The Effect of Wing Leading Edge Contamination on the Stall Characteristics of Aircraft

07ICE-15

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Agenda

- Introduction.
- CRJ-200 In-Service Experience.
- Aircraft Design and Operation.
- Natural Aerodynamic Stall.
- Premature Stall – Environmental Factors.
  - Contamination.
  - Ground Effects and Rapid/Early Rotation.
  - Sideslip.
- Contamination Effects – Slats versus “Hard” Wings.
- Summary.
- Questions?

Introduction

- Recent history of incidents & accidents during Winter operations.
- CFD, Wind Tunnel and Flight Test data used to assess the aerodynamic effects of icing contamination and take-off technique.
- BA has taken action, such as changes to systems, FCOM procedures, Winter Operation CD, and technical presentations.

CRJ-200 - Late “low energy” go-around

- **Freezing fog with a temperature inversion.**
  - **Dual “primary” ice detector did not annunciate.**
    - Initial approach in “Ludlam” limit conditions.
    - Below 400 ft annunciation disabled to reduce pilot workload.
- **Wing anti-ice system off.**
- **Engine power reduced early in approach, drifted left.**
  - **Go-around called below 35 ft AGL.**
  - **Engine power decreasing to flight idle.**
  - **Airspeed decay: ~10 kts below V_{REF}.**

CRJ-200 - Late "low energy" go-around

- **Aircraft maneuvered above stick shaker AOA.**
  - **Aircraft stalled prematurely (prior to activation of stick pusher), rolled right and struck a wingtip.**
- **The aircraft stalled prematurely due to the aerodynamic effects of wing leading edge ice whilst flying at high AOA close to the ground.**

CRJ-200 – Take-off with Contaminated Wing

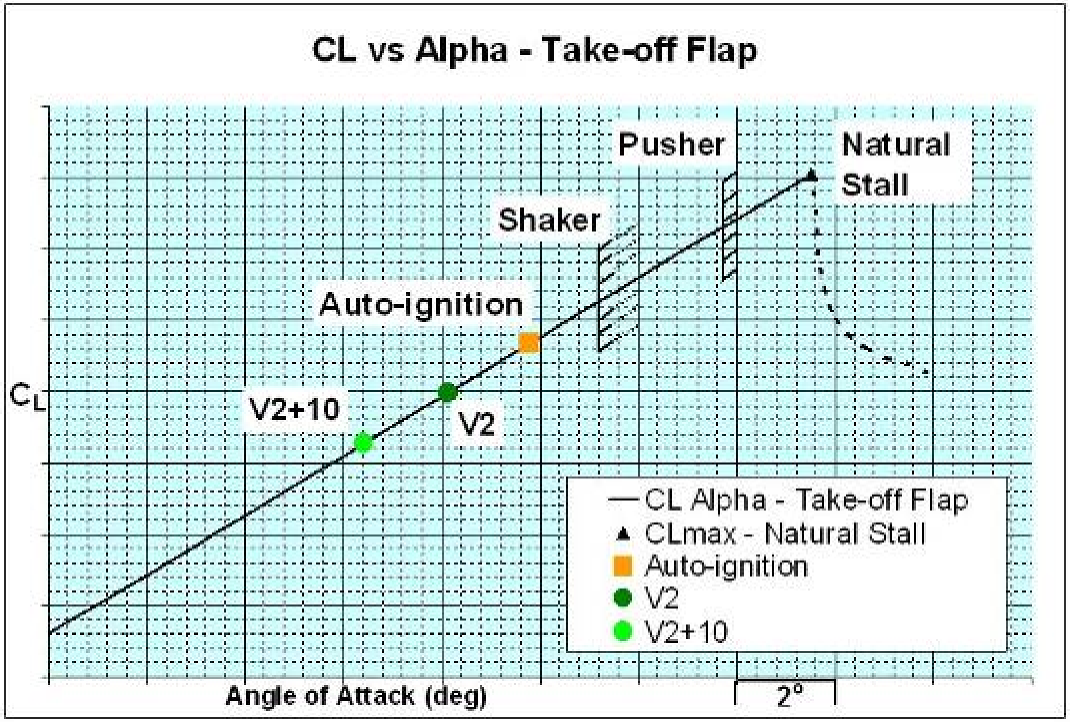
- Conditions were conducive to “Frost” formation.
- Aircraft not de-iced and the wing anti-ice system was off.
- Aircraft stalled: Rolled LWD immediately after WOW.
  - Aircraft experienced a series of roll events.
- Initial stall occurred prior to stall warning.
  - Full opposite aileron and rudder did not arrest roll.

In-Service Experience
Ground Icing - Winter 2004

- Small aircraft, to remain commercially competitive, typically have large simple wings, sometimes referred to as “hard” wings (i.e. no moveable leading edge devices).

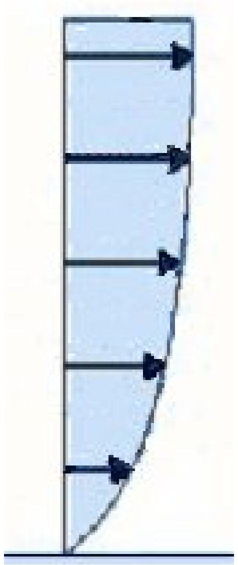
- Stall Protection Systems (SPS) may be used to comply with the certification requirements for stall.

- Pusher/Natural Stall margin defined to accommodate "normally expected" wing contamination.
- Shaker/Pusher minimum speed margin 5% (or 5 knots).
- OEI and AEO take-off speeds positioned below shaker to provide certifiable maneuver margins.
- Consequently, aircraft are normally operated at AOA well below AOA for Natural Stall.



- **Attached Airflow.**
  - **In normal operations the air flows over an airfoil in a continuous manner from leading edge to trailing edge.**
- **Separated Airflow.**
  - **When AOA of an airfoil exceeds a critical AOA the airflow separates from the surface.**
    - The wing is considered to be stalled.
    - Lift decreases with increase of AOA.
    - The stall is defined by separation of the "Boundary Layer" and by reversal of the airflow direction.

