

Proposal For Distinguishing Usable Data Under High Wind Tunnel Blockage Using an RAE2822 Test Case

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Abstract

Transonic buffet, driven by unsteady shock–boundary layer interaction, significantly affects aircraft performance, safety, and structural integrity. Its behaviour is highly sensitive to Mach number and angle of attack, with a weaker dependence on Reynolds number, and remains difficult to predict accurately. Wind tunnel testing typically relies on ventilated walls and correction methods to account for buoyancy, support interference, and blockage effects. However, in smaller facilities operating at moderate to high blockage, these correction methods may become unreliable. Under such conditions, distinguishing between usable and non-usable experimental data for free-air validation becomes difficult. This study proposes a practical methodology based solely on wind tunnel top-wall pressure measurements to (i) estimate model buffet onset and (ii) identify tunnel flow breakdown, for example under choked conditions. The method exploits changes in the curvature and gradient of the wall pressure coefficient with angle of attack, using a limited number of strategically located pressure taps. The approach is demonstrated using a rectangular wing model with an RAE2822 aerofoil section tested in the Pilot European Transonic Wind Tunnel (PETW) over a Mach range of 0.50–0.79 and Reynolds numbers of 9 and 15.7 million. Buffet onset predictions derived from wall pressure measurements were benchmarked against established criteria based on surface pressure, global aerodynamic coefficients and pitching moment behaviour, showing consistently good agreement across the tested conditions. The method also identifies a clear boundary between regimes in which wind-tunnel data remain representative of free-air behaviour and those in which blockage effects increasingly dominate the measured response. As such, the proposed approach offers a simple, low-instrumentation tool for data reduction on datasets prior to CFD validation, thereby improving confidence in transonic wind-tunnel measurements acquired under high-blockage conditions.

Keywords: Transonic Aerodynamics, Wind tunnel Blockage, Data reduction methods, CFD.

1. Introduction

Wind tunnel testing remains a fundamental tool for investigating transonic aerodynamic phenomena. However, its reliability is strongly affected by wall interference effects, particularly under moderate to high blockage conditions. Classical correction methods, largely developed for attached or mildly separated flows, can become less reliable when large scale separation or pronounced shock wave boundary layer interactions (SWBLI) are present.

Advances in correction methodologies, including panel-based techniques and approaches based on wall pressure measurements [1, 2], have improved the estimation of key quantities such as Mach number and effective incidence. Nevertheless, a central practical question remains: how can it be reliably identified which wind tunnel data remains usable for free air comparison as blockage and wall interference effects become increasingly significant?

Existing buffet detection methods, described in Lawson et al [3], typically rely on measurements obtained directly from the model which includes trailing edge surface pressure distributions, lift curve and pitching moment break. While these methods are well established and are quite accurate, such measurement techniques are not always available in industrial or legacy test campaigns. The

proposed method enables prediction of buffet onset of the model, consistent with established approaches in the literature.

