Destabilized Aircraft Response:

The Implications of Pilot Trim Error

by

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ABSTRACT

This thesis uses an aircraft aerodynamic model and propulsion data, which represents a configuration similar to the Airbus A320, to perform trade studies to understand the weight and configuration effects of "out-of-trim" flight during takeoff, cruise, initial approach, and balked landing. It is found that flying an aircraft slightly above the angle of attack or pitch angle required for a trimmed, stabilized flight will cause the aircraft to lose speed rapidly. This effect is most noticeable for lighter aircraft and when one engine is rendered inoperative. In the event of an engine failure, if the pilot does not pitch the nose of the aircraft down quickly, speed losses are significant and potentially lead to stalling the aircraft. Even when the risk of stalling the aircraft is small, the implications on aircraft climb performance, obstacle clearance, and acceleration distances can still become problematic if the aircraft is not flown properly. When the aircraft is slightly above the trimmed angle of attack, the response is shown to closely follow the classical phugoid response where the aircraft will trade speed and altitude in an oscillatory manner. However, when the pitch angle is slightly above the trimmed condition, the aircraft does not show this phugoid pattern but instead just loses speed until it reaches a new stabilized trajectory, never having speed and altitude oscillate. In this event, the way a pilot should respond to both events is different and may cause confusion in the cockpit.

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CHAPTER 1

INTRODUCTION

Engineers Design Aircraft to Be Flown to "Schedule"

The Federal Aviation Administration (FAA) regulates the aircraft industry and has many requirements aircraft must abide by in order to be certified to fly. Engineers design aircraft and develop aircraft performance predictions in accordance with these regulations under the assumption that pilot's closely follow directions. Engineers expect pilots to be able to fly aircraft at specified speeds and at given angles of attack. However, flying an airplane is very dynamic and it has been shown that pilots are often off speed during landing and an initiated go-around. In *Real Pilots Don't Go Around: Discontinued Approach and Balked Landing Climb Performance*, Wood, Beard, and Takahashi (2018) found that the pilots were often running in to stall hazard during a go-around during landing when both engines function properly and when one engine is inoperative. Wood, Beard, and Takahashi (2018) observed training pilots at Arizona State Universities' Polytechnic Campus aviation school to study the inconsistences from pilot to pilot for similar flight configurations. Figure 1, reproduced from Wood, Beard, and Takahashi (2018), shows the minimum speed a pilot should fly during a go-around and what speed the aircraft was actually flown for both scenarios of when both engines are operating and when one engine fails. From the plot it is obvious that pilots are performing maneuvers that lose a considerable amount of speed during a go-around.

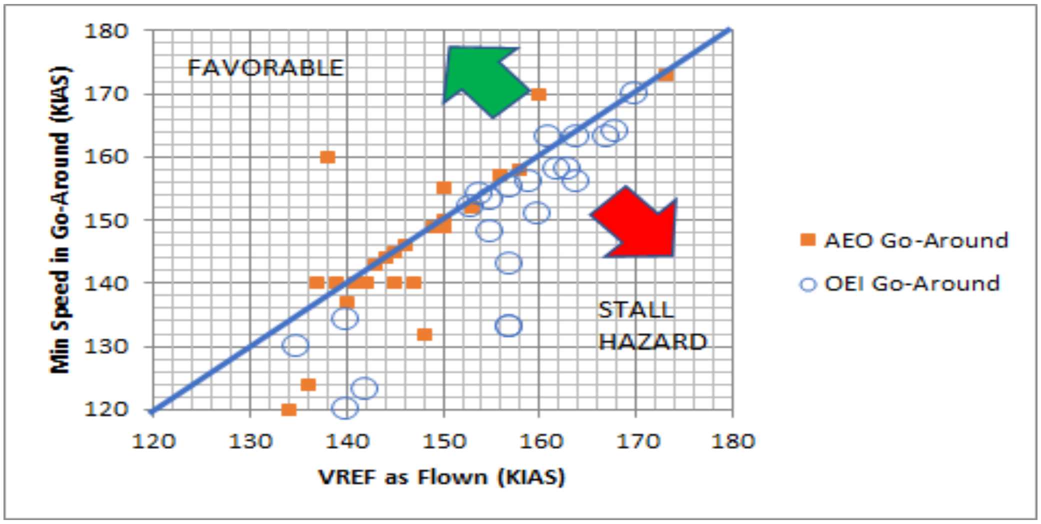


Figure 1. Minimum Speed in a Go-Around Vs. Vref as Flown, Wood, Beard, and Takahashi (2018)

Figure 2, also presented by Wood, Beard, and Takahashi (2018) shows the speed pilots are flying versus the speed that they are trying to hit for a scheduled landing. It is obvious from both figures that pilot speed varies quite a bit, and it is difficult to achieve the proper speed when descending and climbing. The goal of this study is to analyze how pilots are getting off speed and how fast these speed changes occur.