- **At a solid wall (airfoil surface) the relative velocity between a moving fluid and the wall is zero.**
- **Just above the surface the air flows at the free-stream velocity.**
  - **Due to the viscosity of the fluid there is a region of reduced velocity close to the surface called the “Boundary Layer”.**
- **At the front of an airfoil the boundary layer is very thin.**

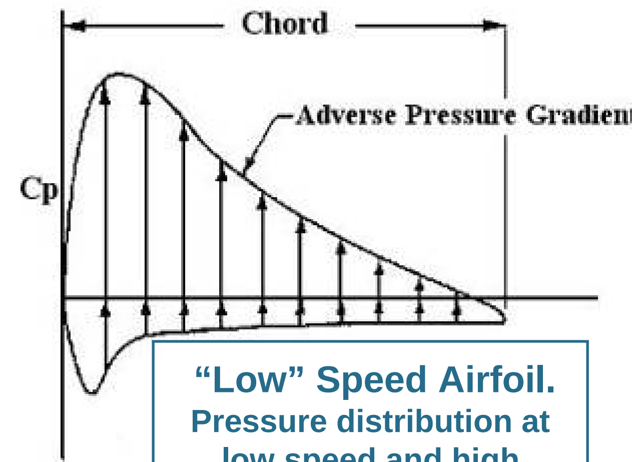


Natural Aerodynamic Stall
The Boundary Layer

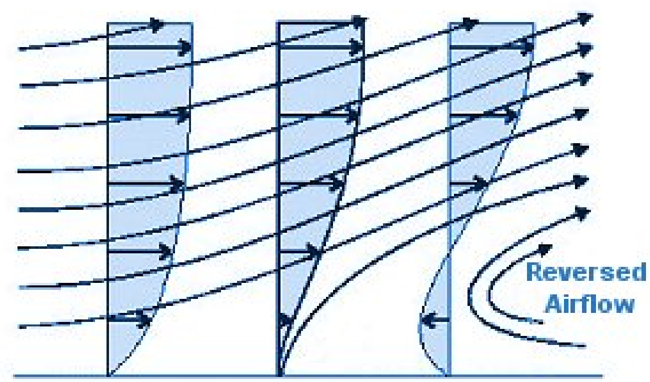
- **The Boundary Layer exists in two basic forms:**
  - **Laminar and Turbulent.**
    - The **Laminar** form exists towards the front of a moving body.
    - The **Laminar** boundary layer consists of smooth and regular airflow with little mixing between layers.
    - **Laminar** boundary layer easily de-stabilized; transitions to the **Turbulent** form.

Natural Aerodynamic Stall
Boundary Layer and Flow Separation

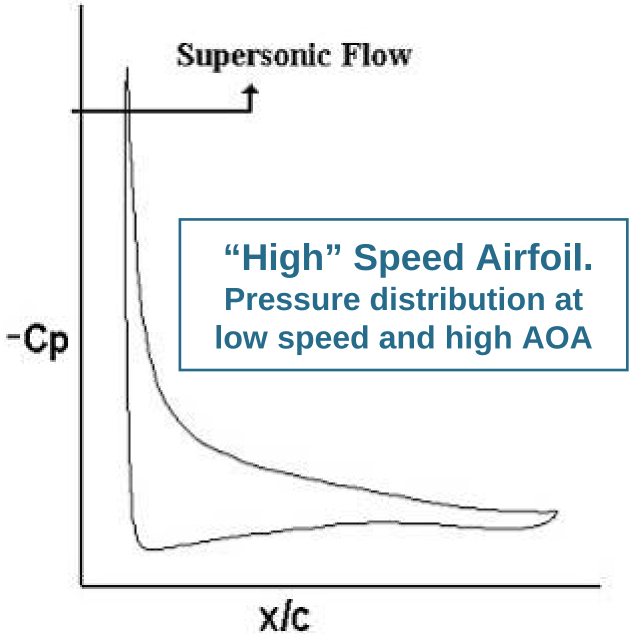
- **Pressure distributions about low speed airfoils include “adverse” pressure gradients.**
  - **As downstream pressure increases the airflow slows and the boundary layer gets thicker.**
- **If downstream pressure increases sufficiently, the boundary layer may reverse direction.**
  - **External flow moves sharply away from the surface: this is flow separation.**
  - **Circulation decreases; lift is lost and drag increases.**



“Low” Speed Airfoil.
Pressure distribution at low speed and high AOA



- **Most high-speed commercial transport and business aircraft are designed with airfoils of thickness to chord (t/c) ratios of 9% to 12%.**
  - **At high AOA and low airspeed the suction peak near the leading edge becomes very deep.**
  - **Suction peak is very close to the leading edge where the boundary layer is laminar.**
  - **Immediately downstream of the suction peak there is an adverse pressure gradient.**
  - **Velocities near the leading edge are very high, and may go supersonic.**



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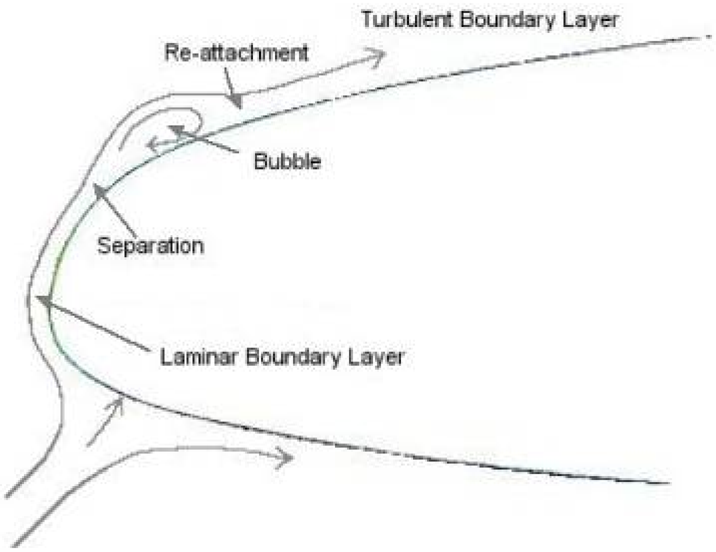
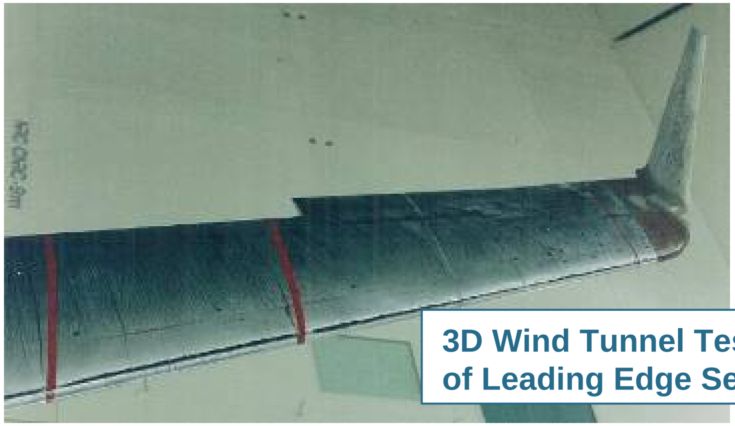
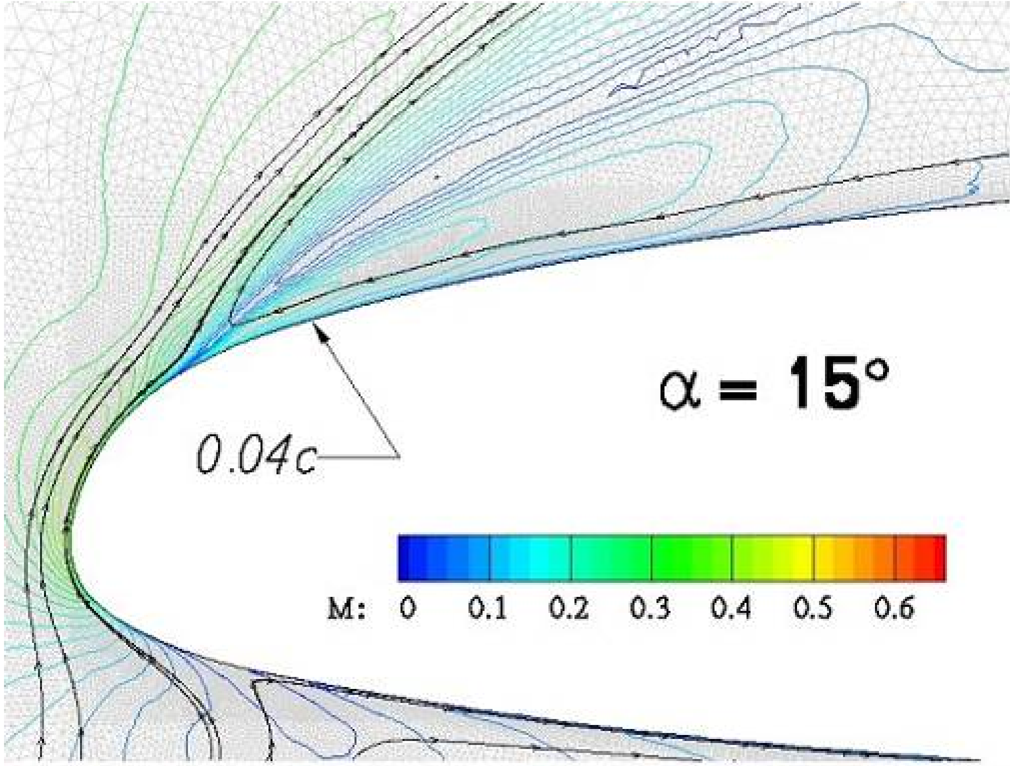
- **Wing Leading Edge Separation – “Short Bubble”**
  - Airfoils of (t/c) ratios of 9% to 12%.
  - Before attainment of maximum lift, separation of the airfoils laminar boundary layer occurs near the leading edge.
  - Transition from a laminar to a turbulent boundary layer occurs in the separated shear layer.
  - Re-attachment of the turbulent boundary layer quickly occurs, enclosing a “short bubble” .

