rotation of both propellers
3. counter-rotating configuration with outboard-up rotation of both propellers

The port-side motor is referred to as motor 1, the starboard-side motor as motor 2.

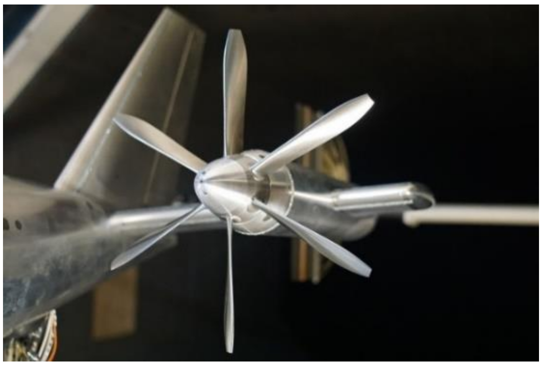


Figure 6: Photograph of the propeller model; image flipped for convenience. Image credit: Nando van Arnhem.

The horizontal tailplane can be removed from the model. This will be required for reference measurements used to define wind-tunnel boundary corrections. Since the setup time of removing/installing the tailplane is in the order of hours, this cannot be done during each test slot.

Instead, the lab-exercise supervisor will provide tail-off measurement data that can be interpolated to the desired conditions. The vertical tailplane was also removed during these measurements.

4.3 Measurement Techniques

Different measurement techniques are applied in the experiment to obtain the desired aerodynamic and aeroacoustic data sets.

4.3.1 External Balance

An external balance is used to measure the aerodynamic forces and moments generated by the model. The 6-component balance returns forces and moments in all three directions. Figure 7 provides the definition of the axis system used during acquisition and processing of the balance data. Note that the balance reference system is not equal to the body-fixed axis system.

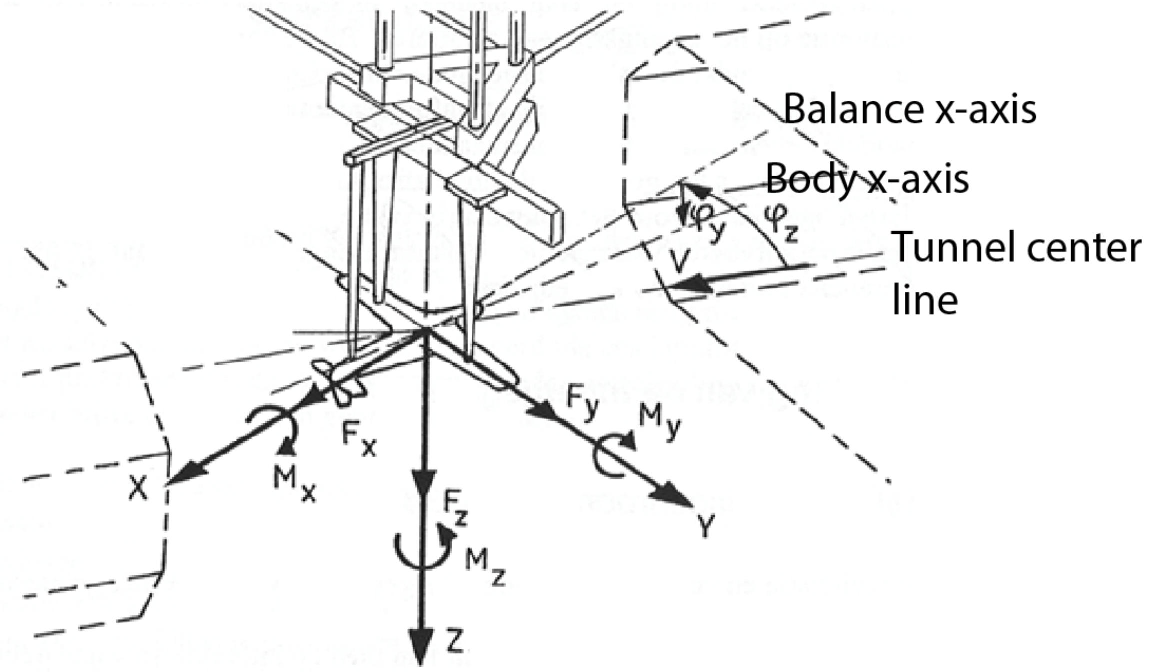


Figure 7: Definition of balance axis system.

Forces and moments acting on the balance that are not of aerodynamic nature (weight, tension due to engine cabling, etc.) should be removed from the test data. This is done by taking 'zero measurements' before and possibly after tests with a constant model configuration. You will need a wind-off 'zero measurement' for each model attitude that is considered in the test. Post-processing routines will be made available on Brightspace to process the data obtained from the external balance.

Since the propellers are not instrumented, the propeller forces will need to be estimated from the external balance data. During the preparation of the experiment, the best approach for determining this propeller thrust will need to be decided upon and described in the pre-test report. If necessary, the associated dedicated test points will need to be included in the test matrix.

