

Digital Twin Development: Aerodynamic Load Reconstruction for the Structural Response of an Aeroplane Wing

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Introduction

Digital twinning is a recent concept that is seeing application in ranges of different fields including structural health and usage monitoring in the aviation industry. A significant challenge has been **reconstructing the aerodynamic loading** of a wing using a limited number of sensors and predicting the **subsequent structural response**.

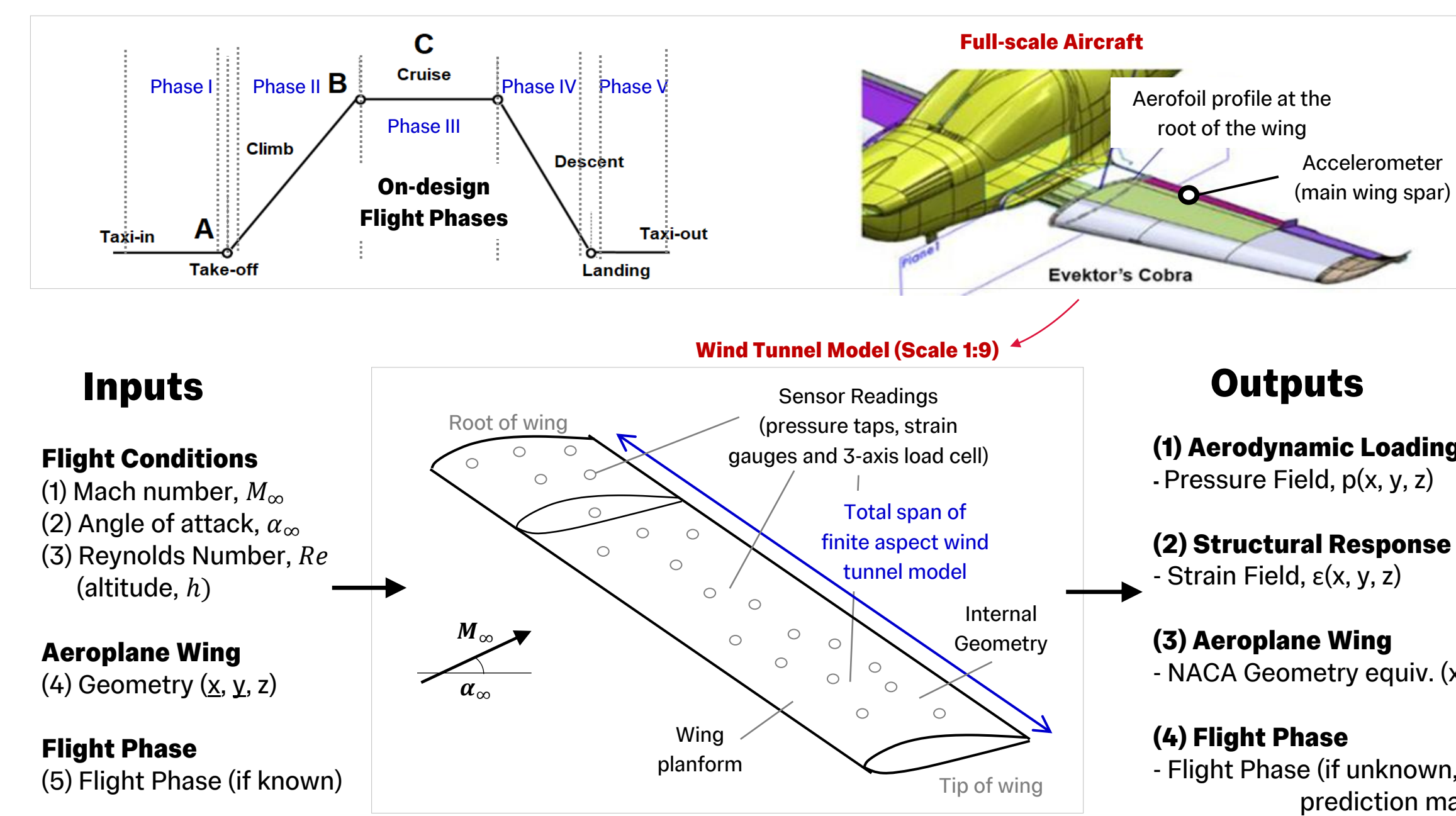


Figure 1: Framework of the DT platform showing the inputs and outputs.