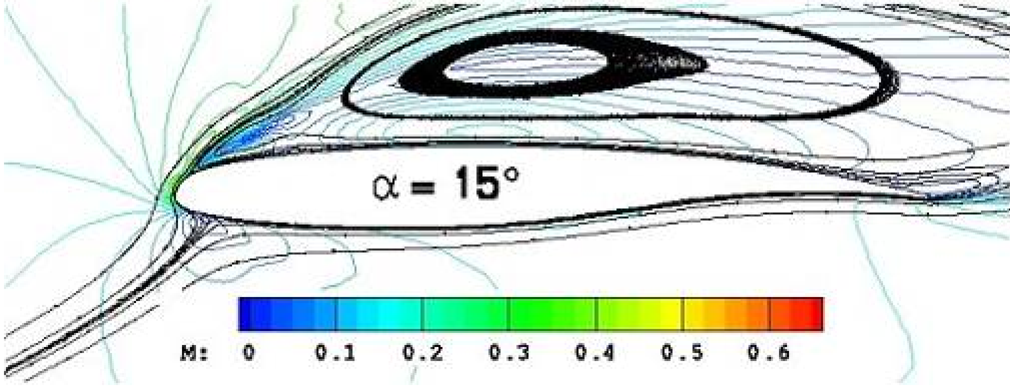




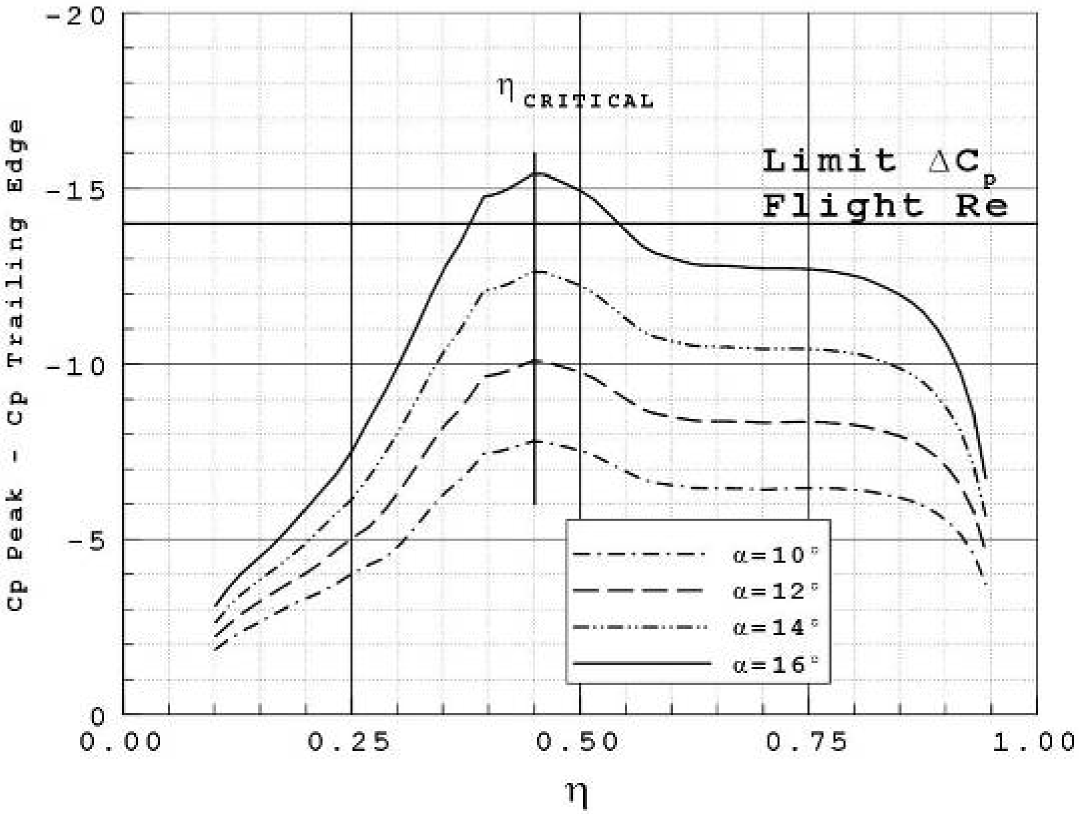
3D Wind Tunnel Test – Oil Flow Visualization of Leading Edge Separation “Bubble”.