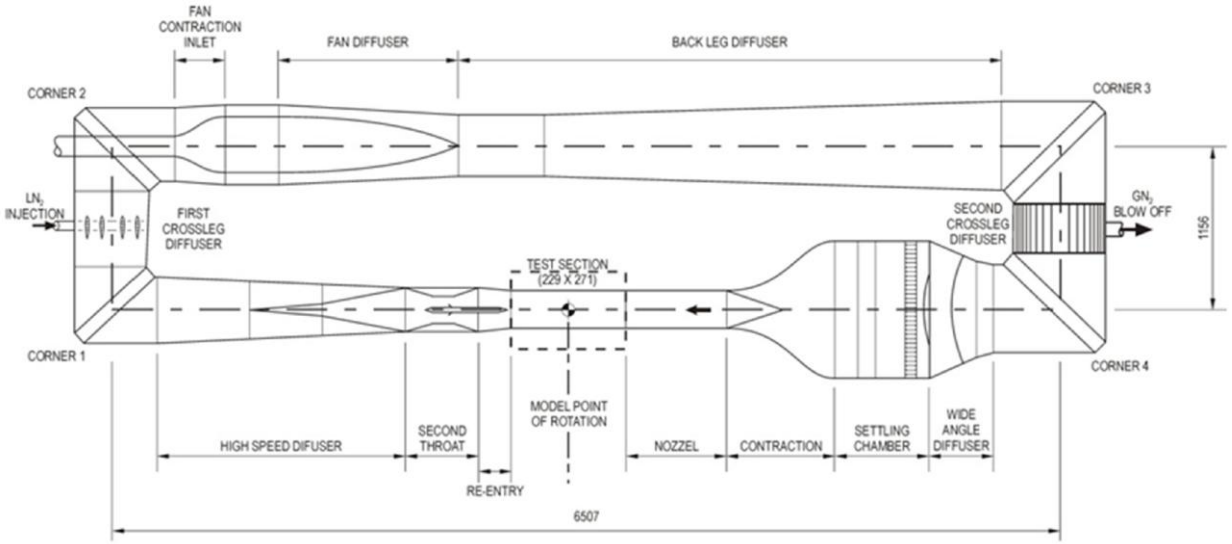
This work addresses this gap by proposing a methodology based exclusively on wind tunnel top wall pressure measurements. The approach uses the changes in wall pressure behaviour with angle of attack to identify both (i) model buffet onset (compared with established criteria from the literature) and (ii) the onset of tunnel flow breakdown associated with excessive blockage.

By doing so, it enables the classification of wind tunnel data into usable and non-usable regimes for free-air applications. The method is assessed using an RAE2822 test case in a transonic facility, with validation against established buffet onset criteria. Emphasis is placed on demonstrating that the method remains reliable in situations where model instrumentation is limited and where RANS based CFD comparisons are high computationally expensive to be used routinely for identifying valid operating conditions.

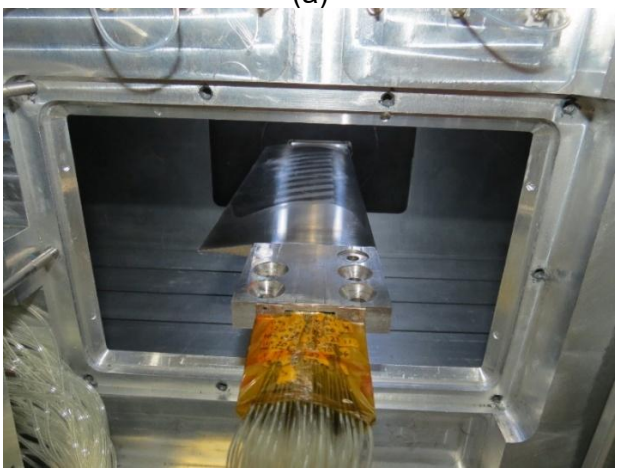
2. Methodology

2.1 Experiment

A series of tests with the RAE2822 2D section were conducted in the Pilot European Transonic Wind tunnel (PETW), shown in Figure 1. The PETW is a small-scale wind tunnel version of the main ETW wind tunnel. The test section opening parameters is 229mm high by 271mm wide. The wing model was 271mm in span with a chord of 90mm. Tests were performed with the 2D wing mounted horizontally in the slotted PETW test section at Mach numbers from 0.50 to 0.79 at two Reynolds numbers, specifically 9.0 and 15.7 million, at cryogenic temperature of 115 K (-158°C). A range of test parameters were covered which included pressure levels from 194 to 365 kPa resulting in dynamic pressure levels from 46.3 to 99.1 kPa. At each discrete test condition, the 2D panel was moved in pitch-and-pause mode of operation over an incidence range from -1° to +5° with pressures data acquired at 0.5° increments. The pressure measurements were taken at the centreline of the model using a total of 74 pressure tappings (46 upper and 28 lower), as show in Figure 2, 17% from the right-side wall and 33% from the left side of the wing, both have 13 taps (9 upper and 4 lower). This is in accordance with the WINDY project from NWTF [4].



(a)



(b)

Figure 1 - (a) The wind tunnel circuit of PETW. (b) The RAE2822 model in the PETW working section.

