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Further Aerodynamics

UFMFXU-15-3

Assignment report

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Abstract:

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Contents:

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Description of Task 1:

Task 1 requires an analysis of the wind tunnel’s capabilities in maintaining constant Mach number, temperature and pressure variations when running in a controlled environment.

The analysis involved several key steps based on the design of the wind tunnel, with full profiles of the bottom and top liners provided in Tables A2 and A3 of the coursework brief. Initially, the theoretical Mach numbers along the working section were predicted using relevant theoretical considerations, and these predictions were presented in a graphical format.

Using data from the pressure transducers for each test condition, the Mach numbers along the working section were calculated for all pressure tapping points, assuming isentropic flow. The predicted pressures at various points along the nozzle were determined from the changes in cross-sectional area. For both runs, the predicted pressure ratio (P0/P) was calculated using isentropic process equations and compared with measured pressure ratios from manometer readings. Similarly, the temperature ratio (T0/T) was predicted using isentropic process equations and compared with experimental pressure measurements. These comparisons for pressure and temperature ratios were presented in a graphical format.

The test section Mach number was calculated from the measured oblique shock wave angle in the wedge section aerofoil. Details regarding the workpiece location within the working section and precise aerofoil measurements were utilized. The evolution of the flow over the wedge was also calculated.

Uncertainties in the results, including the experimental Mach number and pressure ratios, were calculated.

Task 1.1: Mach number variations and Ratios

To start, a visual representation of the wind tunnel was created in MATLAB using the liner dimensions provided in the coursework brief.

As the coordinates for the top and bottom liners have mismatched coordinate locations, interpolation was required to fill in the missing portions and generate usable data. By examining the image of the liner profiles, one can see that the bottom liner is flatter than the top, making this a prime target for interpolation, as the number of coordinate points provided for this liner fell far short of the top liners’.

Following this, the interpolated data was corrected to show how they vary along the working section. To do this, the centre of the wind tunnel(3 inches of its diameter) will be used as a reference point. The coordinates will then be added or subtracted to that constant – 3in – in order to show how the section varies. See the plot below for a better understanding of what this means.

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Following these corrections, the theoretical Mach number variation along the working section was calculated using the Newton-Raphson method. The following equations were used as part of the method:

To fully utilise the Newton-Raphson method here, the ratio of the local area to the area at the throat is needed. This ratio shows how the Mach number varies through the wind tunnel, as pressure, area and velocity(and by extension Mach number) are all related. As pressure increases due to a decrease in area, the velocity of the free stream air must also decrease. With this in mind, we can assume that the velocity - and therefore Mach number - is at its lowest when at the throat, and at its highest elsewhere. We can then use this assumption and set the throat as a reference point to see how much larger the Mach number will be in sections of the wind tunnel with larger areas. In theory, the Mach number should not be lower than one, as that would suggest that the throat does not have the smallest area. The

The resulting Mach numbers were then plotted against the working section length.

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These Mach numbers were then used as part of the formulae below to calculate the theoretical pressure and temperature ratios.

These have also been plotted along the working section length.

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Task 1.2: Mach number, pressure ratio and temperature ratio variation

The wind tunnel is run at 2 different pressures – 150psi and 75psi – which are the 2 conditions under which the working section is tested.

The provided data was given in text format and could not easily be converted to a readable spreadsheet. To achieve a usable tabular format, the data was be split into individual elements and the reassembled into a usable table/array.

Following this, the data was converted from psi into Pascals and made individual by adding 269(the last three digits of my student ID) to the converted values. An average pressure at each operating pressure was then found and used alongside the equations below to calculate and plot the experimental Mach number, temperature ratio and pressure ratio variations along the working section.

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The comparison between the experimental and theoretical results reveals discrepancies in the Mach number variations. Notably, there are inconsistencies between the experimental results under different working conditions and between the experimental and theoretical results. While the theory predicts a smooth transition to supersonic flow and assumes a stable supersonic regime after transitioning at the throat, the experimental results do not align perfectly with these predictions.

This discrepancy can be attributed to factors such as boundary layer formation and shock wave interference with the airflow. The theoretical methods used assume inviscid flow, meaning they do not account for the effects of viscosity. In reality, airflows are viscous, leading to more complex behaviours than those predicted by simple theoretical models.

The divergence between theory and experiment is especially noticeable when examining the experimental results. The flow behaviour trends for each working condition show immediate divergence even before reaching the throat, with some locations exhibiting higher pressures under certain conditions than others. This highlights the limitations of theoretical models which assume perfect gas behaviour in capturing the complexities of real-world airflow.

Task 1.3: Shock

Assuming isentropic flow, the theoretical Mach number is used as a starting point to calculate shocks over and under the wedge, with all shocks considered oblique. The wedge deflection angle (θ) is calculated using trigonometric principles applied to the wedge geometry. The center of the wedge is assumed to be at the center of the working section, allowing determination of the x-coordinate of the wedge leading edge (LE) and subsequent calculation of the theoretical Mach number (M1) at this point via interpolation.