- **Wing Leading Edge Aerodynamics**
  - **At high AOA a critical point is reached where-after the short bubble "bursts" and the airflow detaches suddenly and completely from the leading edge to the trailing edge.**
  - **Prior to the stall there is typically no aerodynamic stall warning in the form of "natural" buffet.**





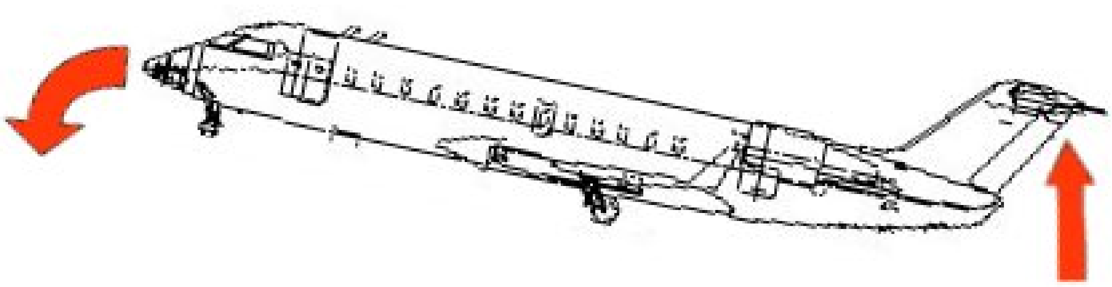
- **"Pressure Difference Rule".**
  - **There is a relationship between the leading edge and trailing edge pressure coefficients (ΔCp) and the "short bubble" stall.**



- If ratio of pressures exceeds a critical value a local stall can occur.
- Inboard wing pressure ratios are not critical and are very difficult to stall.
- Outboard wing is close to the critical threshold at the point of initial stall.
- The spread of the stall will be rapid and outboard.

- **"Stall Characteristics"**
  - **Stall occurs suddenly on the outboard wing, typically on one wing before the other.**
    - **A/C may lose lift asymmetrically and roll.**
    - **Nose-up pitching moment.**
  - **Down-going wing experiences a local increase of AOA, due to roll rate - goes deeper into the stall.**
  - **Up-going wing experiences a local decrease of AOA, increases the margin to stall.**
    - **Classical form of autorotation.**

- **"Stall Characteristics – Stall Recovery"**
  - **Loss of aileron power: Lateral controls cannot arrest the roll.**
  - **Rudder ineffective for picking up the down-going wing.**
    - Wing is stalled - Natural dihedral effect destroyed.
  - **If prompt recovery action not taken bank angle can become large and AOA may rapidly increase.**
- **Must promptly decrease AOA by use of longitudinal controls (elevator) to effect a full recovery.**



Premature Stall – Environmental Factors

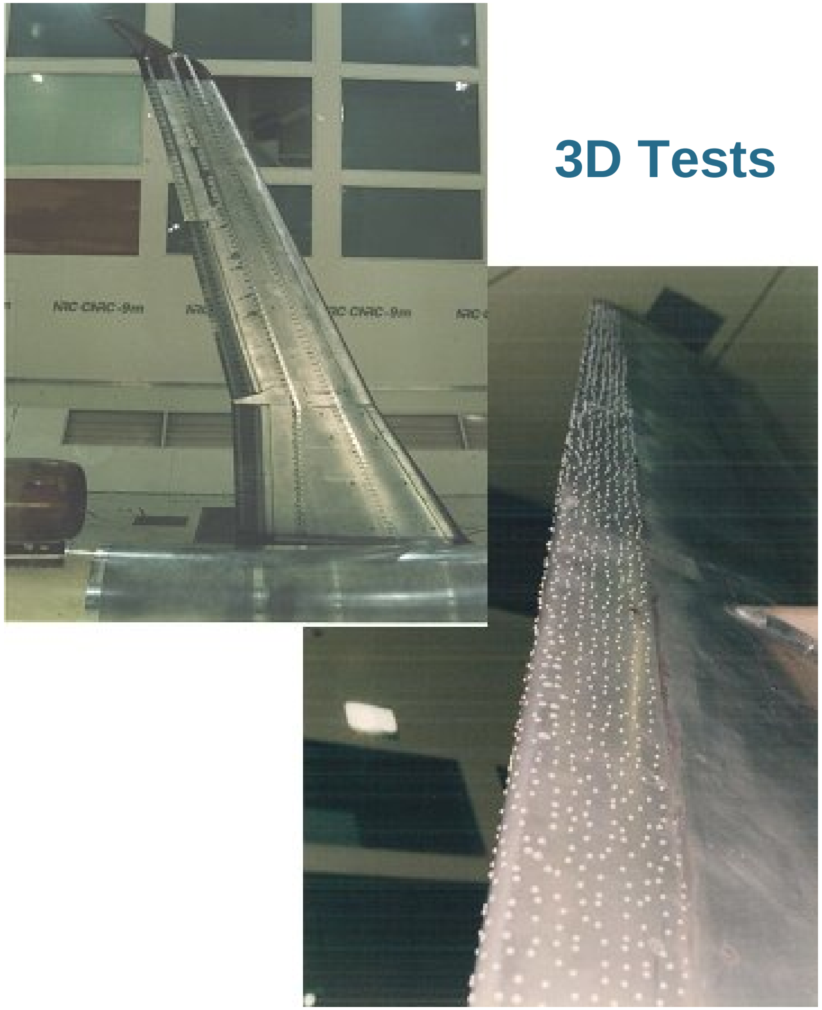
- **The stall AOA may be reduced by external environmental effects such as:**
  - **Contamination Effects.**
  - **Ground Effects.**
  - **Sideslip Effects (e.g. during crosswind take-offs).**
- **It is believed that these three effects may, to a large extent, be additive.**

- **The stall characteristics are similar with or without contamination.**

- **“Contamination Effects”**
  - **Wing leading edge plays a dominant role in stall development of high performance wings.**
  - **For airfoils with t/c of between 9% to 12%, the critical area of the wing is forward of 5% chord.**
  - **Relatively small roughness elements along the wing leading edge can disturb the fine balance of aerodynamic forces at high AOA.**