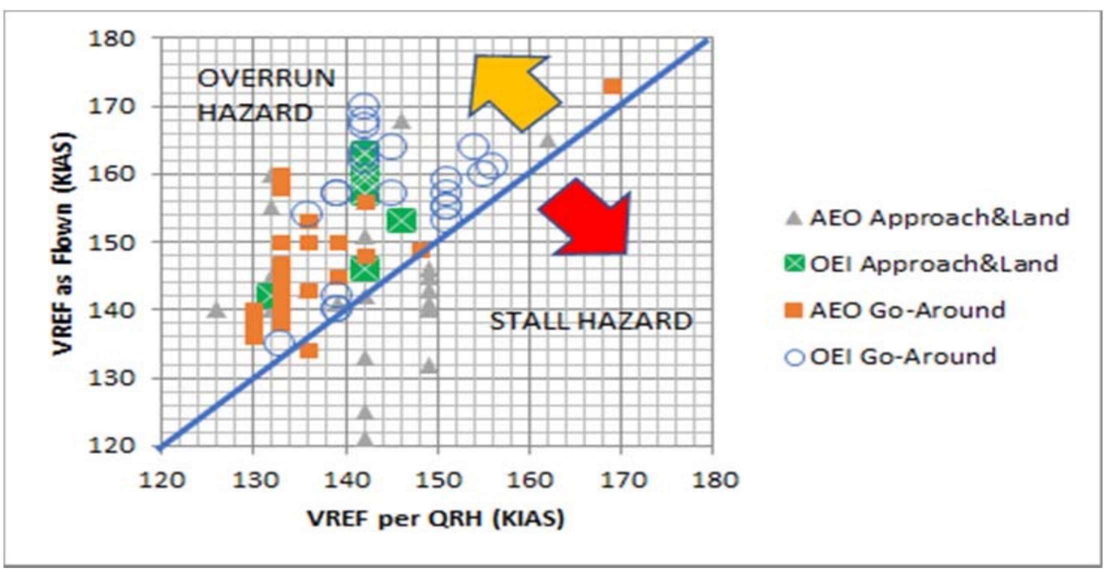


Figure 2. Vref Flown Vs. Vref per QRH, Wood, Beard, and Takahashi (2018)

Takeoff / Landing Procedures

When a pilot flies a scheduled departure from an airport, he relies upon the engineering predictions made for his aircraft based off its dispatch weight. Between the flight-manual and dispatch, the pilot receives a briefing with a checklist and schedule. This lets him know what angle to pitch the aircraft to, what speeds to climb at, and at what speed and altitude he needs to maneuver at.

Interestingly, the pitch attitude indicator that pilots use is marked on the artificial horizon (see Figure 3); cues are given in terms of a pitch angle ($\gamma+\alpha$) (see Figure 4). This is an earth fixed reference system. When his aircraft was designed, engineering based their calculations for lift and drag off the angle-of-attack of the airplane, α. The angle-of-attack is the angle between the flight path of the aircraft, γ and the angle of the aircraft fuselage, this is an oncoming wind fixed reference system.

Figure 3. Aircraft Flight Director (taken from http://krepelka.com/fsweb/learningcenter/navigation/usingtheflightdirector.htm)

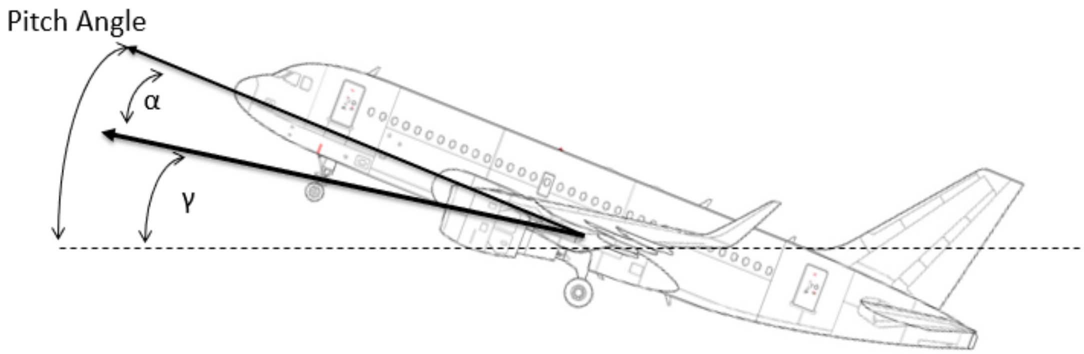
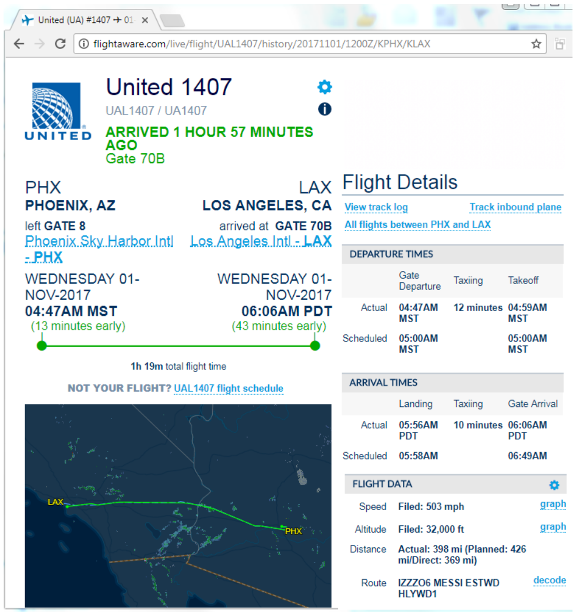


Figure 4. Aircraft Trajectory Decomposition

It is also worth mentioning that according to 14 C.F.R § 25.207(2017), the angle-of-attack of the aircraft is the parameter that triggers the stall warning. Unfortunately, the angle-of-attack is rarely displayed to the pilot; the pitch angle from the artificial horizon is the primary flight indicator.

Engineers assume that pilots fly their aircraft to precise, absolute angles of attack and accurately hold indicated airspeed. In reality, pilots often fly by visually aligning the artificial horizon with a computer generated "flight director" cue for pitch and roll angle; refer back to Figure 3. The flight management navigation software controls the flight director cue; it basically gives the pilot an idea as to what orientation he should align the aircraft to in order to climb, descend and/or turn while follow a preprogrammed altitude/waypoint "trajectory." The waypoint trajectory is constructed during flight planning (see Figure 5), it does not explicitly consider the climb performance of the aircraft.