4.3.2 Near-Field Microphones

Six microphones (Sonion 8044) are installed flush-mounted in the rear end of the fuselage (port side). These microphones provide near-field unsteady pressure measurements, that can be used to assess the propeller noise emissions. Figure 8 illustrates the positions of the microphones in the model. The microphones are positioned at axial directivity angles of 60, 75, 82.5, 90, 97.5, and 105 degrees, with

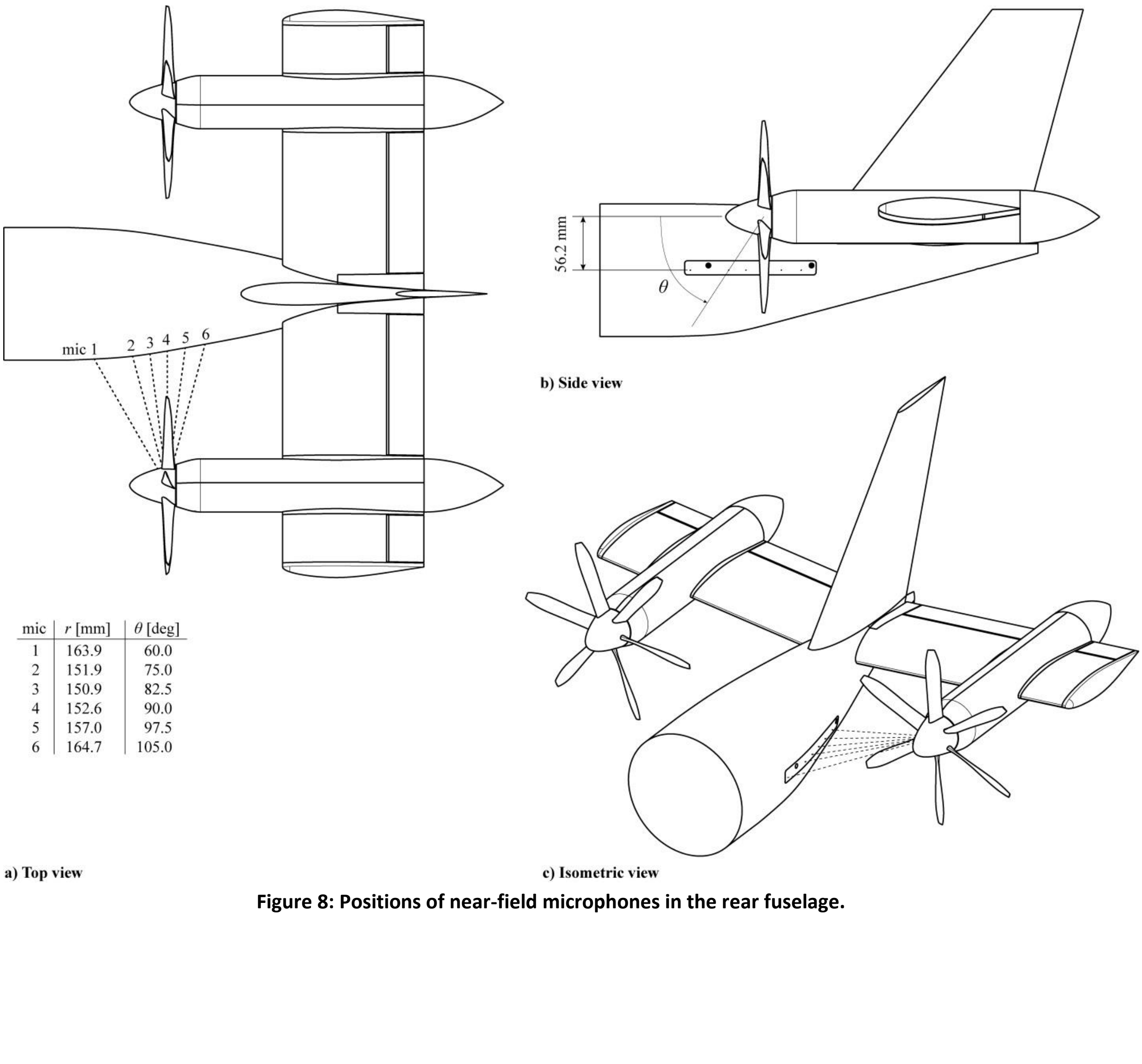
90 degrees indicating the propeller plane. In the vertical direction, the microphones are positioned on the fuselage centerline. These microphones feature a maximum sound-pressure level of 130.5 dB, and a frequency range of 10 Hz up to 15 kHz.

The microphones return an analog output voltage signal, that needs to be converted into pressure through a calibration. This will be done by the lab-exercise supervisor before or after the test, using a pistonphone (G.R.A.S. Pistonphone 42AA) and a reference microphone. Frequency-dependent calibration curves will posted on Brightspace following the experiment.

Post-processing routines will be made available on Brightspace to process the data obtained from the near-field microphones.

4.3.3 Static-Pressure Taps

Six static-pressure taps are integrated into the rear end of the fuselage (starboard side). The pressure taps are positioned at the same locations as the near-field microphones discussed in Section 4.3.2, but then on the opposite side of the fuselage. The six pressures are recorded simultaneously with an electronic pressure scanner, together with reference total and static pressure measurements upstream in the test section. Post-processing routines will be made available on Brightspace to process the data obtained from the pressure scanner.



mic	r [mm]	θ [deg]
1	163.9	60.0
2	151.9	75.0
3	150.9	82.5
4	152.6	90.0
5	157.0	97.5
6	164.7	105.0

Figure 8: Positions of near-field microphones in the rear fuselage.

4.3.4 Stethoscope

A flexibly positioned rod with integrated microphone is available to perform qualitative surveys of the flowfield. The microphone on this stethoscope can be connected to a speaker to auralize the flowfield. In this way, a distinction can be made between for example laminar and turbulent flow. Furthermore, the position of the slipstream over the tailplane can be localized at different test conditions (power setting, angle of attack, advance ratio, etc.), and the degree of contraction of the slipstream can be determined.