- **Wind Tunnel Tests:**

2D Wing Panel Tests



3D Tests

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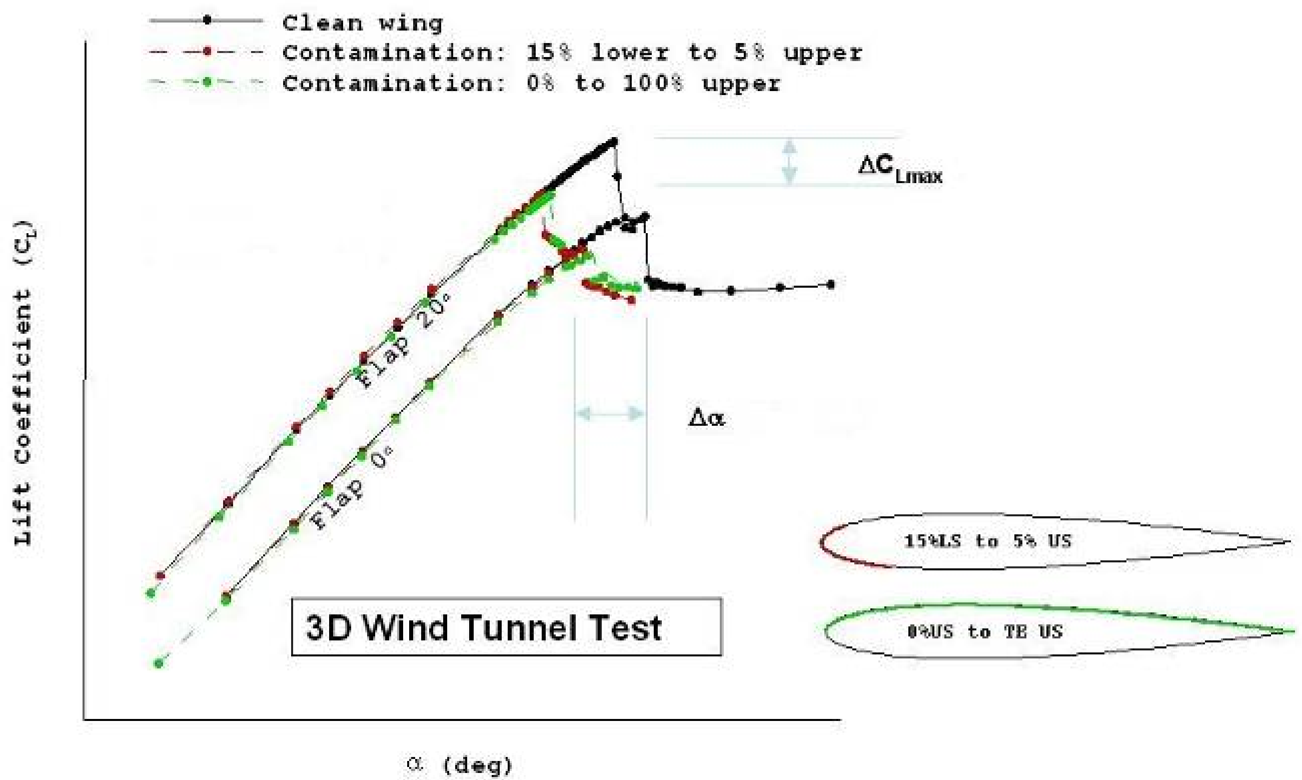
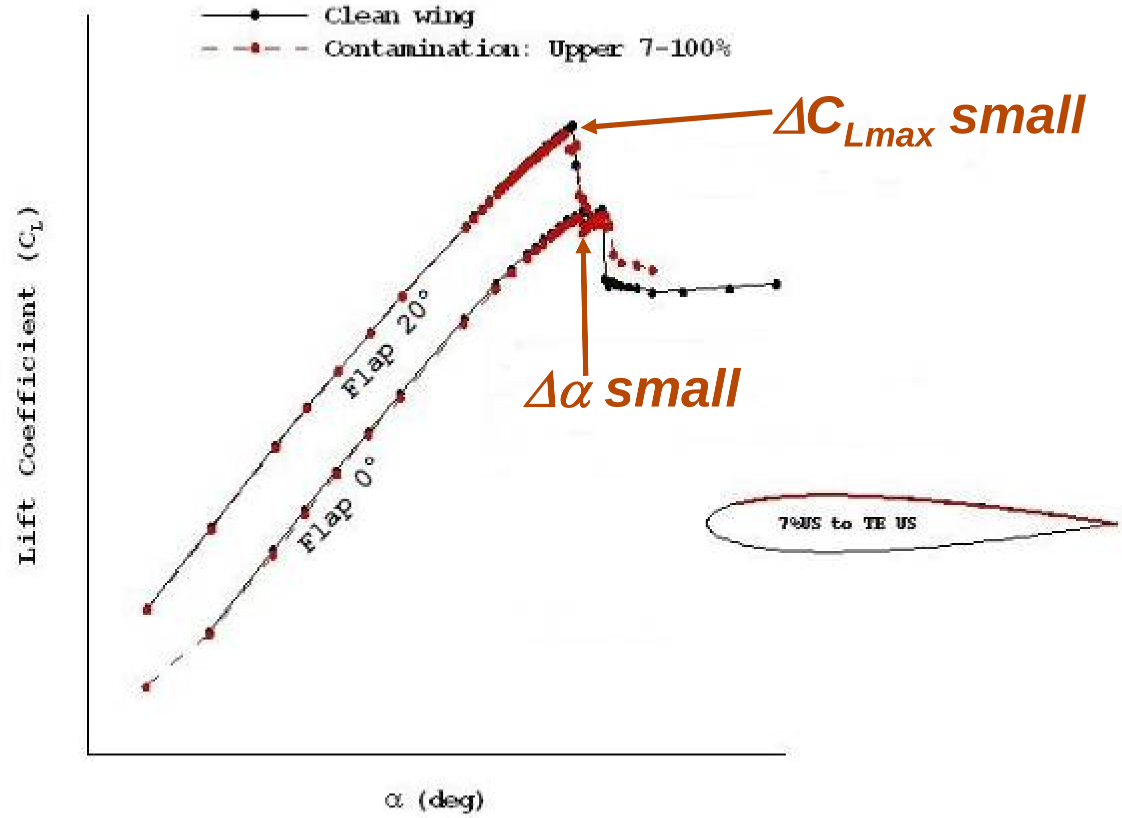
- **Wind tunnel and flight test data show that modern high performance airfoils stall at lower AOA when the wing leading edge is contaminated.**
- **Roughness along the wing leading edge equivalent to #40 grit sandpaper can cause the stall AOA to reduce by over 5° °, with a corresponding loss of maximum lift capability.**

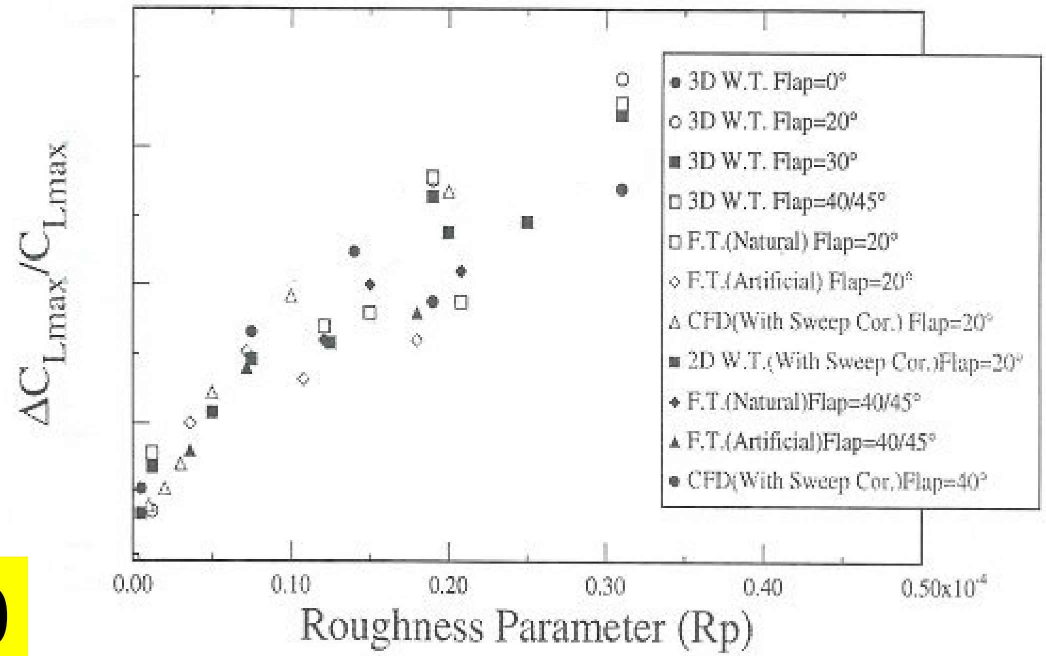
- **“Light” distributed roughness.**
  - **Can have a significant effect on maximum lift when applied to the wing leading edge.**