The main inputs to the DT platform are in terms of the aerodynamics are the free-stream; (i) **Mach number, M_∞** , (ii) **angle of attack, α_∞** ; and (iii) **altitude, h** hence, **Reynolds number, Re** . The main output is the pressure field and subsequently the structural response via the strain field.

Project Aims and Objectives

1. Develop an aerodynamic DT model for **reconstructing the pressure distribution** of an aeroplane wing based on limited pressure readings for different flight phases.
2. Accurately predict the **structural response** of an aeroplane wing based on the reconstructed aerodynamic load and limited strain gauge readings.
3. Use flight test data from the Cobra aircraft to correctly predict the **flight phase categorisation** using advanced machine learning codes.

Aerodynamic Load Reconstruction

The aeroplane wing of Evktor's Cobra can be represented with a NACA3418 representation of the aeroplane wing. Using low-fidelity XFOIL, and accounting for 3D effects due to downwash, a numerical database was created to predict the pressure distribution of a finite aspect ratio wing. For this profile, and assuming a rectangular wing, a lab scale wind tunnel model (scale 1:9) was developed and tested in the T1 wind tunnel at Imperial College London (ICL).

The model was instrumented with; (i) pressure taps, (ii) strain gauges (iii), 3-component load cell, and (iv) flow tuft visualisations. The following free-stream wind tunnel conditions of $U_\infty = 0 - 25 \text{ ms}^{-1}$ and $\alpha_\infty = -4^\circ - +8^\circ$ were investigated. Flow tuft visualisations suggest the flow is attached for the range of the conditions tested.

