Airplane Lift and Stall, Ground Effect, and Takeoff Speeds

Aircraft Performance presentation
Airplane Lift and Stall

Lift is proportional to AOA * (airspeed)^2
Airplane Lift and Stall

LIFT vs AOA Graph

- LIFT increases with AOA
- Stall occurs at high AOA
Airplane Lift and Stall

MAX LIFT

STICK SHAKER AOA

STALL AOA
Rolling Moment Due to Asymmetric Stall

Result: rolling moment to the right

Left wing: not stalled

Right wing: stalled
Ground Effect

LIFT

AOA

Airplane in free air: height > wingspan
Ground Effect

Ground

Airplane on ground

LIFT

AOA

Airplane in free air: height > wingspan

Ground

NTSB
Ground Effect

Ground Airplane on ground

Airplane in free air: height > wingspan

Slope of lift curve increased in ground effect

AOA

LIFT

Ground
Ground Effect

Maximum lift reduced in ground effect

Airplane on ground

Airplane in free air: height > wingspan

Ground Effect
Ground Effect

Airplane on ground

Ground

Airplane in free air: height > wingspan

$\Delta \text{AOA}$

Stall AOA reduced in ground effect

LIFT

AOA
Ground Effect

Stall AOA reduced in ground effect

Estimated $\Delta$AOA (from $V_{MU}$ tests) | Actual $\Delta$AOA (from postaccident CFD) | Difference
---|---|---
1.6° | 3.25° | 1.65°

RESULT: No warning before stall in ground effect

Missed opportunity: Actual $\Delta$AOA indicated by two previous roll events
Takeoff Speeds

• Takeoff roll starts with airplane at rest
Takeoff Speeds

- Takeoff roll starts with airplane at rest
- Decision speed ($V_1$): With a failed engine, distance to climb to 35 feet same as distance to stop
Takeoff Speeds

• Rotation speed ($V_R$): pilot pulls column to raise the nose for takeoff
Takeoff Speeds

- Liftoff speed ($V_{LOF}$): main gear leaves runway
Takeoff Speeds

- Takeoff safety speed ($V_2$): target climb speed with a failed engine, to be achieved by 35 feet above ground level (agl)
- $V_{35}$: actual speed at 35 feet agl
- Test objective: $V_{35} = V_2$
- Test results: $V_{35} > V_2$ (overshoot)
Takeoff Safety Speed ($V_2$)

- $V_2$ requirements intended to ensure
  - Safe AOA margin from stall
  - Safe control of asymmetric thrust with one engine inoperative
  - Safe minimum climb gradient with one engine inoperative
$V_2$ Development

$V_2 \text{min (GIV)}$

$V_2$ SPEED

GIV: $V_{35}$ from traditional method

GIV: Target $V_2$
$V_2$ Development

$V_{2\min} \ (GIV)$

$V_2 \ \text{SPEED}$

GIV: $V_{35}$ from traditional method

GIV: Target $V_2$

G650
V₂ Development

RESULT: G650 target V₂ too low
Change in Flaps 10 Target Pitch Angle

Lift ≥ weight

AOA = 10°

V_{LOF}

Lift < weight

AOA = 9°

V_{LOF}

Lift ≥ weight

AOA = 9°

V > V_{LOF}

Reduction in pitch without increase in speed exacerbated $V_2$ overshoots
V₂ and Takeoff Distance

• Takeoff distance increases with higher $V_2$
• Achieving target $V_2$ necessary to satisfy takeoff distance guarantee
• No analysis of physics of G650 rotation to validate speeds or determine root cause of overshoots
Takeoff Rotation Techniques

- Gulfstream attempted to solve $V_2$ overshoot problem through takeoff rotation technique
- Pitch attitude for climb at $V_2$ greater than target pitch for takeoff rotation
- $V_{35}$ reduced by reducing time to achieve climb pitch attitude
  - Achieve target pitch sooner (high rotation rate)
  - Increase pitch above target sooner
Takeoff Rotation Techniques: Achieve Target Pitch Sooner

• Abrupt column pull with high force
• $V_2$ overshoots reduced but not eliminated
• Primary flight test engineer concerned that technique too difficult to be accepted by FAA
• On accident flight, PIC stated technique “doesn’t work”
Takeoff Rotation Techniques: Increase Pitch Above Target Sooner

- Less abrupt column pull with moderate force
- Reduced pauses at target pitch angle
- Increase in pitch to climb attitude became “almost…continuous”
- $V_2$ overshoots reduced but not eliminated
- Accident takeoff: AOA exceeded stall AOA in ground effect
Summary

• Erroneously low target $V_2$ speeds resulted in overshoots

• Reduction of pitch target without increase in target speeds exacerbated $V_2$ overshoots

• $V_2$ overshoots threatened takeoff distance guarantee

• Pitch angle and AOA increased sooner in successive takeoffs to reduce $V_2$ overshoots
Summary

• Accident takeoff: AOA exceeded stall AOA in ground effect
• Asymmetrical stall resulted in uncontrollable rolling moment
• Estimate of stall AOA in ground effect too high
  • No stick shaker before stall
  • Actual stall AOA could have been determined from previous events