Improved Obstacle Clearance Capability of a Legacy Transport Aircraft Using a Modified Climb-Out Flight Profile

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AIAA SCITECH 2015, JANUARY 5 – 9, 2015, KISSIMMEE, FL
Introduction

After takeoff, an airplane changes speed and configuration:

- Flaps and landing gear are retracted
- Power changes from the takeoff setting to a lower, maximum continuous setting
- Speed is increased from $V_2$ ($V_{OBS}$) to enroute climb speed

Also, during this portion of flight:

- Clearance of any obstacles in the flight path must be assured
- Compliance with minimum gradients must be assured

Obstacle and gradient requirements may reduce the takeoff weight, reducing the range and/or payload
Climb Requirements: Distinct Obstacles

• Clearance of all distinct obstacles must be possible with specified margin with one engine inoperative (OEI)
Climb Requirements: Minimum Gradients

• Compliance with min climb gradients (CG) must be assured
• Min gradients derive from Standard Instrument Departures (SIDs)/Departure Procedures (DPs) from terminal procedures (TERPS)
  • SID/DP climb gradient defined by obstacle clearance surface (OCS) above which obstacle clearance is assured
  • May also be set by ATC or noise constraints
• Strictly speaking, SIDs and DP apply to all engines operating (AEO), but USAF instructions dictate use of one engine inoperative (OEI)
Legacy C-130H Flight Path

- Consists of six segments
- Defined in performance flight manual (TO-1C130H-1-1)
- Segmented according to changes in configuration, airspeed, and/or power
- Two segments “split” energy into simultaneous climb and acceleration:
  - (1) Gear-up to flap-retraction speed
  - (2) Flaps-up to best-climb speed
Legacy C-130H Flight Path: Question?

Why divert excess power from climb in order to simultaneously accelerate?

• Diminishes available climb capability
• Difficult to fly precisely/repeatably
Alternatives

- Civilian regulations 14 CFR § 25.111, § 25.115, and § 25.121 divide the climb-out flight path into four segments, as illustrated below.
- Acceleration at constant altitude
- Flyable/repeatable
- Option to increase acceleration altitude to maximize capability in initial climb

14 CFR 25 takeoff segments and nomenclature (from AC 25-7C11).
Analysis

• Reverse engineer C-130H aero & propulsion using performance flight manual
• Validate by reconstructing legacy flight path
• Evaluate alternative profiles based on conventional 4-segment model

Model Basis: C-130H
• Publicly available data
• Generic transport performance
• Familiar

The C-130H. Image courtesy of Jimmy Van Drunen.
The split in excess power in segments has a profound effect on the height-versus-distance
Assuming split is constant, it can be determined without knowledge of aircraft characteristics
The rate-of-climb is a fraction, $k$, of total excess power
\[ RC = kP_s \]
Since rate-of-climb is also equivalent to $P_s$ divided by the acceleration factor (i.e., $1 + (V/g) \frac{dV}{dh}$), split can be related to change in speed with altitude
\[ dh = \left( \frac{k}{1-k} \right) \frac{V}{g} \, dV \]
Integrating, we can solve for $k$, where the subscripts “f” and “i” refer to final and initial conditions for the segment
\[ k = \frac{1}{\left( \frac{V_f^2-V_i^2}{2g(h_f-h_i)} + 1 \right)} \]
Extracting speeds and altitudes from the flight manual suggests an energy split of $\frac{1}{2}$ was used (see right)
Reconstructed Legacy Profile

• The split of 1/2 was used to re-construct the legacy flight-path using a reverse-engineered performance model
• The result is a reasonable facsimile of the one in the original flight manual
Alternatives: Extended 2\textsuperscript{nd} Segment

• An extended 2nd segment (or “E2S”) features climb with:
  • Gear retracted
  • Flaps extended
  • Constant KCAS climb at $V_{OBS}$
  • Climb to an altitude at which the airplane can level-off and accelerate to the final takeoff speed within the MTP limit (5 minutes)