KPHX IZZZO6 MESSI ESTWD HLYWD1 KLAX

Name	Latitude	Longitude	Outbound Course	Distance this Leg	Distance Remaining	Distance Flown	Type
KPHX	33.4342778	-112.0115833	90°	n/a	370	0	Origin Airport
FUTEP	33.4349167	-111.8728333	144°	8	378	8	Waypoint
AZCRD	33.3942222	-111.8376389	210°	3	380	10	Waypoint
USEYE	33.3504167	-111.8685000	276°	4	379	10	Waypoint
MASVE	33.3551944	-111.9198056	280°	3	376	8	Waypoint
KEENS	33.4501389	-112.6008611	271°	40	336	34	Waypoint
IZZZO	33.4527500	-112.8000556	293°	11	324	46	Waypoint
MESSI	33.7998333	-113.8031667	292°	63	265	106	Reporting Point
ESTWD	33.9051389	-114.1135833	282°	19	246	125	Waypoint
MCQWN	34.0562222	-115.0189722	281°	53	194	178	Waypoint
MDLER	34.1638333	-115.6894444	263°	39	157	217	Waypoint
MNROE	34.1347778	-115.9896667	263°	17	139	234	Waypoint
HLYWD	34.1042500	-116.2987778	263°	18	121	251	Waypoint
BRUEN	34.0731667	-116.5883889	264°	17	105	267	Waypoint
AVATR	34.0451944	-116.8880000	261°	17	87	284	Waypoint
DAAAY	34.0266667	-117.0310278	262°	8	79	292	Waypoint
WADUP	34.0031389	-117.2291111	262°	11	68	303	Waypoint
NEILE	33.9936111	-117.3085000	262°	5	63	307	Waypoint
SEAVU	33.9724167	-117.4885000	268°	10	53	317	Reporting Point
KLAX	33.9424944	-118.4080472	n/a	53	0	370	Destination Airport

Figure 5. Waypoint Flight Plan. (UAL 1407 1-Nov-2017, as reported by FlightAware.com)

While it seems that flying to follow the flight director might be as simple as lining up two lines, it is not surprising us that pilots might command their airplane above or below the preloaded pitch angle by a degree or two. This is especially likely to happen during a maneuver or during an emergency; note that the major angle spacing on the indicator is 10° and the minor hatch lines are given in 2.5° increments.

A study by GE Aviation (2011) found that having an innovative flight avionic system that allows the aircraft to fly precisely-defined trajectories will allow for more consistent and more efficient flight paths. The study also states that at least $65.6 million dollars will be saved annually from the increased efficiency. The performance implications of having outdated pitch directors is to be looked in to in this study.

CHAPTER 2

BACKGROUND INFORMATION AND PRIOR ART

Code of Federal Regulations Regarding Takeoff and Landing

Transport category aircraft may have many different flap settings. At minimum, aircraft have three flap settings representing cruise, takeoff and landing. According to the Airbus A320-212 Flight Manual (1990), the A320 for example, has five flap configurations: FLAPS UP, CONF 1+F, CONF 2, CONF 3 and CONF FULL. Engineers design the aircraft so that the FLAPS UP setting has ideal lift and drag divergence characteristics for en-route as well as high speed flight. CONF 1+F deploys the takeoff leading edge slats and minimally deploys the trailing edge flaps; this is one possible setting for takeoff. CONF 2 further deploys the trailing flaps, increases the maximum lift coefficient (and reduces the stall speed); it is a typical takeoff setting for this aircraft. CONF 3 extends the leading-edge slats to a landing position and fully extends the trailing edge flaps; this provides a further increase in maximum lift coefficient but with some drag penalty. Finally, the conf FULL configuration offers maximally deflected trailing edge flaps to provide the slowest stall speed possible, but with a further increase in drag.

Second Segment Climb Speed.

In order to compute the second segment climb speed, V2, engineers must turn to a complex set of interlocking regulations in the Code of Federal Regulations (CFR): 14 CFR § 25.103(2014), 14 CFR § 25.105(2014), 14 CFR § 25.107(2014), 14 CFR § 25.109(2014), 14 CFR § 25.111(2014), 14 CFR § 25.113(2014, and 14 CFR § 25.121(2017) are a few regulations outlined below.

- 14 CFR § 25.103(2014) describes the method to compute stall speed. Vs is computed from the maximum lift coefficient and the wing loading as:

$$Vs = \sqrt{\frac{(\frac{W}{S_{ref}})}{1481\ C_L max}}\ 660.8 \qquad (1)$$

- 14 CFR § 25.105(2014) describes the overall procedure for takeoff (ensuring that the runway length is adequate for an all-engines-operating takeoff, a rejected-takeoff due to engine failure, as well as continued takeoff where the engine fails above the "decision speed").
- 14 CFR § 25.107(2014) describes the basis for selecting the "decision speed," V1, where an engine-failure will lead to either a rejected or continued takeoff, the "rotation speed," V_R, where the pilot lifts the nose wheel off of the ground to begin flight, and the "takeoff safety speed," V2, that the aircraft should attain or exceed at the point it is 35-feet above the runway.
- 14 CFR § 25.109(2014) describes the accelerate-stop procedure for a rejected takeoff.
- 14 CFR § 25.111(2014) describes the accelerate-go procedure for a flight with all engines operating and a flight with a critical engine failure above the decision speed. It specifies a minimum initial climb capability for the aircraft with an inoperative engine.
- 14 CFR § 25.113(2014) describes the means to compute the total takeoff distance.