4.4 Possible Test Conditions

The wind-tunnel model can be operated at a range of test conditions, taking into account the following operational limitations:

- Freestream velocity: up to 40 m/s (imposed by structural limitations).
- Angle of attack: −5 up to +14 degrees
- Angle of sideslip: −10 up to +10 degrees
- Propeller setting
  - Lowest possible advance ratio at V_∞ = 40 m/s: J = 1.6. At lower V_∞, the advance ratio can be lower as long as aerodynamic performance is acceptable.
  - Highest possible advance ratio: no operational constraint, in practice limited by aerodynamic performance of the propeller

4.5 Timing

<u>Data acquisition</u>

You will need to choose the sampling time for each data point. This will be an input to the data acquisition programs. The data will be recorded during this sampling time, and you will be able to average over this time span to reduce random error. The selection of sampling time will be a compromise between quality (reducing random error) and quantity (duration of each test point, and thus number of test points you will be able to test at). Values of 2-15 s per data point are typical, depending on the operational conditions of interest (e.g. unsteady flow phenomena due to separation require additional measurement time to reach a converged mean compared to conditions with fully attached flow) and measurement technique of interest (e.g. acoustic data require longer sampling time than aerodynamic data due to lower signal-to-noise ratio).

<u>Model attitude and operational conditions</u>

You will be controlling **model attitude** and **wind-tunnel freestream velocity** during the experiment. The model attitude is controlled directly, the wind-tunnel freestream velocity through adjusting the tunnel fan RPM.

- Starting the tunnel and getting it at the right condition will take you about 3-5 minutes.
- Changing from one freestream condition to the other will take you about 1-2 minutes in the beginning, down to around 30 s towards the end of the test.
- Changing model attitude takes about 0.5 deg/s for angle of attack, and 0.25 deg/s for angle of sideslip. Note that you will need to also adjust the tunnel fan operational point to maintain the desired freestream velocity. This will require an additional 10-20 s per change of model attitude.

The lab supervisor will control the **propeller rotational speed** (based on your request)

- Changing from one setpoint to the other takes in the order of 10-15 sec (depending on the change in frequency and the speed and clarity of communication by the group). Note that you will need to adjust the freestream condition whenever the propeller setpoint is adjusted. This may take an additional 10-20 s. So in total about 30 s per change of propeller setpoint.

<u>Model configuration</u>
The **elevator** is adjusted manually. A change in elevator setting will require about 10-15 minutes of wind-tunnel downtime.

The **rudder** is also adjusted manually. A change in rudder deflection will require about 10-15 minutes of wind-tunnel downtime.

A change in **propeller configuration** (on vs off, rotation direction) will require about 10 minutes of wind-tunnel downtime if one propeller needs to be changed, or 15 minutes if 2 propellers need to be changed. Wind-on measurements with fixed propellers (0 Hz) are only possible after fixing the propellers with tape, thus requiring tunnel downtime of about 10 minutes. If not fixed, a set point of 0 Hz will lead to a rotational speed in the order of 2-10 Hz during the measurements.

5 Measurement Challenges

An experimental campaign always needs to be based on clearly defined test objectives, formulated to address predetermined knowledge gaps. In order to simulate this approach in the present lab exercise, five measurement challenges have been defined. Each group is assigned one of these five measurement challenges, according to the schedule given in Chapter 9. The measurements taken during the experiment should be focused on providing data that is useful in completing the assigned challenge. The selected challenge and resulting test plan are discussed in a pre-test report (Section 7.1).

The five different measurement challenges are:

1. Quantify the power effects on longitudinal stability and control, in terms of:
   a. Longitudinal stability,
   b. Elevator effectiveness and control power, and
   c. Aerodynamic performance in trimmed conditions.

2. Quantify the power effects on directional stability and control, in terms of:
   a. Directional stability,
   b. Rudder effectiveness and control power, and
   c. Aerodynamic performance in trimmed conditions.

3. Quantify the directional stability and control in one-engine inoperative conditions, in terms of:
   a. Directional stability,
   b. Rudder effectiveness and control power, and
   c. Aerodynamic performance in trimmed conditions.

4. Quantify the effects of energy-harvesting with the propeller (i.e. using the propellers to extract power from the flow) during approach on aircraft performance, in terms of:
   a. Longitudinal stability,
   b. Elevator effectiveness and control power, and
   c. Aerodynamic performance in trimmed conditions.

5. Quantify the effects of the propeller rotation configuration on aircraft performance in terms of:
   a. Longitudinal stability,
   b. Elevator effectiveness and control power, and
   c. Aerodynamic performance in trimmed conditions.

Note that the determination of performance in trimmed conditions may require consideration of additional variables/model attitudes compared to the other parts of the measurement challenge.

Besides completing the selected measurement challenge, each experiment should address the following topics:

- Effects of boundary corrections on performance parameters,
- Effects of Reynolds number on performance parameters, and
- Effects of operating conditions on the propeller noise emissions.

6 Required Preparation

Because of the scarcity of wind-tunnel time in a high-quality facility like the LTT, and the large number of students taking the practical, each group can be allotted 3 hours of testing time only. Therefore, it is critical that all group members arrive on time at the facility, and that all have actively participated in the test preparation. This is done by preparing a test plan, which should focus on the following topics:

- Test objectives (deduced from the measurement challenge)
- Performance indicators of interest (to be measured or to be derived from measurement data)
- Test conditions of interest (for example: freestream velocity, propeller thrust setting, model attitude, model configuration, etc.)
- Use of measurement techniques to obtain the required data

Based on the consideration of these topics, a test matrix is to be defined. This test matrix will serve as a schedule for the actual experiment, indicating which test points to take when and in what order. This helps the wind-tunnel operators (you) to maximize data quality and productivity. In the definition of the test matrix, account for the time required to:

- Set desired test conditions (freestream velocity, model attitude, advance ratio)
- Take actual measurements (sampling time)
- Perform configuration changes 'wind-off' (change control-surface setting, remove propeller, etc.)
- Acquire wind-off balance data[4]

An example test matrix is presented in Table 1. Note that this test matrix serves as an example only, and does not include all possible test variables. One of the considerations has to remain the efficient use of resources: gather all data required to formulate conclusions, but try to avoid obtaining superfluous data. Be prepared to defend every point in the test matrix. When designing the test matrix, build in a few decision points, so that you can perform checks during testing to verify the chosen strategy and possibly make an optional change.