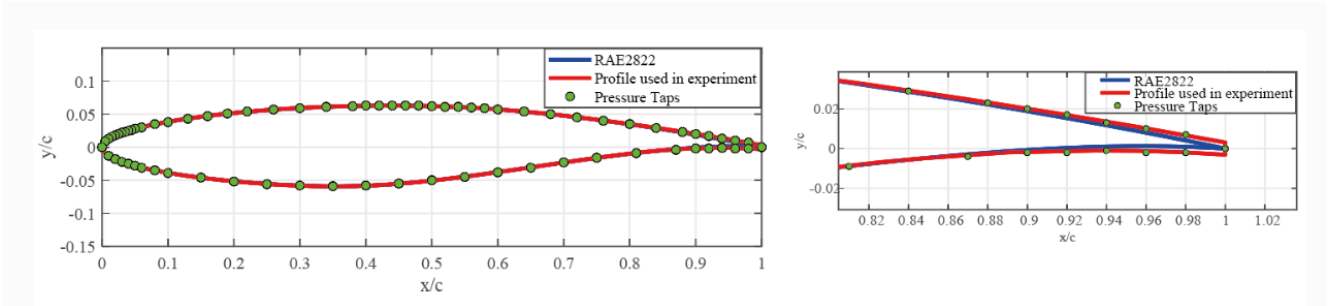
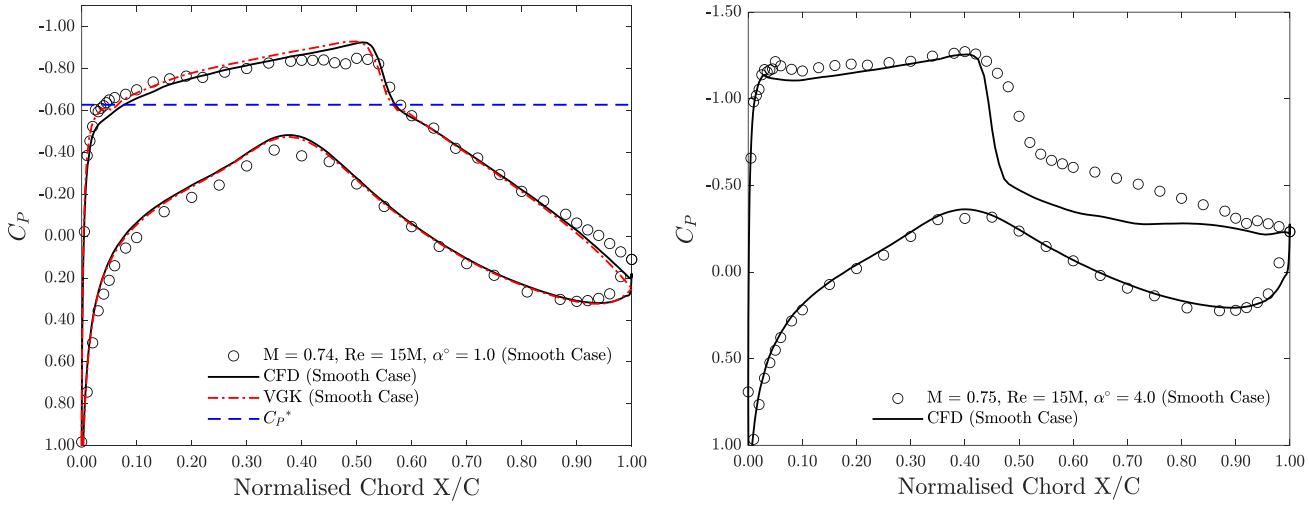


Figure 2 - RAE2822 aerofoil profile and pressure tap location on the centreline of the model [4].

2.2 Numerical Approach

The numerical approach was conducted on a free air RAE2822 test case with a domain radius larger than 10 chord lengths and flow conditions matching the experimental conditions. The side boundary conditions were set to periodic to simulate infinite wingspan. For low angles of attacks, up to ~2.0 degree (of course function of Mach number), the experimental measurement has been matched reasonably well but not for the higher angles of attack, near separation onset. Figure 3 (a) and (b) show the differences in comparison. It is important to mention that these figures are given as an example to showcase the pressure mismatch observed in Figure 3 (b).