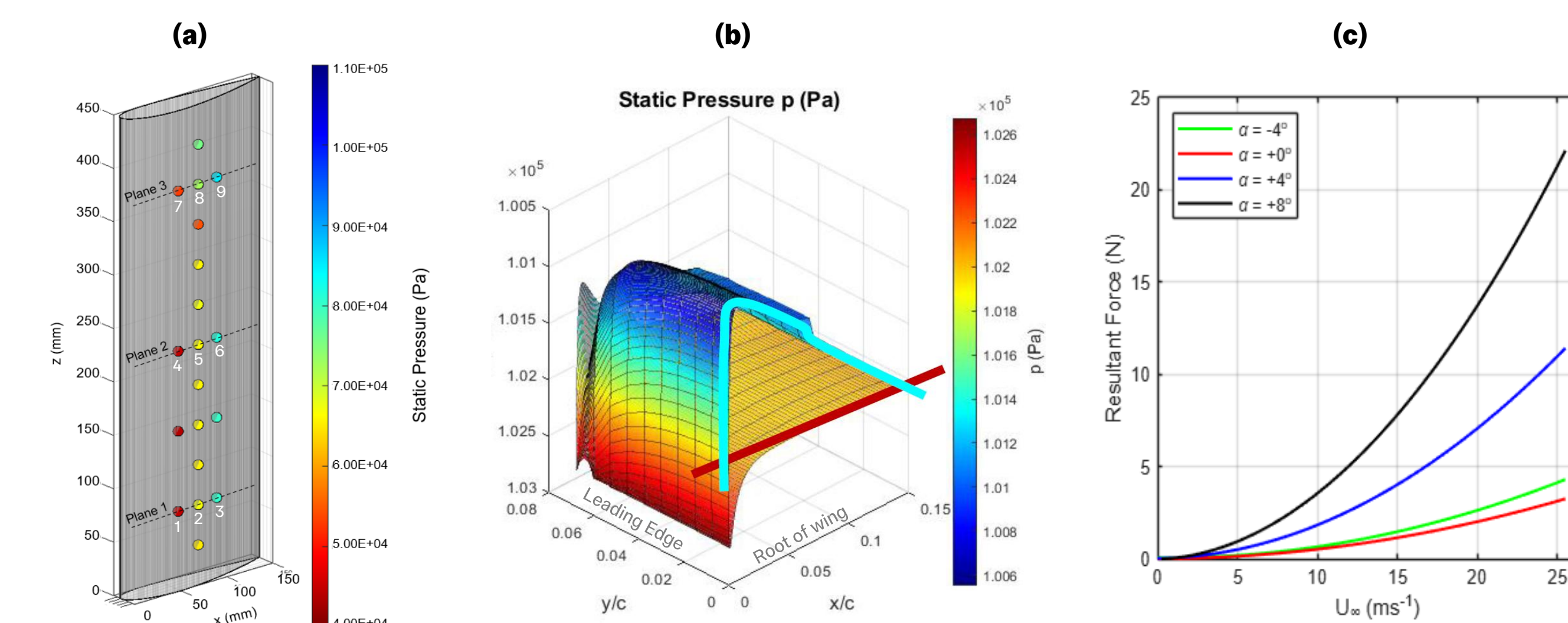


Figure 2. (a) Pressure tap readings for $U_\infty = 25 \text{ ms}^{-1}$ and $\alpha_\infty = +8^\circ$. (b) Pressure distribution predicted from XFOIL. (c) Load cell measurements for $U_\infty = 0 - 25 \text{ ms}^{-1}$ and $\alpha_\infty = -4^\circ - +8^\circ$ with a 2nd polynomial fit based on the raw data.

Reconstruction Method Outline

1. Combine sparse pressure tap data with XFOIL predictions to estimate the loading. Integrate this this estimated aerodynamic loading and compare the results to load cell measurements where $F = \frac{1}{2} \rho U_\infty^2 A$.
2. Predicted aerodynamic loading based on reduced-order Navier-Stokes equations for the full-scale wing and the wind tunnel model. Predicted loading compared to load-cell measurements.
3. Conduct salient CFD calculations and compare these results to experimental results for both the lab-scale model and the full-scale wing to establish Reynolds number effects and accuracy of the load reconstruction.

Structural Response

1. Estimate the material properties of the PLA-based 3D printed model using the experimental data collected from the strain gauges.
2. Input the reconstructed pressure field into ABAQUS and calculate the structural response in terms of stress and strain fields.
3. Directly link the pressure tap readings to the stress and strain field.