- **“Light” distributed roughness.**
  - **Applied to the wing upper surface, behind the front spar, is much less critical than light roughness applied to the wing leading edge.**



- **Rp – Roughness Parameter**
  - **Rp - empirically derived from test data.**
    - Rp relates loss of maximum lift to geometry of distributed wing leading edge roughness elements:

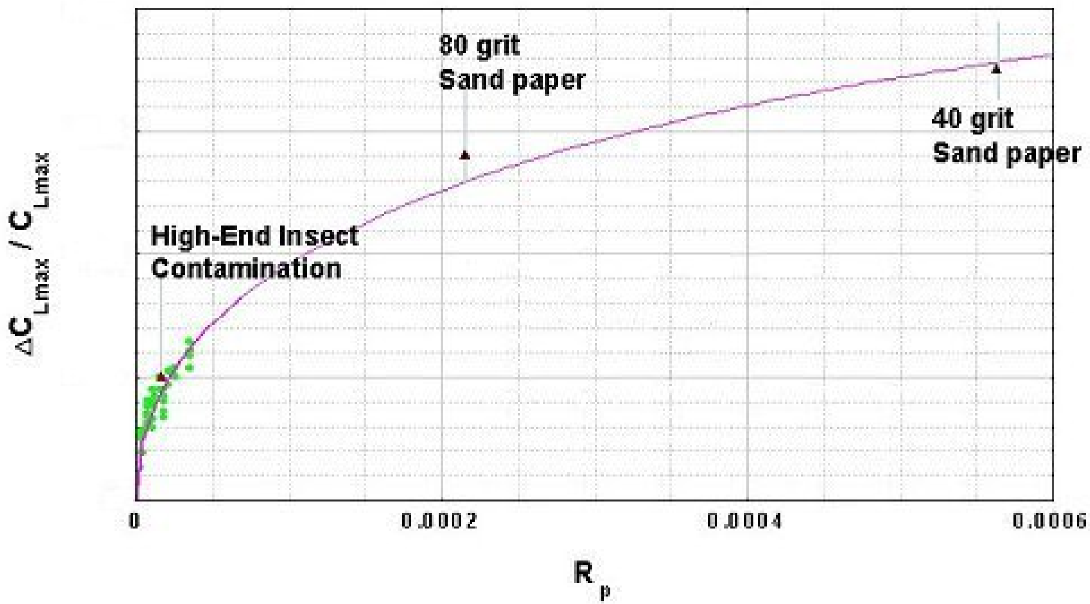


- **Rp - function of:**
  - **k - Height.**
  - **N - Density.**
  - **A - Cross sectional area.**

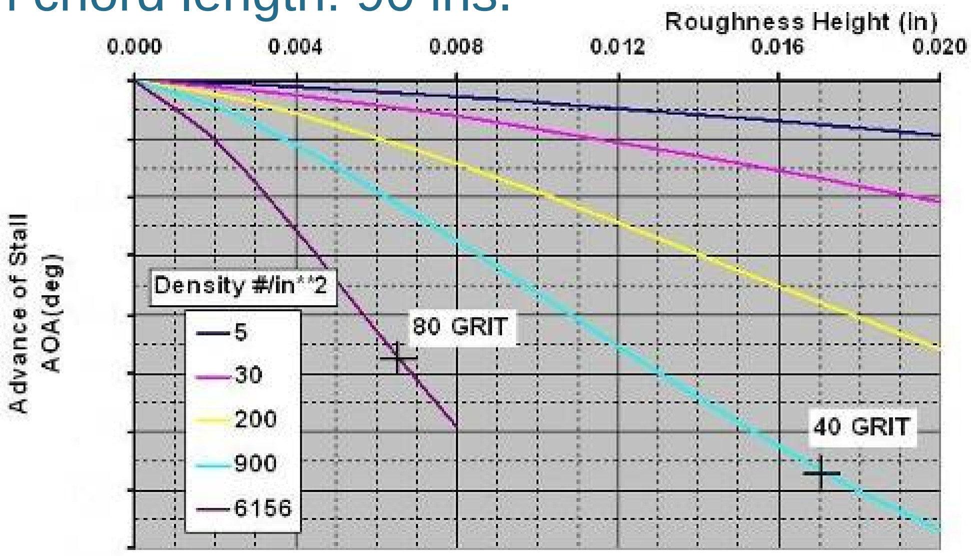
$$R_p = A \times \left(\frac{k}{c}\right) \times N \times 10$$

- **Rp – Roughness Parameter:**
  - **Certification of Reduced Reference Speed Factors – Vs1g.**
    - TC Issue Paper - Must account for “normal” insect contamination.
    - Dedicated flight tests performed to quantify insect contamination.
    - “Insect shapes” defined.
    - SPS pusher set to protect against “normal” insect contamination.

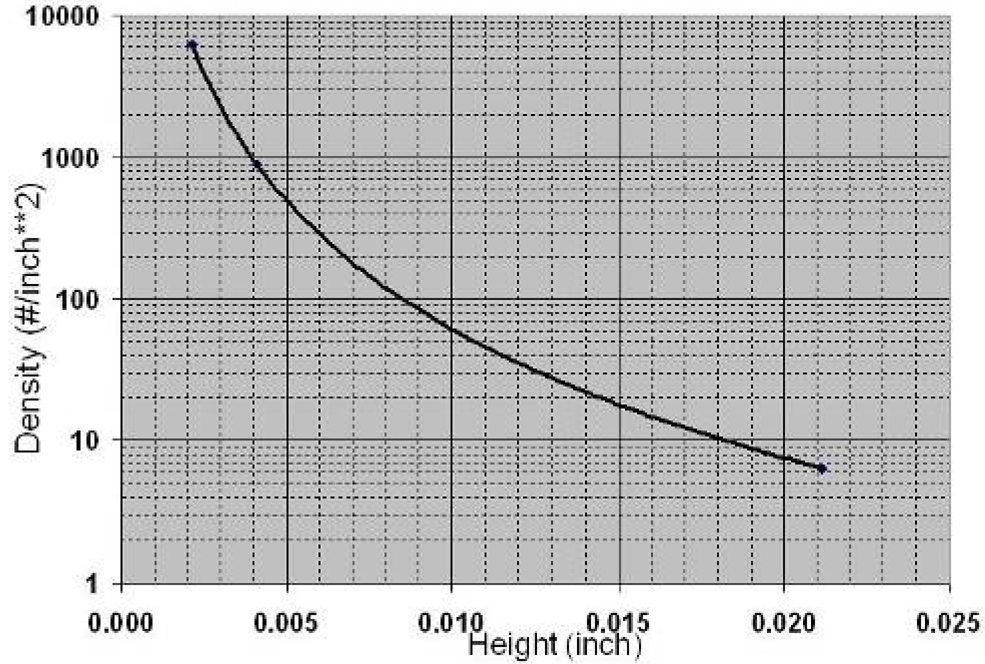
- **Insect Shapes:**
  - **Height: 0.015 ins.**
  - **Density: 5 #/in**2**
  - **Cross sectional area: Width=6*height (cylinder).**