(a) (b)

Figure 3 (a) Comparison at low α. (b) Comparison of free air RANS $\kappa - \omega$ SST (CFD) under high blockage experimental conditions. The "Smooth Case" in the figures describe the clean wing with no flow control added to it. Results are part of a broader study. Viscous Garabedian and Korn (VGK) is a 2D viscous full potential CFD software.

Further CFD analyses have been conducted, including the effect of the solid side walls. The analysis demonstrated that the flow can be captured more accurately at moderate angles of attack (up to ~3°), indicating the importance of modelling wind tunnel walls in CFD especially under large tunnel blockage. The selection of cases for CFD validation relied heavily on the method introduced in the following section, which provides a systematic approach for identifying conditions suitable for free-air comparison.

2.3 Proposed Method

A methodology is developed to identify the onset of tunnel and model flow breakdown, defining the Mach number–angle of attack boundary below which agreement with free-air data remains valid. The method uses measured pressures on the upper wall of the PETW working section. The centreline had 16 pressure taps. Only top-wall pressure taps were used for two reasons. First, streamline blockage occurs around the model and is significantly influenced by increased pitch at high subsonic speeds, where shock formation is already incipient. Wall effects reduce the available flow area, leading to local acceleration and increased blockage. The second reason is that the larger pressure variations are observed on the top wall when compared to those on the lower wall.

To determine the flow breakdown boundaries, specifically the buffet onset limit on the model and the onset of tunnel flow breakdown, a single fixed wall pressure tap was selected in the vicinity of the model. The chosen tap needed to exhibit trends consistent with neighbouring taps across the Mach and Reynolds number ranges, ensuring that the indicator was robust and insensitive to local anomalies. Based on this criterion, the top-wall pressure tap closest to the model's trailing edge (pressure tap 11, PT = 11) was selected as the primary indicator. Its location is highlighted in Figure 4.