Table 1: Example test matrix. (DPN = datapoint number, IU = inboard-up)

Polar	DPN	V_∞ [m/s]	Prop	*M1 RPS [Hz] (J)*	*M2 RPS [Hz] (J)*	α [deg]	β [deg]	δ_f [deg]	δ_e [deg]	Time [min]
1	1	0	On, IU	0 (N/A)	0 (N/A)	-5	10	10	0	0:01
1	2	0	On, IU	0 (N/A)	0 (N/A)	0	10	10	0	0:02
2	3	40	On, IU	98.24 (2.0)	98.24 (2.0)	-5	10	10	0	0:06
2	4	40	On, IU	98.24 (2.0)	98.24 (2.0)	0	10	10	0	0:07
2	5	40	On, IU	98.24 (2.0)	98.24 (2.0)	0	10	10	0	0:08
3	6	20	On, IU	49.12 (2.0)	49.12 (2.0)	0	10	10	0	0:09
3	7	20	On, IU	49.12 (2.0)	49.12 (2.0)	-5	10	10	0	0:10
etc.	…	…	…	…	…	…	…	…	…	…

For the tests with propellers installed, the limitations on the testing domain imposed by the available engine power should be considered. Performance data of the *isolated* propeller are provided in Appendix B to aid in the selection of the advance ratio for each propeller.

[4] When defining your test matrix, already define at what points you will need wind-off measurements, and at which conditions you will have to perform them.

7 Required Deliverables

The lab exercise involves two mandatory deliverables: the pre-test report and the post-test report. Submission deadlines are listed in Chapter 9.

7.1 Pre-Test Report

The pre-test report is a prerequisite for admission to the wind-tunnel test. The pre-test report describes the group's test plan. The report should fulfil at least the following requirements:

- Introduction discussing the selected measurement challenge and resulting test objective(s)
- Description of test plan (performance indicators, test conditions, measurement techniques, etc.)
- Description of approach envisioned to estimate propeller thrust from external balance data
- Complete test matrix including motivation of test points, and complete time planning with motivated selections of measurement time, accounted time for setup changes, etc.
- Maximum 8 pages (excluding pages taken for test matrix)
- Submitted as PDF file on Brightspace

The pre-test report serves as an extensive preparation of the experiment. The rubric provided in App. C (and on Brightspace) will be used by the lab-exercise supervisor to grade the report. The final result will be registered in the form of pass or fail, while the numeric mark obtained from the rubric will be communicated to the group for information only. Besides a mark, written and oral feedback will be provided by the course instructor before the experiment to make sure the test plan is realistic and feasible, and to allow for optimization of the test plan. The mark and feedback will be communicated through Brightspace. A support lecture is organized in week 2.5 of the course to have a central discussion in which you can pose your questions related to the preparation of the lab exercise.

A group is only admitted to the wind-tunnel experiment in case a pass is obtained for the pre-test report. In case of a fail, the group will need to improve the report until a pass is obtained.

7.2 Post-Test Report

The experiment is to be documented in a post-test report. This report should be understandable as a stand-alone document without reference to the pre-test report. You can re-use parts from the pre-test report if needed. The post-test report should fulfil at least the following requirements:

- Title page with (at least) names+student numbers, group number, measurement challenge
- Introduction discussing test objective(s) and measurement approach (from pre-test report)
- Concise description of experiment (facility, model, measurement techniques, test conditions)
- Concise description of applied boundary corrections
- Results section including:
    - Discussion of results in response to the measurement challenge
    - Comparison of raw data with the corrected data in a graphic form
    - Discussion of the adequacy of the corrections applied
    - Identification of the relevant scaling effects for:
        - Aircraft performance including power effects
        - Aircraft noise simulation including power effects
- Appendix with code used to implement boundary corrections and process data
- Maximum 20 pages excluding title page, test matrix, code listings
- Submitted as PDF file on Brightspace

The report describing the above aspects is to be submitted in advance before the oral exam. The rubric provided in App. D will be used by the lab-exercise supervisor to grade the report. The final result will be registered in the form of a numeric mark. Besides the mark, written feedback is provided on the report. The mark and feedback will be communicated through Brightspace.

The presentation of the results should be accompanied with a discussion of those results. The discussion should at a minimum cover the importance of the stability and control of the aircraft and the importance of including power effects when simulating it. This should also be done for the acoustic component of the power integration. Attention should be paid to the question of representativeness of the presented results for a realistic situation, and to the importance of boundary corrections. Recommendations for additional experimentation (other techniques, setups, facilities) aimed at increased representativeness of flight can be formulated. Since the experiment is performed with a scaled model, all results should be discussed in the scaled (non-dimensional) domain, with the scaling clearly defined and discussed.

8 Assessment

The formal assessment of the AE4115 course is done based on four deliverables/milestones: the pre-test report, the wind-tunnel test, the post-test report, and a final oral examination. The final grade is computed as the average of the numeric grades for the post-test report (group work) and oral exam (individual work), with weighting factors of 1/2 (post-test report) and 1/2 (oral exam, which will consist of both a defense of the lab report and an examination of all other course materials).

The interconnections between the four deliverables are shown in Figure 9. To pass the course, the following conditions should be met:

- The student's group has obtained a pass for the pre-test report (mandatory condition for admission to wind-tunnel test);
- The student has participated in the wind-tunnel test (mandatory condition for writing of post-test report);
- The student's group has obtained a mark of 5.0 or higher for the post-test report (mandatory condition for participation in oral exam);
- The student has obtained an individual mark for the oral exam of 5.0 or higher;
- The final averaged grade is 6.0 or higher.

The final grade is rounded to the nearest half mark, following the BSc and MSc rules and guidelines of the board of examiners of the faculty of Aerospace Engineering of Delft University of Technology.