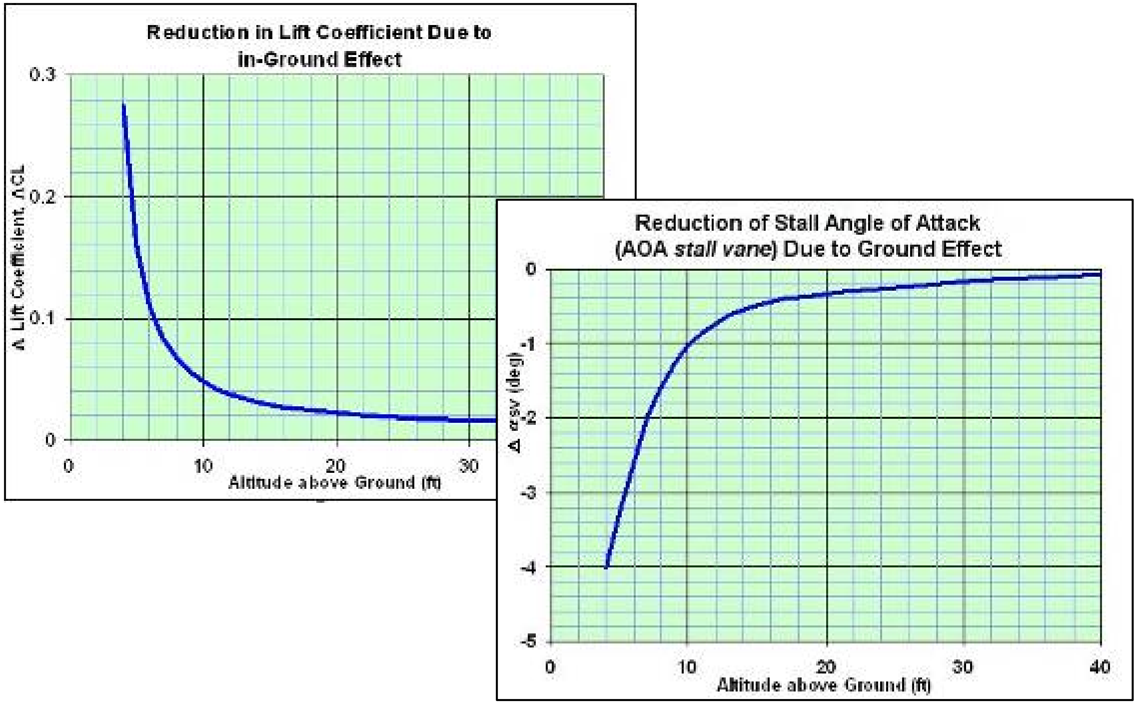
- **Rp – Roughness Parameter**
  - **Accident Investigation.**
    - Loss of stall AOA due to “contamination” estimated to be approximately 5° (after removing ground effects).
  - **Assumption:**
    - Spherical contamination.
    - Critical wing station chord length: 90 ins.
  - **Rp method used to predict size of contamination.**
  - **Aerodynamic effect equivalent to #80 grit contamination along the wing leading edge.**



- **Rp – Roughness Parameter**
  - **Rp generalized method used as a guide to support the development of SAE standard for Remote on Ground Ice Detection Systems (ROGIDS) – AS5681.**
  - **Acceptable stall speed (C_{LMAX}) penalty due to contamination; 3% or 3 knots.**
  - **Heights and densities of "frost" type (spherical) contamination that could cause 3% or 3 knot speed penalty:**
    - Rp = 0.000008 on a small commuter A/C.



- **“Ground Effects”**
  - **The aerodynamic performance of an A/C can be affected during flight in close proximity to the ground:**



- **Lift increases.**
- **Drag reduces.**
- **Tailplane downwash reduces.**
- **The stall AOA reduces.**