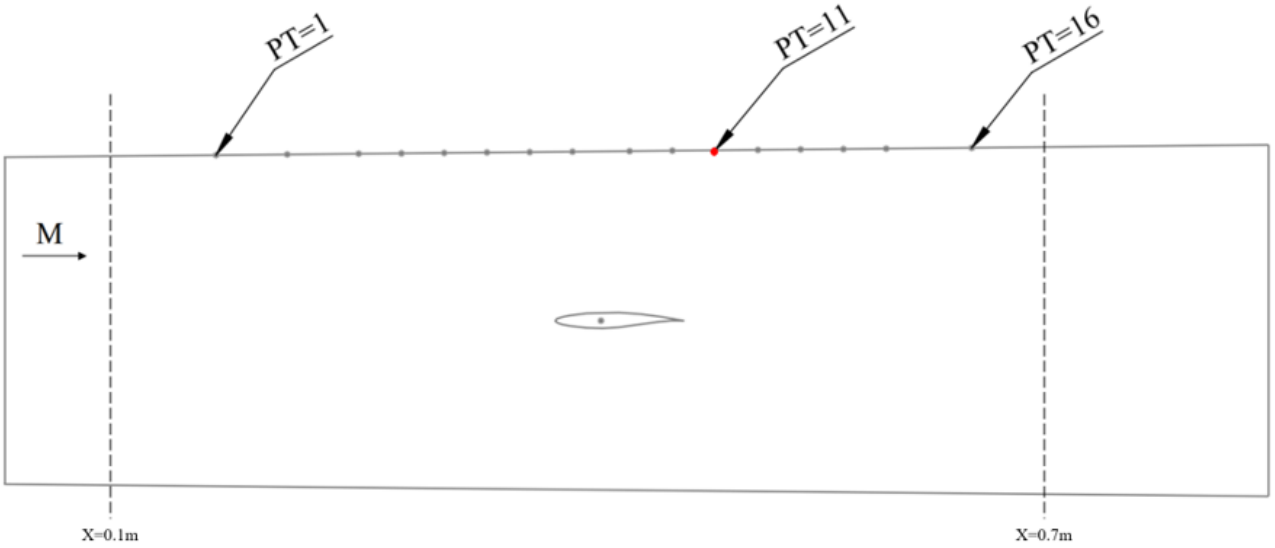
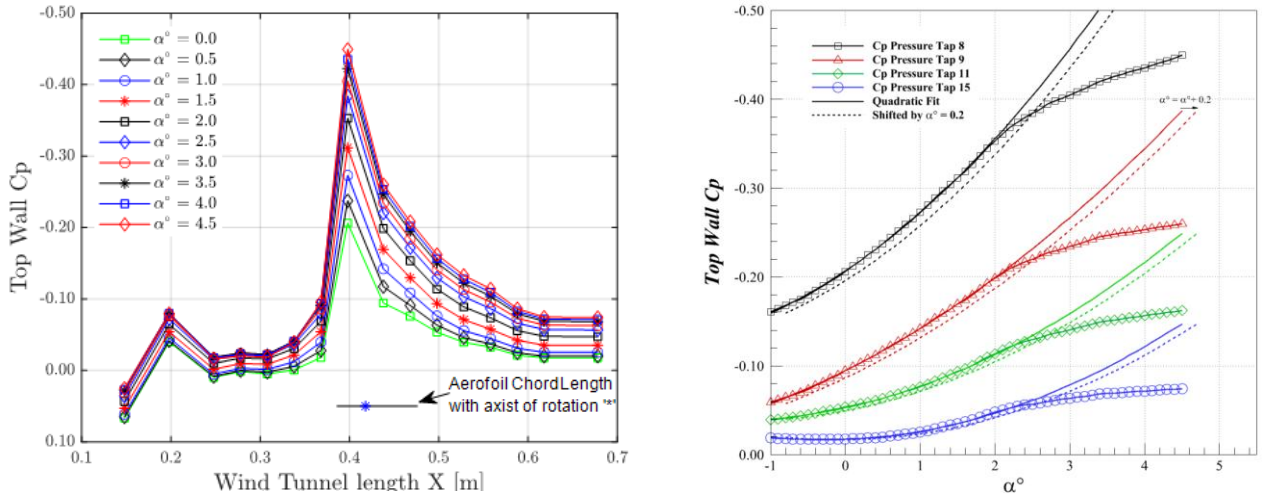


Figure 4 - Pressure tap location in the wind tunnel.

The top-wall pressure distribution was plotted and compared with that of the lower wall. However, as mentioned earlier, the lower-wall pressures were slightly lower in magnitude, therefore, the top-wall pressures were selected for further analysis. Figure 5 (a) shows the Cp distributions across the top wall of the wind tunnel. These pressure distributions were plotted for several angles of attack increments of $0.5°$. The maximum change is observed near the axis of rotation of the RAE2822 model in the tunnel.

To determine the trend of the pressure across the range of angles of attack, four separate pressure taps (PT) were selected. The first two, PT=8 and PT=9 were selected above the model near the axis of rotation. The third one was selected to be at the trailing edge behind the model, PT=11, the fourth one was selected further downstream near to the last PT and that was PT=15. The fourth one, was selected because it was above the wake of the model. Top-wall pressure taps were selected and compared to assess the consistency of their trends. In particular, it was verified that the behaviour above of the model aligned with that observed further downstream, ensuring the reliability and sensitivity of the approach. The evolution of pressure coefficient over the range of α was plotted for each pressure tap location, as seen in Figure 5 (b). The similarity in the trends shows that the quadratic rising trend breaks at similar angles of attack across the four pressure taps (PT8, PT9, PT11, PT15). The transition from a quadratic trend to a linear increase is associated with rising blockage intensity, as strong shock-induced adverse pressure gradients develop along the tunnel walls, may cause the flow separating from the wall. To estimate the model angle of attack at which flow breakdown occurs in the tunnel working section, a quadratic fit is applied, and the angle at which the initial deviation from this trend occurs is identified. The shift of the quadratic curve to the right by $0.2°$ highlights the separation onset angle of attack of the model when intersection between the shifted curve and the wall pressures is taken as the buffet onset angle of attack. The $0.2°$ shift was derived after analysing the original methods to detect buffet onset using Lawson et al methodology [3] and tuning this approach to match those results. This offset should be interpreted as a calibration parameter specific to the present dataset, rather than a universal value. To validate the method, the buffet boundary was compared with existing methods such as those by Lawson et al which are shown in the third section.