In case of a grade below 5.0 for the post-test report, a revised version of the report needs to be submitted within 3 weeks of the day the feedback was sent to the group by the lab-exercise supervisor. The maximum possible grade for the revised version of the post-test report is 6.0.

In case of an insufficient grade for the oral exam, a resit can be scheduled at a convenient date for both examinee and examiner. In this case, the lab exercise will not need to be repeated if the post-test report mark was 5.0 or higher.

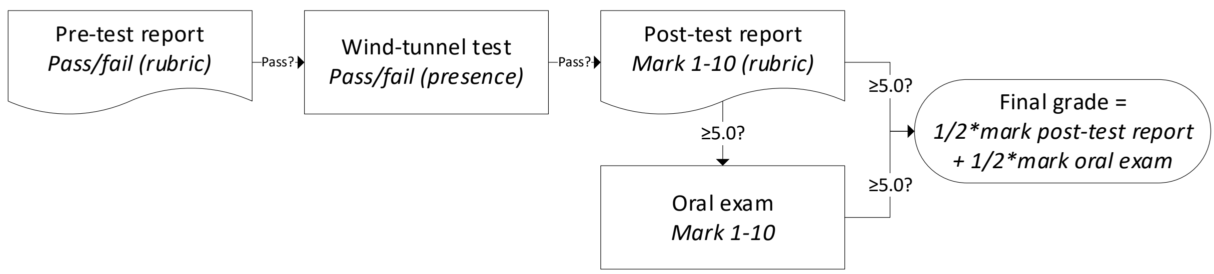


Figure 9: Assessment policy.

9 Planning

An overview of key events and associated deadlines is provided in Table 2.

Table 2: Key events and associated deadlines.

Event	Deadline
Group enrolment	22 Nov 2023 23:59
Pre-test report due	23 Jan 2024 23:59
Wind-tunnel test	19 Feb 2024 – 08 Mar 2024 (weeks 8/9/10)
Post-test report due	03 April 2024 23:59

One wind-tunnel test is to be performed by each group, following the schedule given in Table 3. **When enrolling in a group, please make sure that you have no other obligations during the test slot indicated for that group. Presence at the wind-tunnel test is mandatory, no exceptions made.**

Table 3: Wind-tunnel test slots for the different groups.

Time	Monday 19 February	Tuesday 20 February	Wednesday 21 February	Thursday 22 February	Friday 23 February
08:30 – 11:30	Reserved for preparation by staff	Reserved for preparation by staff	Group 1 (MC 1)	Group 4 (MC 4)	Group 7 (MC 2)
11:45 – 14:45			Group 2 (MC 2)	Group 5 (MC 5)	Group 8 (MC 3)
15:00 – 18:00			Group 3 (MC 3)	Group 6 (MC 1)	Group 9 (MC 4)

Time	Monday 26 February	Tuesday 27 February	Wednesday 28 February	Thursday 29 February	Friday 01 March
08:30 – 11:30	Group 10 (MC 5)	Group 13 (MC 3)	Group 16 (MC 1)	Group 19 (MC 4)	Group 22 (MC 2)
11:45 – 14:45	Group 11 (MC 1)	Group 14 (MC 4)	Group 17 (MC 2)	Group 20 (MC 5)	Group 23 (MC 3)
15:00 – 18:00	Group 12 (MC 2)	Group 15 (MC 5)	Group 18 (MC 3)	Group 21 (MC 1)	Group 24 (MC 4)

Time	Monday 04 March	Tuesday 05 March	Wednesday 06 March	Thursday 07 March	Friday 08 March
08:30 – 11:30	Group 25 (MC 5)	Group 28 (MC 3)	Additional groups if needed	Additional groups if needed	Additional groups if needed
11:45 – 14:45	Group 26 (MC 1)	Group 29 (MC 4)			
15:00 – 18:00	Group 27 (MC 2)	Group 30 (MC 5)			

MC = measurement challenge

The schedule is tight because of the large number of groups. Please note:

- The first slot of each day starts at 8:30. Be on time!
- Unfortunately it is unavoidable that the second slot of each day is scheduled around lunch time. Please be advised that it is not allowed to have lunch in the control room of the wind tunnel, so you will need to have lunch before or after the test slot.
- In case of serious delays due to a technical issue during earlier slots, a message will be posted on Brightspace to inform the remaining groups that are scheduled for testing on the same day.

A Detailed Specification of Wind-Tunnel Model

Technical drawings of the wind-tunnel model are provided in Figure 10. Detailed geometry characteristics are provided in Sections A.1 through A.5.