- **"Ground Effects"**
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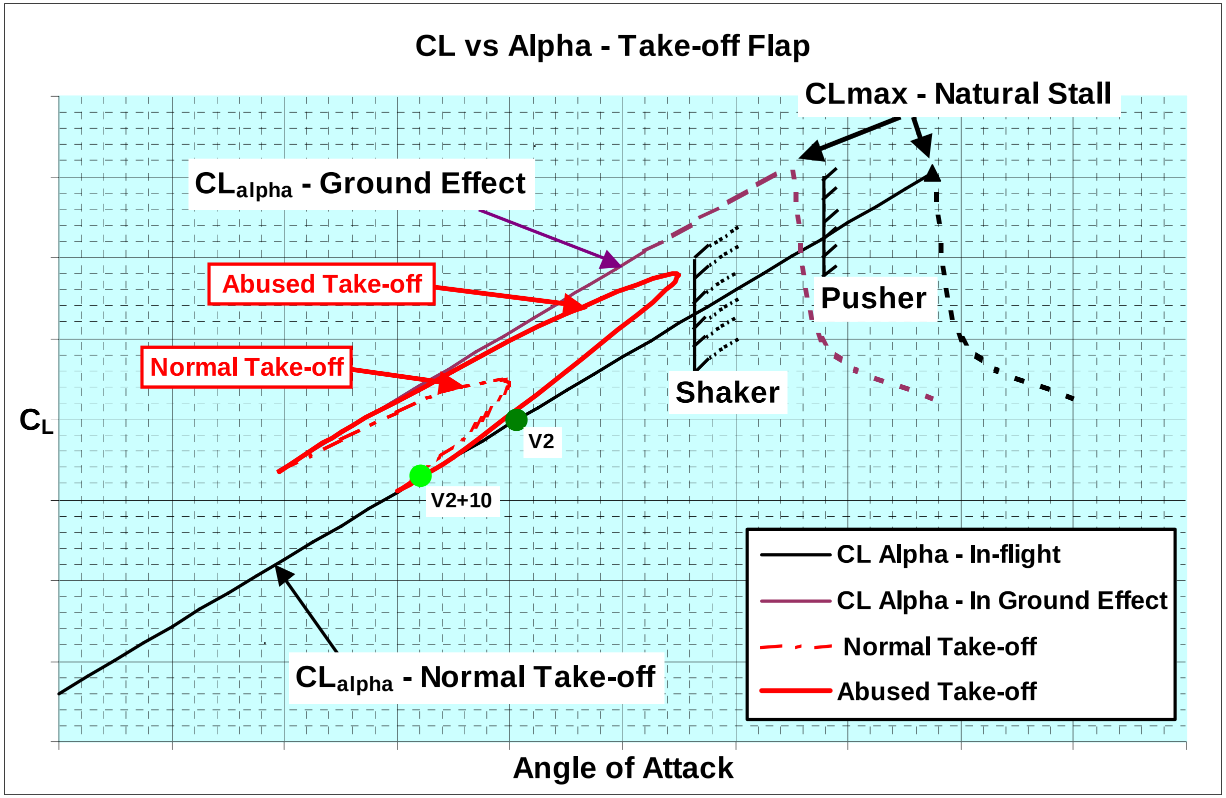
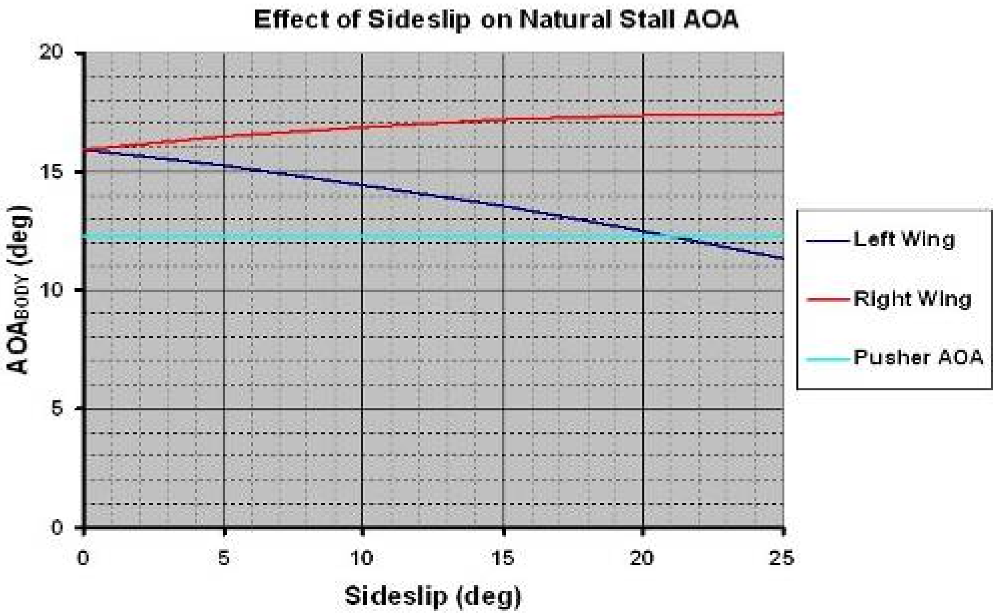


- **"Sideslip Effects"**
  - **High aspect ratio wings, typical of modern high performance A/C, stall at lower AOA the more the wing is swept.**
    - The forward going wing has an increased stall AOA and the trailing wing has a reduced stall AOA.
  - **Crosswinds induce sideslip on an A/C during take-off and landing.**
  - **Pilots induce sideslip by use of rudder in an attempt to raise a down-going wing in a stall departure.**



SUMMARY

- Contaminated wing leading edges cause a significant loss of maximum lift capability and the aircraft will stall prematurely.
- Abuse of rotation technique (early or rapid rotation) can position the aircraft at higher than normal AOA whilst close to the ground.
  - High AOA reduces the margin to the stall.
  - Ground effects cause the stall to occur prematurely.
- Crosswinds (sideslip angle) cause the trailing wing to stall prematurely.

THE ABOVE EFFECTS ARE ADDITIVE

CLEAN WING POLICY

THE WINGS OF AIRCRAFT MUST BE INSPECTED BEFORE FLIGHT AND ANY ICE, SNOW, FROST OR SLUSH CONTAMINATION MUST BE REMOVED PRIOR TO TAKE-OFF.

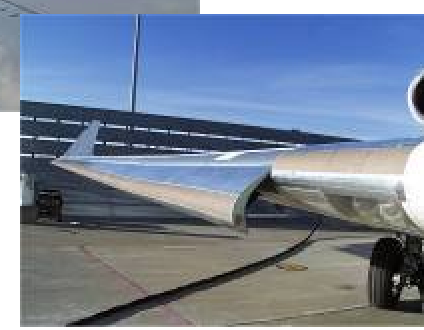
- **Question:**
  - **Why do “hard” winged A/C have a reputation in the industry that they are more susceptible to the effects of contamination than slatted A/C?**
    - Wind tunnel and flight test data confirm that both “hard” winged and slatted A/C stall at reduced AOA when the wing leading edges are contaminated.
    - At the same scale the reduction of stall AOA are similar.

- **Possible Contributing Factors – For Discussion.**
  - **There are more “hard” winged A/C in operation than slatted A/C.**
  - **Scale (see Rp):**
    - Slatted A/C tend to be large A/C. The larger the A/C the less are the effects of contamination.

- **Possible Contributing Factors – For Discussion.**
  - **Slatted A/C Aerodynamics:**
    - Slatted A/C have high C_{LMAX}:
      - The *percentage* reduction of lift due to a given reduction of stall AOA is less on a slatted A/C than on a “hard” winged A/C.
    - There may be natural stall warning (buffet) that precedes the stall on a slatted A/C.
    - The trailing edge stall spreads gradually, which reduces the tendency for large imbalance between the wings. The aircrew can typically maintain wings level throughout the stall maneuver.

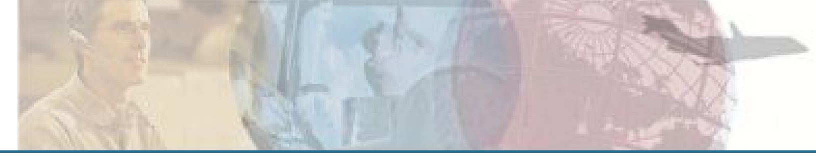
Contamination Effects
Slats Versus "Hard" Wings

- **Possible Contributing Factors – For Discussion.**
  - **Aircraft Design:**
    - Geometry Limit:
      - Due to the high operating attitudes of slatted A/C some are geometry (tail strike) limited.Take-off speeds may be increased due to increase of Vmu.



    - Large A/C typically have fully powered irreversible flight controls.
    - Large turbojet (slatted) A/C have fully evaporative hot air wing anti-ice systems.
    - Large A/C typically have onboard ice detection systems.

- **Possible Contributing Factors – For Discussion.**
  - **Flight Operations:**
    - Large airlines operate the majority of slatted A/C:
      - Detailed SOPs and sophisticated flight operations and training departments.
      - Generally operate from large airports that possess state-of-the-art weather reporting, runway de-icing and clearance equipment and A/C de-icing equipment.




Thank You!
Questions?