The oblique shock angle for M1, measured from the schlieren screen image, is 40°. For other oblique shock angles, the Oblique Shock Angle Chart (NACA Report 1135) is referenced. The normal Mach number for region 1 is calculated using:

The Mach number for region 2 is calculated using:

For downstream Mach numbers, the Prandtl-Meyer function table and the following formulas are used:

To find the Mach number in region 4, the normal Mach number in region 3 is calculated:

and then the Mach number in region 4 is found using:

|  |  |  |  |
| --- | --- | --- | --- |
| Position | Mach Theo. | Experimental | Shock Angle - Theoretical and Experimental |
| Free stream(M1) | 2.3940 | 1.7533 | 40, 41 |
| M2 | 1.4464 | 1.4008 |  |
| M3 | 1.4450 | 1.7850 | 36, 38 |
| M4 | 1.9015 | 1.6258 |  |

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Task 1.4: Comparing Theory to Experimental Observations

Assumptions of low and high Mach numbers, derived from compressible flow equations using the Newton-Raphson method, reveal the variations in Mach numbers along the tunnel due to differing pressures. The experimental data often peaks later than the theoretical predictions. Notable discrepancies, such as decreases in Mach number at the wedge's leading and trailing edges, indicate phenomena like shock-induced flow separation and reattachment, which reduce velocity. Factors contributing to these lower Mach numbers include boundary layer viscosity effects causing flow separation under adverse pressure gradients, design imperfections like non-ideal gas behaviour, and limitations of the experimental instruments. An ideal situation, where 'choking' occurs at the throat as flow reaches Mach 1 before transitioning to supersonic speeds comes into direct contrast with the experimental results. This suggests that there exist deviations from adiabatic and isentropic assumptions due to boundary layer and shock interactions not accounted for in theoretical models (Babinsky & Harvey, 2011).

The slight decrease in experimental Mach number both before the leading edge and after the trailing edge indicates potential shock-induced flow separation. The slight rise in Mach number between these points could be a sign of the flow reattachment. The flow through the nozzle is often assumed to be adiabatic and isentropic. Under such conditions, conservation of energy implies that the gas's thermal energy decreases as its kinetic energy increases, allowing the gas to reach sonic speeds at the throat where the kinetic energy is maximized for a given total enthalpy.

The experimental Mach number is calculated using the pressure ratio, assuming isentropic flow conditions, meaning that the flow, while following conservation laws of energy, mass, and momentum remains reversible and adiabatic. As the theoretical approach does not account for measurement uncertainties like human error, or boundary layer growth, further discrepancies between the theoretical results and experimental results may be observed.

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Task 1.5

To calculate uncertainties, the following formulae was used:

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Summary of Task 1

To summarise, task 1 is an investigative exercise to investigate the differences between experimental findings and theoretical predications of the behaviour of supersonic flow over an angled wedge. Missing data, invalid data and the need to represent physical phenomena graphically necessitated the use of functions such as interpolation and the use of iterative methods such as the Newton-Raphson method.

The result of this exercise is to discuss the reasons for any discrepancies between experimental and theoretical methods of supersonic airflow analysis as well as explore the potential reasons for these differences.

Description of Task 2

Task 2 requires an investigation of the drag forces acting on an aerofoil using the momentum method inside of a low-speed wind-tunnel.

As part of this investigation, data measured at the wind tunnel is used to calculate the absolute drag, coefficients of drag and speeds of the airflow while the wind tunnel was in operation.

Task 2.1: Momentum Method Analysis

The momentum method was employed to calculate the aerofoil drag, revealing the impact of flow separation and angle of attack on drag. The findings indicated that the drag coefficient rises with increasing angle of attack, consistent with the theoretical concept that flow separation increases drag. This highlights the intricate relationship between the aerofoil's orientation and the airflow, suggesting that more detailed analysis, possibly including computational simulations, is required for a deeper understanding.

Adhering to the principle of momentum conservation, the following method was used. The experimental dynamic pressure is converted to the downstream fluid velocity(u­2)​ using:

This downstream velocity is then integrated to determine the momentum loss, allowing calculation of the drag force using:

Here, ρ2\rho\_2ρ2​ and u2u\_2u2​ are the fluid density and velocity downstream of the wing, and u1u\_1u1​ is the freestream velocity.

Finally, the drag coefficient is calculated with:

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Task 2.2: Uncertainty Analysis

Analysing the uncertainties inherent in this experiment showed that small errors in measurement(human or otherwise) had an outsized impact on the resulting mach numbers and other critical experiment parameters. To provide a quantitative view of the data, statistical method were applied to the uncertainties of the equipment used in order to provide clarity on how reliable the results generated are and how reliable the setup used to perform these experiments may be.

The following formulas were used to perform this analysis:

A math equations and formulas

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The uncertainties of the equipment used in the experiment are as follows:

|  |
| --- |
| NACA-0012 aerofoil – 0.5 mm |
| Extech HD350: Pitot Tube Anemometer – 0.5 Pa |
| Dynamic pressure transducer – 0.01 Pa |
| Barometer – 0.5 mbar |
| Angle of Attack protractor – 0.5° |

The calculated uncertainty values for the total coefficient of drag are as follows.

Summary of Task 2

Using a low speed wind tunnel, an analysis of the drag forces acting on the NACA-0012 aerofoil was carried out using the momentum method. The final outputs of this exercise is a table showing the uncertainties of the equipment as well as graphical representations of the relationship between flow velocity and coefficient of drag to the height of the working section.

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Holger Babinsky and Harvey, J. (2011) *Shock wave-boundary-layer interactions*. Cambridge University Press. [Accessed 01 July 2024].

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Supersonic WT raw test data;

Subsonic WT raw test data;

Any formula used not shown in main body of the report, you can cite UFMFXU-15-3 formula sheet file in the reference.