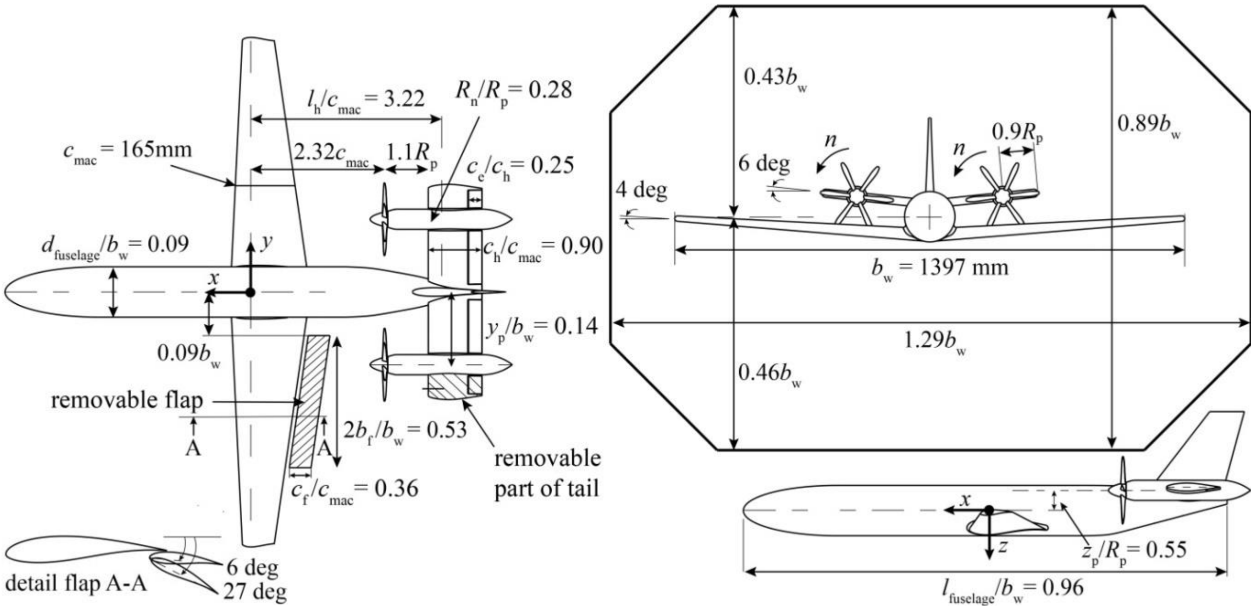


Figure 10: Technical drawing of wind-tunnel model.

A.1 Fuselage Geometry

The characteristic dimensions of the fuselage are provided in Table 4.

Table 4: Fuselage geometry.

Parameter	Value
Length	1.342 m
Diameter	0.140 m
Volume	0.0160632 m^3
Volume aft support strut (estimate)	0.0004491 m^3
Volume of wing support struts (estimate for both struts together)	0.0035296 m^3

A.2 Wing Geometry

Details of the wing geometry are provided in Table 5. The effects of ailerons can be evaluated by using the plain flaps integrated into the tip sections of the wing. A high-lift flap can be installed to the wing to simulate the aircraft behavior under high-lift conditions.

Table 5: Wing geometry.

Parameter	Value
Span	1.397 m
Area	0.2172 m^2
Mean aerodynamic chord	0.165 m
Aspect ratio	8.98
Taper ratio	0.40
Sweep angle at 0.25c	0 deg
Incidence angle	0 deg
Dihedral angle	4 deg
Twist	2 deg

Parameter	Value
Airfoil (constant over span)	DU 96-150
Aileron span	0.197 m
Aileron spanwise position	0.71 < $y/(b/2)$ < 0.99
Aileron chord	0.029 m
Flap span (per side)	0.369 m
Flap chord	0.060 m
Wing 0.25*c* from fuselage nose	0.680 m
Volume	0.0030229 m^3

A.3 Horizontal Tailplane Geometry

Details of the horizontal-tailplane geometry are provided in Table 6. A plain flap is available on the horizontal tailplane on both sides of the nacelle to simulate the effects of an elevator. A nacelle is integrated into both sides of the horizontal tailplane, with its centerline positioned at 70% of the tailplane's semispan. Each nacelle houses an electric motor with maximum power output of 2.5 kW.

Table 6: Horizontal-tailplane geometry.

Parameter	Value
Span (without rounded tip)	0.576 m
Area (without rounded tip)	0.0858 m^2
Mean aerodynamic chord	0.149 m
Aspect ratio	3.87
Taper ratio	1.00
Sweep angle at 0.25c	0 deg
Incidence angle	0 deg
Dihedral angle	6 deg
Twist	0 deg
Airfoil (constant over span)	NACA 64_2A015

Parameter	Value
Elevator chord	0.25c_{HT}
Elevator span inboard/outboard	0.148 m / 0.049 m
Elevator deflection range	±25 deg
Nacelle length	0.345 m
Spinner length	0.0485 m
Tail arm (tail *c*/4 to wing *c*/4)	0.535 m
Volume (without nacelle)	0.0009751 m^3
Volume 1 nacelle	0.0007921 m^3

A.4 Vertical Tailplane Geometry

Details of the vertical-tailplane geometry are provided in Table 7. The geometry of the vertical tailplane is defined according to a NACA definition, as provided in Figure 11.

Table 7: Vertical-tailplane geometry.

Parameter	Value
Span	0.258 m
Area	0.0415 m^2
Mean aerodynamic chord	0.170 m
Aspect ratio	1.606
Taper ratio	0.43
Sweep angle at 0.25c	33 deg
Incidence angle	0 deg
Dihedral angle	0 deg
Twist	0 deg

Parameter	Value
Airfoil (constant over span)	NACA 0015
Rudder chord	c_r = 0.0642 m c_t = 0.0438 m
Rudder span	0.182 m
Rudder deflection range	±20 deg
Tail arm (tailplane 0.25*c* to wing 0.25*c*)	0.543 m
Volume	0.0003546 m^3

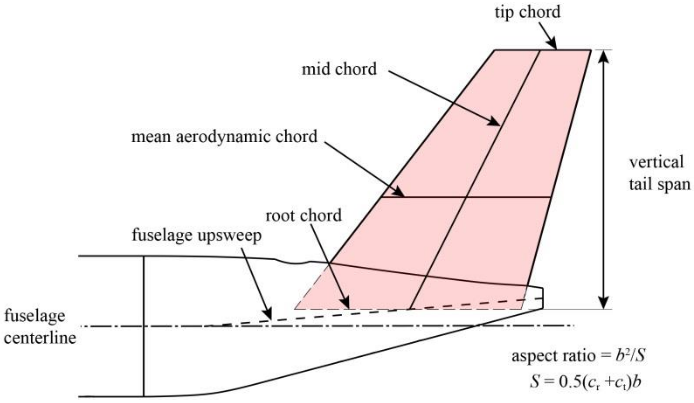


Figure 11: Definition of vertical-tail geometry.