(a) (b)

Figure 5 (a) Top wall pressure distribution against the angles of attack. (b) Variation of upper wall pressure coefficient above the model with model angle of attack, highlighting the divergence from quadratic behaviour with tunnel flow breakdown. $M = 0.75, Re_c = 9M$.

An alternative approach to identify when tunnel flow breakdown occurs is to apply a first-order central differencing scheme. The central differencing scheme highlights the global rising trend of the curve and clearly identifies the point at which the deviation occurs. Figure 6 presents the first-order differencing of the Cp variation at PT = 11, showing a pronounced increase in the overall trend that peaks at approximately $\alpha = 1.8°$. At this point, the trend deviates sharply, transitioning into a negative gradient. This angle is therefore identified as the onset of flow breakdown in the tunnel beyond this condition.

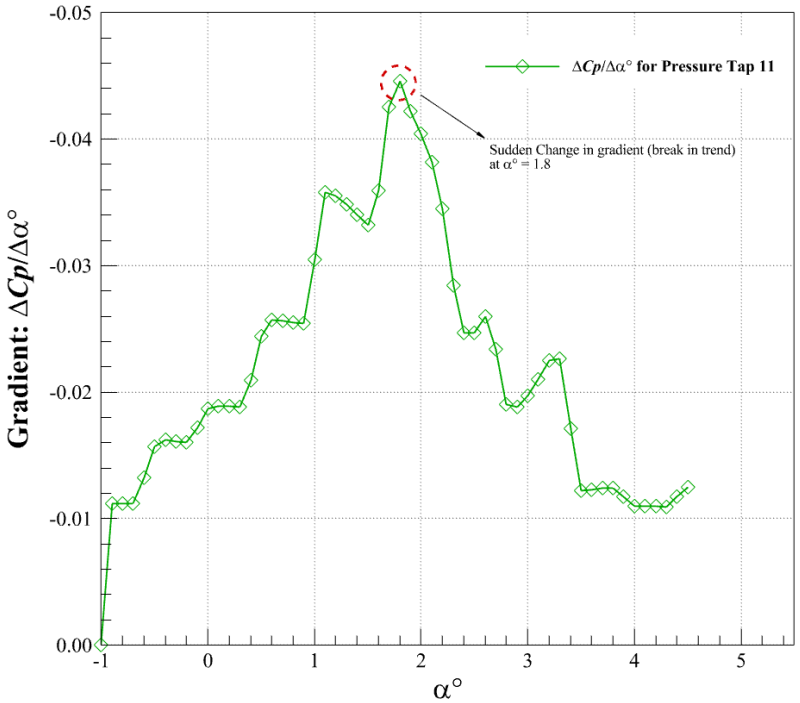


Figure 6 - Gradient of the pressure values at pressure tap 11 using 1st order central differencing to determine the breakdown in trend.

3. Results and Discussion

The buffet onset boundaries were determined using several established methods, including the lift-kink, pitch break, axial force divergence and trailing edge separation based on Cp behaviour [3]. These methods were compared across Reynolds number and surface configuration to determine the most accurate representation of the model's performance envelope. As shown in Figure 7, the tested wing was used to assess the applicability of existing methods and to validate the buffet onset curve derived from the top-wall Cp distribution (proposed method). The top wall pressure-based buffet onset curve agreed well with those obtained using the established criteria for both Reynolds number cases. Specifically, the top wall pressure derived buffet curves showed a close match with those obtained using the pitching moment break and Cp_{TE} divergence criteria for both Reynolds numbers and flow control configurations. Almost all the methods, except for the axial force criteria method, suggest that the buffet onset occurred between $\alpha = 3.5°$ at $M = 0.73$ to $\alpha \sim 0.9°$ at $M = 0.79$. The axial force criteria predicted that the buffet onset occurs well before incipient trailing edge separation. Across all the test conditions, buffet onset was consistently identified within the same range of angles of attack as the reference methods, demonstrating that the wall-pressure based approach provides a reliable indicator of model behaviour.