- 14 CFR § 25.121(2017) provides a minimum climb capability for the aircraft with a critical engine inoperative and landing gear retracted; this is the "second segment climb gradient" constraint.

The second-segment climb speed, V2, is the target obstacle clearance speed for a failed engine takeoff run. For a turbofan powered aircraft, this value may not be less than 113% of the stall speed with the flaps in takeoff position or 110% of the minimum control airspeed, whichever is lower. In other words:

$$V2 = \max\left(1.13 \cdot Vs,\ 1.1 \cdot VMCA \right) \tag{2}$$

For example, consider an Airbus A320 with a flight weight of W=170,000-lbm, Sref= 1,319-ft^2, and $C_L$max=2.48 and VMCA ~ 110 KIAS to represent flight with the flaps in the CONF 2 takeoff setting. The stall speed governed by these parameters is ~124 KIAS. Thus the obstacle clearance speed will be 140 KIAS; that is controlled by 1.13 times the stall speed as opposed to 1.10 times the minimum control speed.

Under normal operating conditions, with all engines operating, pilots will typically overshoot scheduled V2 and stabilize second segment climb speed around V2+10 or V2+15 knots. This phenomenon occurs because pilots follow the handbook procedure to initiate takeoff rotation at the scheduled V_R speed. Engineers select V_R to be the airspeed where the aircraft must begin to nose up so that with one engine inoperative, it will attain the obstacle clearance speed, V2, at the time it is 35-ft above the runway.

Final Segment Climb Speed.

The final segment climb speed is usually the flaps-up safety speed, V4=VFTO. This speed serves as a minimum enroute climb speed during a continued takeoff with a failed engine. For a turbofan powered aircraft, 14 CFR § 25.123(2014) stipulates that this value may not be less than 118% of the stall speed in cruise configuration or the minimum control airspeed whichever is lower. In other words:

$$V4 > \max\left(1.18 \cdot Vs,\ VMCA\right) \quad (3)$$

Continuing the example of an A320 with flight weight, w=170,000-lbm, Sref= 1319-ft^2, VMCA= 110 KIAS and $C_L max$=1.4 with the flaps in the cruise setting. One would therefore predict a cruise configuration stall speed Vs=165 KIAS. Thus, V4 can be set no lower than 194 KIAS; that is controlled by 1.18 times the cruise configuration stall speed rather than the minimum control airspeed.

During the takeoff procedure, with the aircraft in the takeoff flap configuration, the pilot must accelerate to a flap retraction speed very close to V4 before initiating flap retraction. In the case of an A320, under typical conditions the pilot must accelerate from V2+15 to V4 before retracting flaps; in other words, from ~155 KIAS to ~194 KIAS. Under engine inoperative conditions, pilots must fly a level acceleration to flap retraction speed from V2 to V4; in other words, from ~140 KIAS to ~194 KIAS (54 knots acceleration). Premature flap retraction could leave the aircraft in a position where pilots attempt to "fly" it beneath stall speed. An unstable second segment flown slower than the scheduled V2 speed will also increase the level acceleration time and distance.

Enroute Climb Speed (over 10,000-ft).

Engineers select the scheduled enroute climb speed to maximize the rate of climb, subject to regulation 14 CFR 25.123(2014) as cited above. In Airbus parlance, this is known as the "green dot" speed. For an A320 flown at w=170,000-lbm, Airbus would suggest that pilots should fly a "best climb to altitude" by maintaining ~240 KIAS. Above 10,000-ft AGL, U.S. air traffic regulations no longer limit the aircraft not to exceed 250 KIAS per § 91.117(2014). Note that the 250 KIAS "speed limit" does not impact A320 during normal operations.

Final Approach Speed.

The landing reference speed, Vref, is the lowest stabilized airspeed flown during the landing sequence. It represents the airspeed that the aircraft maintains on its final approach until it just begins to enter ground effect, 50-feet above the runway surface. Regulation 14 CFR § 25.125(2014) holds that Vref must be the greater of either 123% of the stall speed in the landing configuration or the minimum control speed in landing, VMCL:

$$Vref = \max\left(1.23\, Vs_{landing}, VMCL \right) \tag{4}$$

The minimum control landing airspeed, VMCL, represents the lowest airspeed during flight, prescribed in 14 CFR §25.149(2014), where "when the critical engine is suddenly made inoperative, it is possible to maintain control of the airplane … and maintain straight flight with an angle of bank of not more than 5 degrees" with the flaps in the touchdown setting and landing gear deployed.

Continuing the example of an A320 with flight weight, w=146,000-lbm, Sref= 1319-ft^2, VMCL= 110 KIAS and $C_L max$=2.67 with the flaps in the FULL setting, one can predict a stall speed Vs=111 KIAS. Thus, VREF can be set to 136 KIAS; that is controlled by 1.23 multiplier on final approach stall speed rather than the minimum control airspeed.

In these scenarios, for safe operation the aircraft must maintain a flight speed above a specified minimum. If an aircraft lost significant speed during a maneuver, dropping below VMCA or approaching stall, it becomes a theoretical or actual safety hazard. During second-segment climb on an Airbus A320 at a typical flight weight, the federally mandated scheduled climb speed is only 16 knots faster than the published stall speed. This expresses how even small decreases in speed can be dangerous.

Flight Manuals

When an aircraft is produced, extensive manuals on how to safely operate the vehicle are developed. Everything from anti-icing to tire speed limits are detailed in these manuals.

However, when searching through manuals it seemed as though they lacked sufficient direction on pitching the aircraft to the proper attitude. For example, the Canadair CL-65 Training Manual (2011) that is used for the CRJ high fidelity flight simulator lists the following regarding pitch during a takeoff:

"The function of the target pitch attitude is only to provide guidance for initial airplane rotation. Pitch attitude must be adjusted immediately after initial rotation in order to achieve the recommended climb speed.