A.5 Propeller Geometry

Details of the propeller geometry are provided in Table 8.

Table 8: Propeller geometry.

Parameter	Value
Number of blades	6
Diameter	0.2032 m
Pitch angle at r/R=0.7	45 deg
Rotation direction (from rear)	CW (2x) CCW (1x)

In principle, the pitch angle of the propeller blades can be varied. However, during this lab exercise insufficient time is available to do so. Therefore, all tests will need to be done with the pitch angle indicated in Table 8.

Each propeller is driven by an electric motor. The operating conditions of the electric motors are included in the data output files. The port-side motor is referred to as motor 1 (_1 appended to motor output variables), and the starboard-side motor as motor 2 (_2 appended to motor output variables).

B Performance Characteristics of Isolated Propeller

The performance characteristics of the isolated propeller in terms of thrust coefficient ($C_T = T/\rho n^2 D^4$) and efficiency ($\eta = JC_T/C_P$) are provided in Figure 12. The data are based on measurements and numerical simulations. A clear change in performance can be observed with changing freestream velocity, which is attributed to Reynolds-number effects on the propeller blades. Clearly, this will lead to a difference in performance with respect to a full-scale version of the same propeller.

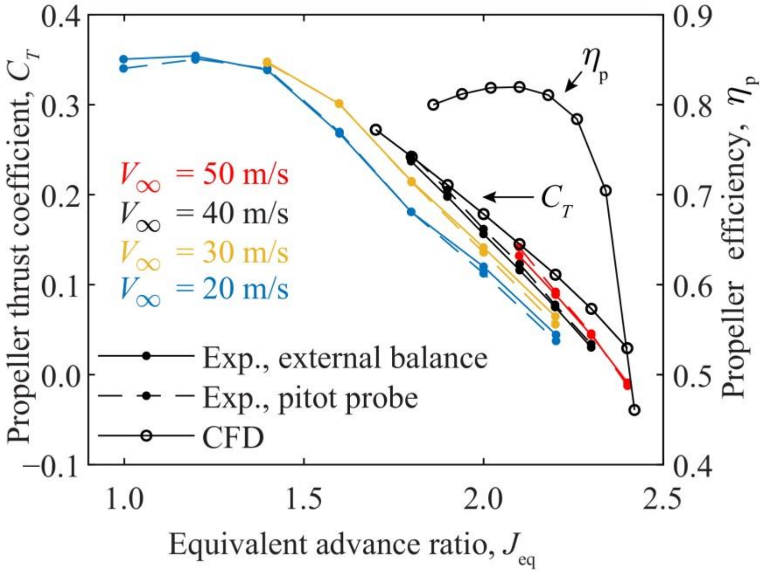


Figure 12: Performance characteristics of the isolated propeller.

No measurement data are available for the propeller performance in the negative thrust/power regime. In order to support the selection of operating conditions in this regime, blade-element-momentum simulations have been performed of propeller at realistic operating conditions:

- V_{inf} = 40 m/s
- Pitch setting at r/R=0.70 = 45 deg
- Advance ratio $J = V_{inf} / nD$ between 0.8 and 5.0

The resulting data in terms of thrust and power were used to define response models for the thrust and power coefficients C_T and C_P w.r.t. the advance ratio J:

- $C_T = \frac{T}{\rho n^2 D^4} = -0.0051J^4 + 0.0959J^3 - 0.5888J^2 + 1.0065J - 0.1353$
- $C_P = \frac{P}{\rho n^3 D^5} = -0.0093J^4 + 0.1832J^3 - 1.1784J^2 + 2.2005J - 0.5180$

If you want to assess drag and power generation performance you may want to convert to T_C and P_C ($T_C = C_T/J^2$, $P_C = C_P/J^3$).

Note that the numerical simulation of propellers at low Mach number and low Reynolds number is difficult, hence these results should only be used to obtain an impression of representative operating conditions in the negative thrust/power domain.