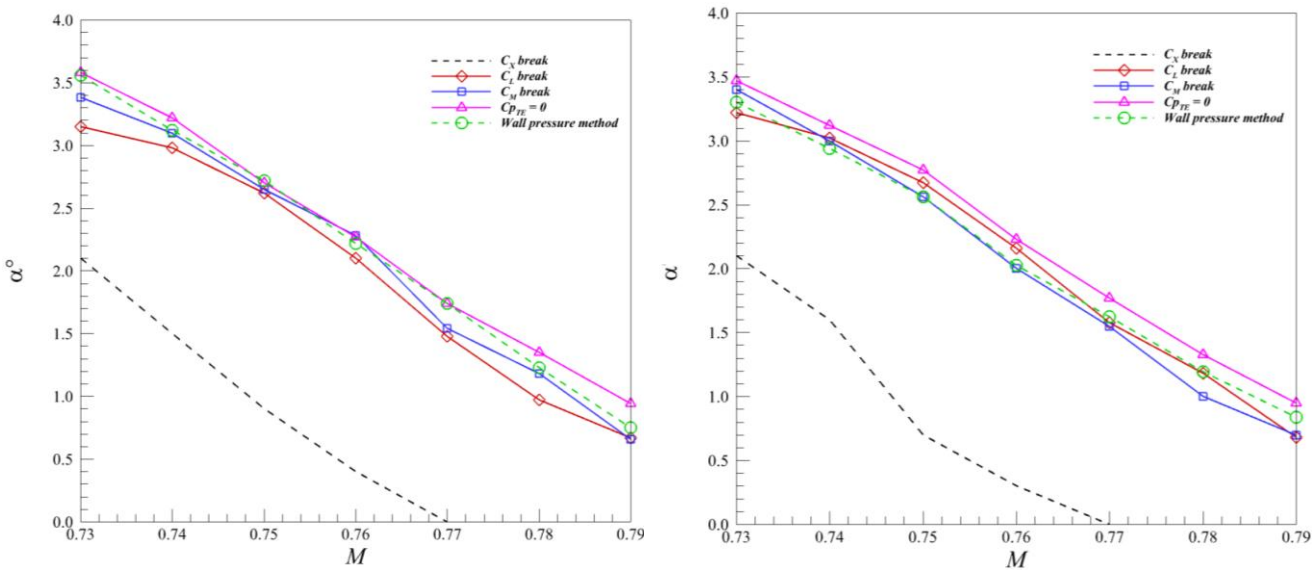


Figure 7 - Variation of model flow separation boundary with angle of attack, predicted, by several methods. (a) $Re_c = 9M$. (b) $Re_c = 15.7M$.

4. Conclusion

In this study, a wind tunnel wall pressure-based data reduction methodology was developed to identify buffet onset and tunnel flow breakdown in a transonic wind tunnel experiment which operated under high blockage conditions. The approach requires only a limited number of tunnel wall pressure measurements and does not rely on model mounted instrumentations. Application of the method to the RAE2822 test case shows that the approach can distinguish between conditions where experimental data remain representative of free-air flow and those influenced by tunnel wall confinement effects. The results further indicate that data acquired near or beyond buffet onset may not be suitable for direct comparison with free-air CFD unless tunnel effects are explicitly modelled and the experimental trends are carefully interpreted. While further validation across different models and configurations is required, the present work demonstrates that wall pressure measurements provide a practical and robust basis for assessing data usability in a small-scale transonic wind tunnel testing, but further research is still required to fine tune the methodology with a wider dataset from different tunnels and experiments.

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