• 2\textsuperscript{nd} seg permitted to end as early as 400 feet, may extend to greater for obstacle clearance
Alternative: Extended 2nd Segment

- Three sample weights for C-130 evaluated:
  - 100,000 lb (light)
  - 140,000 lb (medium)
  - 180,000 lb (heavy)
- E2S results [solid black lines] are superimposed with those of legacy [dashed gray lines]
- Show significant benefit of E2S profile

**Example:** TOW = 140,000 lb, Obstacle at 3 nm
  - E2S > 1,000 ft
  - Legacy ~750 ft
  - Legacy would have to reduce TOW nearly 13,000 lb to achieve same height as E2S

- Legacy profile provides quick transition to best climb speed
  - Once airplane at best climb, power reduced to max continuous (MCP)
  - In contrast, E2S uses full 5-minute limit for MTP
  - Combination of energy split and early MCP transition makes legacy inferior to E2S at nearly all conditions
    - Exception: very distant obstacles at heavy weight (180,000 lb)
Alternative: Extended 2\textsuperscript{nd} Segment (Cont’d)

- A SID or DP may be more limiting than a defined obstacle in the flight path
- To further compare profiles, evaluated the effective gradient, defined as the height/distance at every point along the climb-out
- Illustrates the detrimental effect of energy split on legacy profile and benefit of E2S

\textbf{Example}: T\text{OW}= 140,000 \text{ lb},
\begin{itemize}
  \item 400 ft/nm DP
\end{itemize}
- E2S would comply with the 400 ft/nm DP up to a height 4,000 ft
- Legacy would be capable of no greater than 300 ft/nm over same height interval
- Legacy would have to reduce T\text{OW} about 12,000 lb to achieve same DP as E2S
Alternative: Extended 2\textsuperscript{nd} Segment with Overspeed

- Excess power characteristics vary with airspeed
- Greater gradient available at higher speeds (> $V_{OBS}$) for Wt>108,000 lb
- Such an “overspeed” trades increased takeoff distance for greater climb capability
Alternative: Extended 2\textsuperscript{nd} Segment with Overspeed

- 10-knot increase in rotation and $V_{\text{OBS}}$
- Results shown at right [green lines]
- Increases distance from brake release to liftoff
  - Actually \textit{diminishes} close-in capability, especially light weights
- Improves rate-of-climb
  - Increases acceleration height at all weights
  - Results in comparable or slightly greater clearance beyond the acceleration height
  - For obstacles within the range of the horizontal acceleration, significant increase in clearance possible

Example: TOW= 140,000 lb, obstacle at 11 nm
- Overspeed E2S achieves 300 ft greater height than baseline E2S and 660 ft greater height than legacy profile
- Legacy would have to reduce TOW about 9,300 lb to achieve same height as overspeed E2S, or 5,200 lb to achieve same height as baseline E2S
Alternative: Extended 2\textsuperscript{nd} Segment with Overspeed (Cont’d)

- Overspeed slightly reduces the effective gradient at lower heights compared to baseline E2s, but the increase to acceleration height may accommodate a SID or DP that extends to greater height.

**Example:** TOW = 100,000 lb
- Baseline E2S supports a gradient of 800 ft/nm up to about 7,750 ft
- Overspeed E2S supports a gradient of 800 ft/nm to a height of 8,170 ft.
Other possibilities: Extended with 10-Minute Limit

- Previous E2S profiles predicated on current 5-minute MTP limit
- What if an extension of MTP time limit were possible?
  - 10-minute MTP limit used on Boeing 787 and Gulfstream G650
  - Would require demonstration and/or certification
  - Significant service experience with T56 engines may help establish increased limit with minimal expense
- Not “free” like basic E2S with 5-minute limit
- Results [red dashed lines] show improvement available beyond baseline E2S acceleration heights

**Example:** TOW = 140,000 lb, obstacle at 11 nm
- 10-Minute E2S achieves 370 ft greater height (4,420 ft) than baseline E2S (4,050 ft)
- 10-Minute E2S achieves 730 ft greater height than legacy profile (3,690 ft)
- Legacy would have to reduce TOW about 10,200 lb to achieve same height as 10-minute MTP E2S
Other possibilities: Extended with 10-Minute Limit (Cont’d)

- The figure below shows the effective gradient of the 10-Minute E2S.
- The MTP extension produces no change at low heights, but may accommodate a SID or DP that extends beyond the baseline E2S acceleration height.