The flight director guidance represents an initial target for the rotation only and does not guarantee that the recommended climb speed will be achieved / maintained under all conditions. Pilots must transition to speed immediately after initial rotation."

The above passage is included in multiple sections of the Canadair Training Manual that specifically entail takeoff, climb, balked landings, and go-arounds. Here it is shown that pilots will have a set pitch angle target to rotate the airplane up to, but once the aircraft is off the ground, the pilots are given vague direction as to what pitch angle is desired. Instead the pilots are directed to manipulate the pitch angle in order to attempt achieving given flight speeds.

The flight manual for the Boeing 737 airplanes gives similar instruction regarding rotation and takeoff. The Boeing Flight Crew Training Manual (2011) states:

"For optimum takeoff and initial climb performance, initiate a smooth continuous rotation at V_R toward 15° of pitch attitude… After liftoff, use the attitude indicator as the primary pitch reference. The flight director, in conjunction with indicated airspeed and other flight instruments is used to maintain the proper vertical flight path… Pitch, airspeed, and airspeed trends must be crosschecked whether the flight director is used or not."

This manual provides instruction for the pilot to pitch the aircraft to 15° horizon attitude (regardless of flight weight) for initial takeoff. The manual then instructs the pilot to follow the pitch given by the flight director while also paying attention to the indicated airspeed and other flight instruments. This implies that if the indicated airspeed falls below or increases beyond the desired airspeed, the pilot may have to deviate away from what pitch the flight director is calling for in order to achieve the proper airspeed.

In almost all scenarios presented in both manuals, the pilots are instructed to follow the flight director (horizon attitude cue) in order to achieve proper climb gradients and profiles. The following question becomes what happens when a pilot is unable to follow the flight director exactly or has to deviate from the flight director in different scenarios. The Boeing Flight Crew Training Manual (2011) also makes note of how important the pilot's ability to pitch the aircraft is on airspeed and climb performance by noting:

"Early or rapid rotation may cause a tail strike. Late, slow, or under-rotation increases takeoff ground roll. Any improper rotation decreases initial climb flight path."

This decrease in climb flight path and performance is the aim of the research presented in this paper.

Gulfstream Crash

In 2011, a test flight performed by Gulfstream resulted in a crash and death of four people onboard. Gulfstream was preforming a takeoff with one engine inoperative on the G650. The National Transportation Safety Board (NTSB) found that "[the crash] was the result of an aerodynamic stall and uncommanded roll… the crash was the result of Gulfstream's failure to properly develop and validate takeoff speeds". The G650 was moving too slow when the pilots attempted to pitch the aircraft up, resulting in a right wing stall that lead to the aircraft rolling right and crashing in to the ground. This is an unfortunate scenario that shows how achieving proper speeds and rotating to correct pitch angles is important for safe departures.

Phugoid Approximation

Along with stalling hazard, other situations may arise from being off speed or at an incorrect angle of attack. A student pilot quickly learns that it is easy to "wallow;" to fly in oscillatory rather than steady manner, when the aircraft is imperfectly trimmed. If the aircraft is not perfectly balanced in pitch, and the pilot lacks the steadiest of hands, it quickly develops a dynamic response in pitch, speed and trajectory.

Classic texts, like Airplane Flight Dynamics by Roskam (1982, Part I), define stick-fixed longitudinal stability as the "tendency of the airplane to develop forces or moments which directly oppose an instantaneous perturbation of a motion variable from a steady-state flight condition." Thus, when the nose of an aircraft is disturbed above its natural equilibrium point, the aircraft develops a nose-down moment that returns the nose to its original attitude.

Similarly, Roskam (1982, Part I) introduces the classic concepts of inherent speed stability. Any increase in forward airspeed should be met by an opposing force that opposes the increase in airspeed. Since drag typically increases proportional to the dynamic pressure that, in-turn, is proportional to the square of the indicated airspeed; this criteria is fairly easy to meet unless the aircraft has unusually high induced drag and/or a propulsion system whose thrust increases (rather than lapses) with increasing airspeed.

Roskam (1982, Part I) also introduces the concept of the longitudinal Short-Period Mode. This is a naturally developing damped oscillatory mode where the aircraft angle-of-attack varies in time with no change in airspeed. The aircraft typically "wobbles" within 10-ft of its nominal altitude at a frequency that is typically less than 1-hz. Analysts consider the short-period mode is a "nuisance mode," but pilots find an excessively slow short-period frequency coupled with an airframe that is unusually responsive in pitch difficult to hand-fly.

Figure 6. Short Period Mode Schematic Hurt (1960)

Roskam (1982, Part I) finally introduces the concept of the longitudinal Phugoid Mode. This is another naturally developing oscillatory mode. In the Phugoid, the aircraft "wobbles" about a nominal straight-and-level trajectory with larger changes in speed, altitude and angle-of-attack. The period of the Phugoid Mode is measured in 10's of seconds, with altitude variations on the order of 100's of feet.