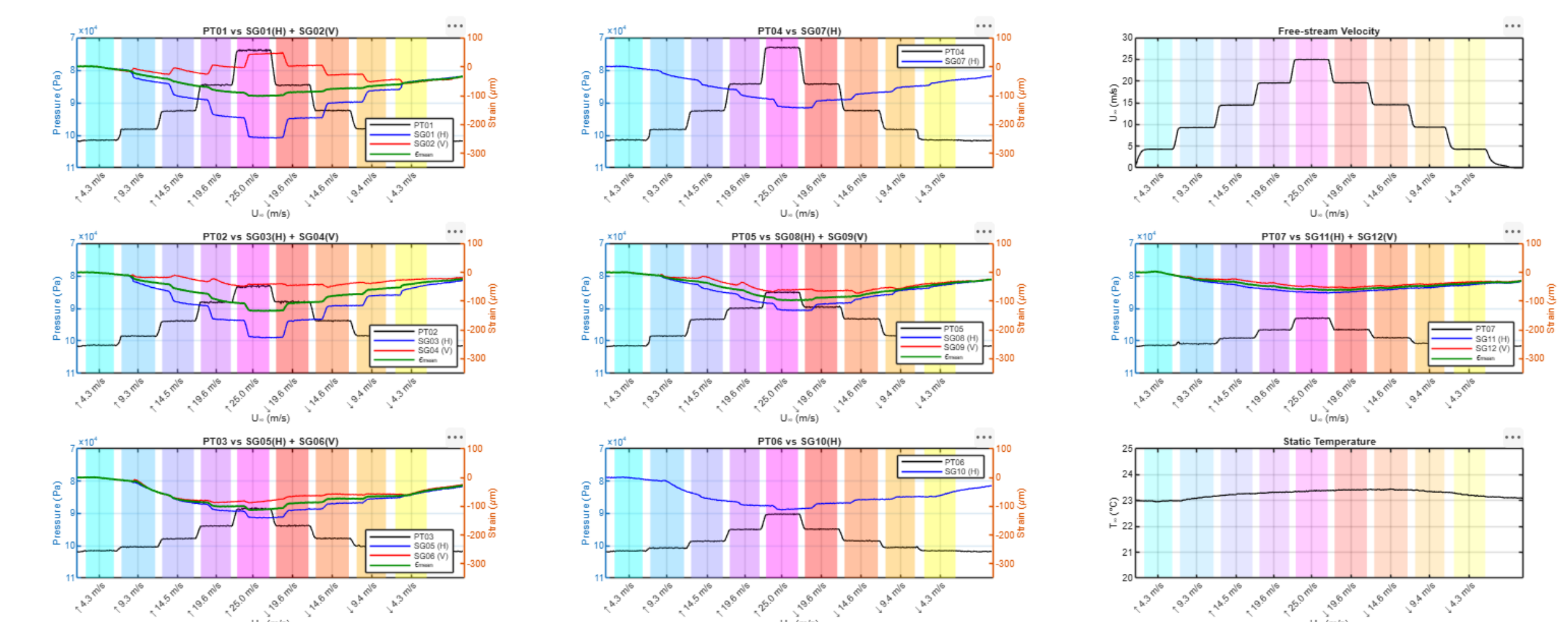


Figure 3: The relationship between pressure taps 1-9 and 12 strain gauges, with the horizontal strain gauge measurements in red, vertical in blue; and where applicable, average of horizontal + vertical in green for $U_\infty = 25 \text{ ms}^{-1}$ and $\alpha_\infty = +8^\circ$.

Flight Phase Detection

The flight test data can be split into on-design; taxi, climb, cruise and landing; and the off-design manoeuvres. Self-Organising Maps (SOM) are used to categorised the different flight phases using sensor readings only without manual labelling. For the on-design flight regimes, there is perfect classification for taxi, cruise and landing, with an overall accuracy 85.7%.

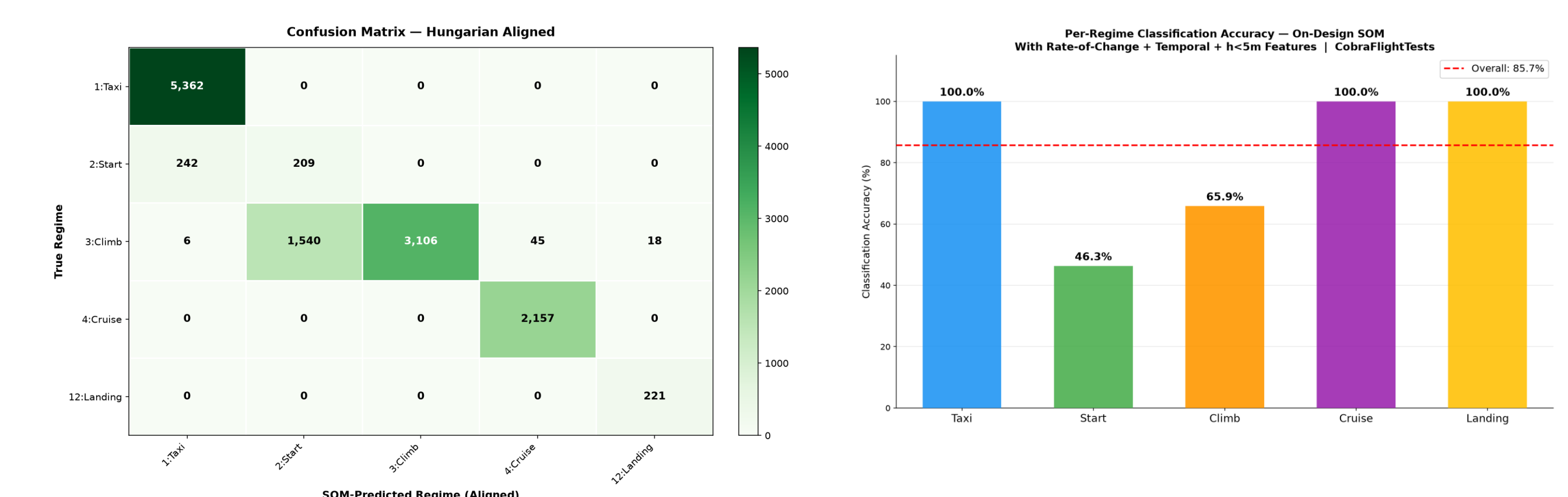


Figure 4. (a) Confusion matrix (Hungarian aligned) for the on-design regimes. (b) Bar chart showing the classification accuracy per on-design flight regime with an overall accuracy of 85.7%.