**Example**: TOW = 140,000 lb
- 10-Minute E2S supports a gradient of 400 ft/nm up to about 7,050 ft.
- Baseline E2S supports a gradient of 400 ft/nm up to about 4,050 ft.
Other possibilities: Extended with Continuation at MCP

- As an alternative to extending MTP time limit, simply maintain $V_{\text{OBS}}$ after 5-minute limit, continuing climb at reduced MCP setting
- Not high-risk; akin to reduced-power takeoff
- Results [blue dashed lines] not as beneficial as 10-minute MTP limit, but still provides significant increase in capability for distant obstacles
- Avoids certification or development costs

**Example**: TOW = 140,000 lb, obstacle at 11 nm
- E2S with MCP achieves 310 ft greater height (4,360 ft) than baseline E2S (4,050 ft)
- E2S with MCP achieves 60 ft less height than 10-Minute MTP E2S profile (4,420 ft)
- Legacy would have to reduce TOW about 9,400 lb to achieve same height as E2S with MCP
Other possibilities: Extended with Continuation at MCP (Cont’d)

• The figure below shows the effective gradient of an E2s profile with continuation at MCP
• The profile is unchanged at low heights, and is not as beneficial as the 10-minute MTP extension, but may help accommodate a SID or DP that extends beyond the acceleration height of the baseline E2S

**Example**: TOW = 140,000 lb
• E2S with continuation at MCP supports a gradient of 400 ft/nm up to about 5,380 ft
• 10-Minute MTP E2S supports a gradient of 400 ft/nm up to about 7,050 ft
• Baseline E2S supports a gradient of 400 ft/nm up to about 4,050 ft
Other Possibilities: Acceleration at 400 ft

- All alternatives so far involve some form of extended 2nd seg
  - These profiles move acceleration height as high as possible
- Opposite approach is to accelerate at minimum allowable altitude (400 ft in 14 CFR § 25.111)
  - Conceptually, moving to the lowest drag configuration as quickly as possible may help clearance of distant obstacles
- The figures at right show two such profiles:
  - One in which power is transitioned to MCP immediately at the end of the level acceleration (standard 14 CFR 25) [solid orange lines]
  - One in which the power is transitioned to MCP at the expiration of the 5-minute limit [dashed orange lines]
- At heavy weight, these "min-accel height" profiles cross the baseline E2S profiles at the E2S acceleration height
- Thus, min-accel profiles provide the expected benefit, at least for heavy aircraft at very distant obstacles
- Min-accel profiles do not match capabilities of the 10-minute E2S or MCP E2S profiles

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Other Possibilities: Acceleration at 400 ft

- Figure below shows the effective gradient of the min-accel height profile
- Suitable for small SID/DP gradients only, due to greatly diminished gradient during initial climb
More Possibilities: Reduced Flap Setting

- The above profiles are based on the normal C-130H takeoff flap setting (50% flap extension)

- Typically, greater gradient capability is available via reduced flap deflection, at the cost of increased takeoff distance
  - Assumes that other factors, such as brake energy and tire-limit speeds do not become limiting
  - The results at right [blue lines] indicate greater capability available with flaps-up
  - If penalty in takeoff distance is excessive, use of an intermediate flap setting may provide an optimal compromise between field-length and climb limits