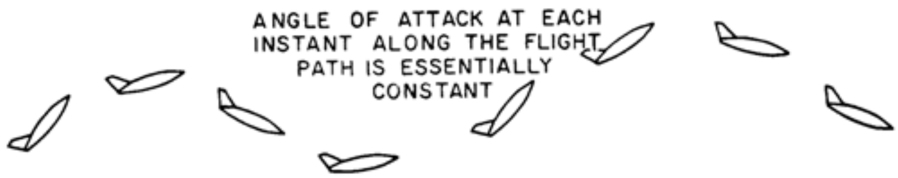


Figure 7. Phugoid Mode Schematic Hurt (1960)

Roskam (1982, Part II) also covers the concept of the human pilot plus the airframe acting as a closed loop system. If the pilot can provide control inputs with zero "transportation delay," he "would have no difficulty controlling pitch." Any amount of "lead" in inputs to counteract the inherent aircraft oscillatory behavior is beneficial. But Roskam (1982, Part II) states that increasing transportation delay, a reactive – the proverbial "drunk" pilot - as opposed to a proactive pilot is likely to be unable to maintain control. As the pilot reactive gain or transportation delay to disturbances increases, the system stability decreases.

So what flight dynamics do pilots experience while hand flying an airplane that is imperfectly trimmed in pitch? Pilots may experience this phenomenon during initial takeoff climb, after a major change in power setting, after a major change in aircraft drag (flap retraction), and/or after a major change in flap setting. It can be conceived of even more destabilizing events occurring during a balked landing "go-around." During a go around, the pilot must quickly transition from descending flight at a constant airspeed, part-power, and flaps and gear deployed to a climbing flight at a different airspeed at full power, with flaps and gear retracted. If an engine fails during a go-around, it may suddenly introduce lateral-directional as well as additional longitudinal trim challenges to the pilot.

Thus, an out-of-trim aircraft with a mechanical failure introduce cockpit confusion and disarray that can lead to an increase in pilot reaction time and gain. Both of these factors can further destabilize otherwise stable, but dynamic flight modes, introduced by the trim-error.

Wood and Takahashi (2018) performed observations of pilots flying in a CRJ-200 simulator study described in *The Effect of Piloting Practices Upon Actual as Opposed to Scheduled Landing Field Performance*. They noted significant speed and flight path instability during many approaches. During a balked landing, with an engine failure during the "go-around," they noted several occasions where pilots completely destabilized the aircraft – situations that triggered the stick-pusher and ultimately led to a crash.

CHAPTER 3

MATHEMATICAL AND SIMULATION BASIS

Simulation

Climb performance is computed using a time-step integrating point-mass simulation shown in *Aircraft Performance and Sizing* by Takahashi (2016, Vol. 1). The code requires a tabular aerodynamics file, a 5-column propulsion data file, and a mission command keyword file outlining the mission profile. This code simulates flight under nominal trimmed conditions.

For this project, this code was extended to add additional modes to permit flight under out-of-trim conditions. The two added modes simulate the aircraft behavior when a pilot commands flight at either a constant angle-of-attack or a constant pitch angle. Both modes offer different approaches to simulating out-of-trim flight.

While tracking aircraft trajectories in terms of classical piloted aircraft state variables: indicated airspeed, Mach number, and height-above-ground, the simulation no longer begins with a pretense that lift opposes weight and thrust-vectored propulsive forces.

The new algorithm begins each time step by calling the standard atmosphere table to determine the dynamic pressure, q, and speed-of-sound, a. From these values, it is possible to infer the Mach number from the aircraft linear velocity, VFTS:

$$VFTS = a * M \tag{5}$$

Then the linear velocity is converted into true airspeed with a simple unit conversion:

$$KTAS = VFTS * \frac{3600}{6080} \tag{6}$$

Similarly, the "indicated airspeed" is inferred from the dynamic pressure:

$$KIAS \approx KCAS \approx KEAS = 661 * \sqrt{\frac{q}{1481}} \tag{7}$$

If flight is commanded at constant angle-of-attack the angle, α, is explicitly defined by the keyword driven mission file.

If flight is commanded at constant pitch angle, the angle-of-attack is computed from the specified pitch angle and the flight path angle of the previous iteration (see Figure 4):

$$\alpha = pitch - \gamma \tag{8}$$

Once the angle-of-attack has been determined, one may interpolate the lift coefficient from the tabular aero data: $C_L = C_L(M,\alpha)$.

With the coefficient of lift the net lift is now calculated from the coefficient of lift, dynamic pressure, and reference area of the aircraft:

$$L = q * C_l * S_{ref} \tag{9}$$

Subsequently the coefficient of drag is calculated from interpolating the aero data given the Mach number, coefficient of lift, altitude, and drag increase due to landing gear or engine inoperative.

$$C_D = C_D(Mach, C_L) + \Delta C_{D_{Reynolds}}(M, ALT) + \Delta C_{D_{Windmill}} + \Delta C_{D_{Gear}} \tag{10}$$

With the coefficient of drag, the net dimensional drag is computed from the coefficient of drag, reference area, and dynamic pressure.

$$D = C_D * q * S_{ref} \tag{11}$$

Now all the forces are summed up in the horizontal and vertical (relative to ground) directions; see Figure 8 below. The forces summed are the thrust interpolated from the five-column propulsion data, net lift, drag and weight.

$$F_x = T * Cos(\gamma + \alpha) - L * Sin(\gamma) - D * Cos(\gamma) \tag{12}$$

$$F_z = T * Sin(\gamma + \alpha) - W - D * Sin(\gamma) + L * Cos(\gamma) \tag{13}$$