C Rubric Pre-Test Report

Levels (mark) / Criteria (weight)	*Insufficient (fail)*	*Sufficient (6)*	*Good (8)*	*Excellent (10)*	Feedback/ Comments
Performance indicators (10%)	The identified performance indicators are insufficient to complete the measurement challenge, and are incomplete, not clearly defined, not specific, realistic, or quantifiable.	The identified performance indicators are aligned with the measurement challenge, but are incomplete. Some parameters are not specific, realistic, or quantifiable.	The identified performance indicators are aligned with the measurement challenge. Some parameters are not specific, realistic, or quantifiable.	The identified performance indicators are clearly defined, fully cover the measurement challenge, are specific, realistic, and quantifiable.	
Governing parameters and dimensional analysis (20%)	The identified governing parameters do not relate to the test objectives. Parameters are presented in dimensional form, without appropriate scaling, or no systematic dimensional analysis has been performed.	The identified governing parameters relate to the test objectives. No motivation is provided for the selected parameters. Parameters are presented in dimensional form, without appropriate scaling, or no systematic dimensional analysis has been performed.	The correct governing parameters are identified. An incomplete motivation for the selection of the proposed governing parameters is provided. Parameters are presented in nondimensional form and based on systematic dimensional analysis, but scaling of some parameters is not appropriate for the test objectives.	The correct governing parameters are identified and a solid motivation is provided for the selection of the proposed governing parameters. All parameters have been nondimensionalized with relevant parameters for the measurement challenge at hand, based on a systematic dimensional analysis.	
Limitations experimental setup (20%)	The limitations of the test setup have not been identified and discussed.	A partial identification and discussion of the limitations of the test setup is provided, without discussing ways of minimizing the impact of these limitations on the test results.	The limitations of the experimental setup are identified and discussed, but only partially related to the test objectives. Some ways of reducing the impact of these limitations on the test results have been described.	The limitations of the experimental setup are identified and discussed, linked to the test execution and measurement objectives, and a discussion is presented on how to reduce the impact of these limitations on the test results.	
Feasibility of test matrix (15%)	Time planning is absent or overly optimistic. The test matrix will need to be redefined in order to make it fit into 3 hours. In the current form, the test objectives will not be met by performing the first 3 hours of the test matrix.	Time planning needs to be improved to be able to complete the proposed test matrix in 3 hours. The first 3 hours of the test matrix will be sufficient to reach the defined test objectives.	The proposed test matrix can be completed in 3 hours by removing unnecessary measurements without compromising the test objectives.	The proposed test matrix can be fully executed in 3 hours.	
Quality of test matrix (15%)	The test objectives can partially be met by executing the test matrix. Required data points are missing. No measures have been taken to optimize data quality and test productivity.	The test objectives can be met by executing the test matrix. No measures have been taken to optimize data quality. The test productivity has not been considered.	All test objectives can be met by executing the test matrix. Limited measures have been taken to optimize data quality. The test productivity can be improved by changing the test matrix.	All test objectives can be met by executing the test matrix. Effective measures have been taken to optimize data quality and test productivity.	
Motivation of test matrix (20%)	The selection of the test points in the test matrix is not motivated.	An incomplete motivation is provided for the selection of the test points in the test matrix. Additional explanation is needed to justify the choices made.	A motivation is provided for the selection of all test points in the test matrix. This motivation is not fully defendable.	A complete motivation is provided for the selection of test points in the test matrix. This motivation is fully correct, complete, and fully defendable.	
Knock-out criteria	The mark for each subcategory needs to be 6 or higher for a student group to be eligible for participation in the wind-tunnel experiment. Participation in this wind-tunnel experiment is a mandatory condition for admission to the final exam of the course.				

D Rubric Post-Test Report

Levels (mark) / Criteria (weight)	*Insufficient (≤5)*	*Sufficient (6)*	*Good (8)*	*Excellent (10)*	**Feedback / Comments**
1 - Introduction (10%)	The measurement challenge and test objectives are not described. Insufficient identification and motivation of scaling parameters and key variables: not clearly defined, wrongly defined, not specific, realistic, or quantifiable. Scaling parameters are not derived from a dimensional analysis.	The measurement challenge and test objectives are described, but the description is incomplete and partially incorrect. Incomplete identification and motivation of scaling parameters and key variables, with some incorrect or not specific, realistic, quantifiable. Scaling parameters are based on a dimensional analysis without fully systematic derivation.	The measurement challenge and test objectives are described and the interpretation is correct. Complete identification and motivation of scaling parameters and key variables, but some are not specific, realistic, or quantifiable. Scaling parameters are derived from a systematic dimensional analysis with some exceptions.	Complete description of the measurement challenge and test objectives with detailed interpretation. Complete identification and motivation of scaling parameters and key variables: all are specific, realistic, and quantifiable. Scaling parameters are derived from a systematic and complete dimensional analysis	
2 - Description of experiment (25%)	The test setup is not described, and its limitations have not been identified and discussed. The choice of test conditions is insufficient to answer the measurement challenge. A motivation for the selection of test conditions is missing.	The test setup is described but the identification and discussion of its limitations is incomplete. The choice of test conditions is sufficient to answer the measurement challenge but not aimed at maximum productivity and data quality. A motivation for the selection of test conditions is included but additional explanation is needed to justify the choices made.	The test setup and its limitations are identified and discussed. The choice of test conditions is sufficient to answer the measurement challenge and aimed at maximum productivity or data quality. A motivation for the selection of test conditions is included, but this motivation is not fully defendable.	The test setup and its limitations are identified and discussed. The choice of test conditions is excellent to provide a complete answer to the measurement challenge and aimed at maximum productivity and data quality. A motivation for the selection of test conditions is included, and this motivation is fully defendable.	
3 - Description of boundary corrections (15%)	The selection of boundary corrections is insufficient for the studied model configuration. The description of the corrections applied contains major scientific errors.	The selection of boundary corrections is suitable for the studied model configuration but some effects are ignored. The description of the corrections applied contains some scientific errors.	The selection of boundary corrections is appropriate for the studied model configuration and only minor effects are ignored. The description of the corrections applied is correct and complete, with only minor errors.	The selection of boundary corrections is complete for the studied model configuration. The description of the corrections applied is fully correct and complete.	
4 - Analysis of results (50%)	The discussion and/or analysis of results in the report is insufficient. The report does not answer the measurement challenge and cannot be used for scaling the observed phenomena to full-scale free flight.	There is a discussion and/or analysis of the results, but the quality is poor. The report partially answers the measurement challenge but can hardly be used for scaling the observed phenomena to full-scale free flight.	The discussion and/or analysis of the results covers the data set obtained and also reflects a critical view of the quality of the data. The discussion and/or analysis gives a good overview of what is requested for in the measurement challenge. The report can be used for scaling the observed phenomena to full-scale free flight with limited additional explanation.	The discussion and/or analysis of the results covers the data set obtained and reflects a well-balanced critical view of the quality of the data. Reading the discussion and/or analysis gives a very accurate and complete overview of what is requested for in the measurement challenge. The report can be used for scaling the observed phenomena to full-scale free flight without any problem and has the quality of a high level scientific publication.	
Determination of final mark	- Partial marks for each criterion are defined as integers from 1-10. - The final mark is the weighted average of the marks received for the four criteria, rounded to the nearest half. - The final mark must be 5.0 or higher to be admitted to the oral exam. - If the final mark is below 5.0, then a revised report will need to be submitted within 3 weeks of the day the first evaluation of the report was sent to you. The maximum possible mark for the revised report is 6.0.				
Final mark					