Example: TOW = 140,000 lb,
  - obstacle at 11 nm
    - Flaps-Up E2S achieves 550 ft greater height (4,600 ft) than baseline (flaps 50%) E2S and 910 ft greater than legacy
    - Legacy would reduce its weight 12,600 lb to achieve the same height as the flaps-up E2S

- Further improvement possible with the 10-minute MTP extension or continuation at MCP after 5-minutes
More Possibilities: Reduced Flap Setting (Cont’d)

• The figure below shows the effective gradient of the flaps-up E2S profile
• Results in increased gradient across all heights and increased acceleration height
• May be very useful in accommodating greater SID/DP gradients

Example: consider TOW= 140,000 lb
• Flaps-Up E2S supports a gradient of 400 ft/nm up to about 5,690 ft
• Baseline E2S supports a gradient of 400 ft/nm to a height of only 4,050 ft
More Possibilities: Dynamic Overspeed

- SIDs/DPs may establish maximum takeoff weight, especially with engine failure
- Gradient capability abundant at start of climb, often in excess of required
- Diminishes with altitude, drops discontinuously at accel height, may be inadequate at top of DP
- What if we maintain only the minimum gradient at the start of climb, and “bank” excess power as speed
- The increasing speeds in this “dynamic overspeed” (DOSC) climb provide greater rate-of-climb
- The increased rate-of-climb further increases the energy state of the airplane, and results in greater height at the expiration of the 5-minute MTP limit
- Energy “banked” at the start of climb is exchanged for gradient by bleeding off speed toward the end of the climb
More Possibilities: Dynamic Overspeed (Cont’d)

• Consider a 140,000 lb airplane, requiring 420 ft/nm CG
• Two DOSC profiles evaluated:
  • Flaps in takeoff position throughout the climb
  • Flaps retracted once the airplane achieves min flap retraction speed
• Flap retraction:
  • Reduces drag, enables greater acceleration
  • However, once flaps retracted, the min flap retraction speed becomes min speed for the end of climb, restricting energy recovery
• The figure at top right shows speed traces for the two DOSC profiles, as well as legacy and basic E2S
• The DOSC with flap retraction reaches a maximum speed about 12 knots faster during the initial climb at MTP due to diminished drag
• Both DOSC profiles must reduce speed quickly after the 5-minute MTP limit in order to maintain 420 ft/nm
• DOSC with flap retraction achieves a greater height before the time limit, and bleeds-off speed at a lower rate after the limit
More Possibilities: Dynamic Overspeed (Cont’d)

- Compared to the basic E2S profile, which holds the CG to 4,600 feet, the DOSC profiles hold the CG much longer:
  - 5,000 feet without flap retraction
  - 5,600 feet with flap retraction
- Further development is needed before operational implementation of a DOSC profile
- Modifications to the autopilot, or additional indications to the pilot, perhaps via a heads-up display, may be required

![Graph showing Effective TERPS Climb Gradient vs. Height Above Airfield](image)
Conclusions

- Significant increase in aircraft capability available via simple changes to the climb-out flight path in the performance flight manual
- Basic improvements (basic E2S) require no changes to the aircraft
  - Not an expensive development program
  - Funding is likely within the range of sustainment dollars
- Will benefit operations every day
  - Increase the range and/or payload out of many currently accessible airfields
  - Enable transport of payloads into/out of previously inaccessible airfields
  - Fuel savings: reduces sorties to carry equivalent payload
  - Safer: greater margins everyday, using a more repeatable/standard profile
- The more aggressive improvements would likely incur additional cost
  - 10-minute MTP limit shows significant additional benefit, but would require engine cert (possibly mitigated by operational experience with T56 engine)
  - Continuation of E2S at MCP provides nearly same benefit, with no changes to engine limits
  - Dynamic overspeed most aggressive improvement, could be slated for future aircraft/avionics development

In contrast, the typical improvements proposed for legacy aircraft, such as new engines or winglets, involve technical risk, are much more expensive, require a protracted development cycle, and may not deliver a return on investment in the remaining life of the aircraft.