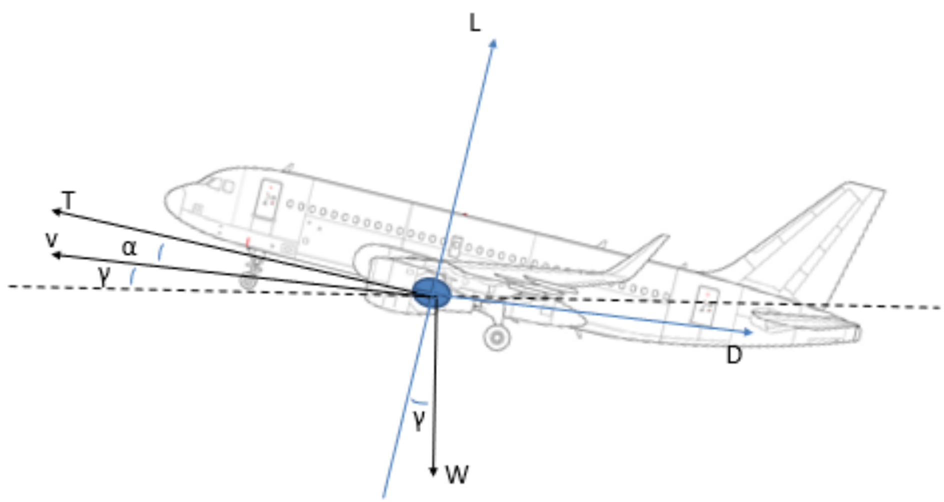


Figure 8. Free Body Diagram for Aircraft Flight Forces

Now with the forces summed, the accelerations in the corresponding directions are calculated in feet per second.

$$a_x = F_x * \frac{32.174}{w} \tag{14}$$

$$a_z = F_z * \frac{32.174}{w} \tag{15}$$

The true airspeed is now updated from the accelerations multiplied by the time step of the iteration and the true airspeed calculated from before and broken down in to its components.

$$V_x = VFTS * Cos(\gamma) + a_x * dt \tag{16}$$

$$V_z = VFTS * Sin(\gamma) + a_z * dt \quad (17)$$

With the updated components of velocities the updated altitude, distance, rate of climb, flight path angle, Mach number, and true airspeed are calculated for the next time step iteration.

$$alt = alt + V_z * dt \quad (18)$$

$$dist = dist + V_x * \frac{dt}{6080} \quad (19)$$

$$R.O.C. = V_z * 60 \quad (20)$$

$$\gamma = Tan^{-1}\left(\frac{V_z}{V_x}\right) \quad (21)$$

$$M = \frac{VFTS}{a} \quad (22)$$

$$KTAS = \sqrt{V_x^2 + V_z^2} \quad (23)$$

$$t = t + dt \quad (24)$$

At the end of the timestep, the flight weight is then decremented by the incremental fuel consumption based off the propulsive data.

The kinematics produced by the point-mass-simulation maintain validity because it derives from conservation of mass, momentum and energy equations.

Classic Flight Dynamics - Phugoid Approximation

The Boeing Stability & Control short course notes (1975) explains the industrial viewpoint of the aircraft Phugoid mode. This short course correctly states that the fundamental equations of motion may be solved, in general, for the transfer function of response to a forcing function. They explain that the response can be divided two ways: 1) into the steady-state response due to the forcing function and 2) into the initial transient response due to the inherent stability characteristics of the airplane.

The transient mode typically expresses itself as a damped oscillation. For most aircraft, the oscillatory modes manifest themselves as one of long period (the Phugoid mode) with low damping and one of short period (the Short Period Mode) with heavy damping.

The short period mode causes transient motion in angle-of-attack (α) and load factor (Nz) but occurs at a high enough frequency where the airspeed does not change. Holding the aerodynamic design fixed, the frequency of the short period mode increases as the mass properties move the CG position forwards. The short period frequency grows higher as the indicated airspeed increases. The damping tends to decrease as the CG position moves forwards. Interestingly, an aircraft with an aft mounted horizontal tail inherently has positive damping of the short period mode.

The long period mode causes transient motion in airspeed (VKTAS) and pitch attitude (α+γ) as the aircraft exchanges altitude for speed in a trade between potential and kinetic energy. If only long-term low frequencies are considered, the fundamental equations of motion reduce to describe an oscillatory mode with frequency:

$$\omega_{Phugoid} = \frac{g}{VKTAS}\sqrt{2} \qquad (25)$$

and damping ratio:

$$\zeta_{Phugoid} = \frac{1}{\sqrt{2}\left(\frac{L}{D}\right)}) \qquad (26)$$

Thus, the frequency is inversely proportional to the flight speed VKTAS and the damping ratio is inversely proportional to the aerodynamic efficiency (L/D). In other words, the faster the aircraft travels the slower the phugoid frequency and the greater the aerodynamic efficiency, the weaker the damping.

The Boeing handbook (1975) notes that the actual aircraft response to a step change in elevator deflection; a change in trimmed angle-of-attack should result in damped oscillatory motion which should stabilize about a new airspeed.

Aero Model

The aerodynamic model used in this simulation was based upon a reverse-engineered A320 flight performance model developed by Beard (2017) in *Takeoff Obstacle Clearance Procedures: The Feasibility of Extended Second Segment Climb* and utilized in other work published by Wood, Beard, and Takahashi. Zero lift drag estimates for the clean configuration derive from an EDET model created by Feagin and Morrison (1978) in *Delta Method, An Empirical Drag Buildup Technique*, and is developed from Airbus published geometry from Civil Jet Aircraft Design (2001).

While attempting to match Airbus published climb performance, Beard (2017) derived zero-lift-drag increments appropriate for a variety of flap settings (FLAPS 1+F, FLAPS 2, FLAPS 3 and FLAPS FULL), all-engines-operating and one-engine-inoperative flight with a windmilling engine, and flight with landing gear extended. An inoperative engine will no longer allow air to pass through it unobstructed. This blockage exhibits itself as windmill drag. Beard (2017) estimated that the drag increases due to an engine failing results in an increase in coefficient of drag of 0.0134. The model also takes in to account the drag increases for having the gear extended. Having gear extended will increase drag similarly to an engine inoperative. Beard (2017) estimated that the drag due to landing gear extension results in an increase in coefficient of drag of 0.100.

The aerodynamic model was reverse-engineered for multiple flap configurations. The aerodynamic model accurately represents the increases in lift and drag for increasing flap extension. Table 1 below shows the maximum coefficient of lift available for these various flap settings. The maximum coefficient of lift for the clean configuration is 1.4 while deploying the flaps fully will allow for a maximum lift coefficient of 2.67.

Table 1. CLmax Estimates Inferred From A320 Published Stall Speeds. Beard(2017)

FLAPS SETTING	CLMAX
CLEAN	1.4
FLAPS 1+F	2.1
FLAPS 2	2.48
FLAPS 3	2.52
FLAPS FULL	2.67

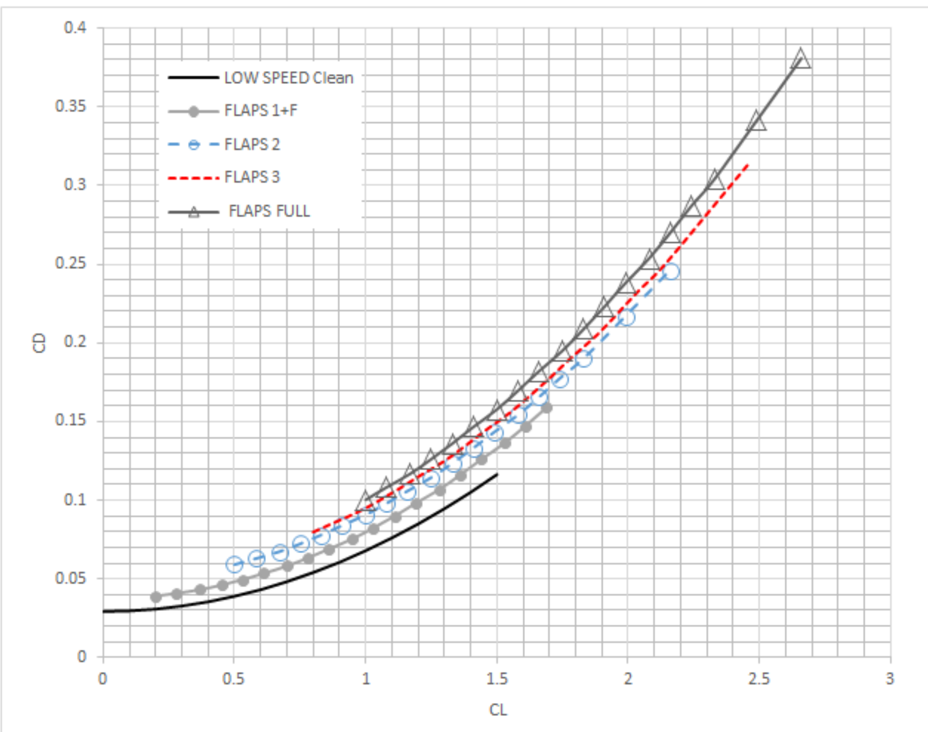


Figure 9. Drag Polars Inferred From A320 Published Climb Performance – Gear Up. Beard(2017)

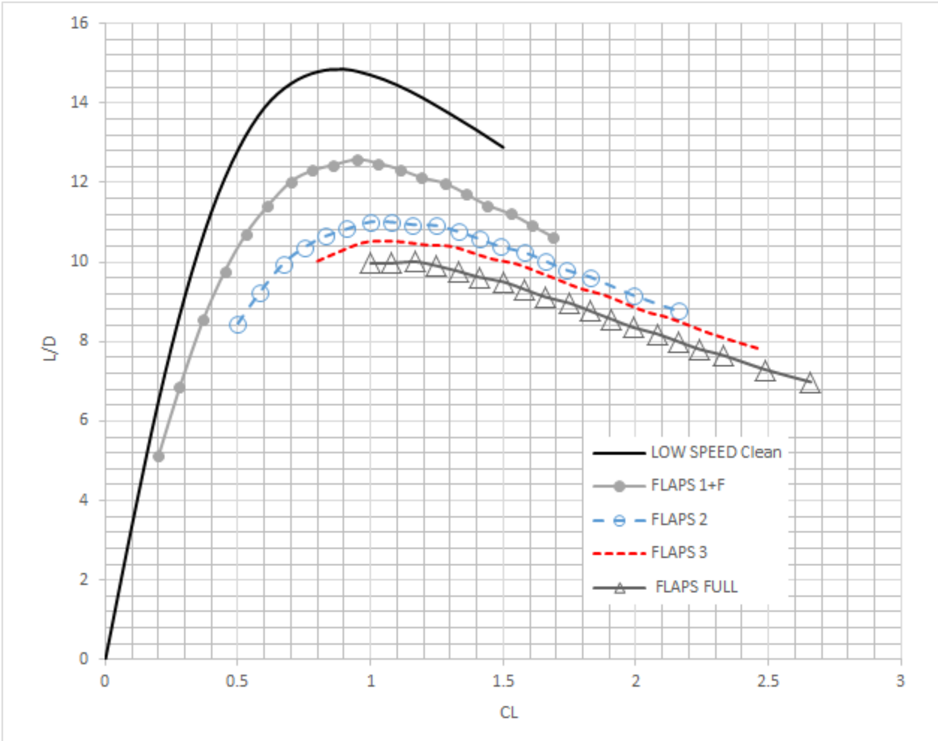


Figure 10. Drag Polars Inferred From A320 Published Climb Performance – AEO / Gear Up. Beard(2017)

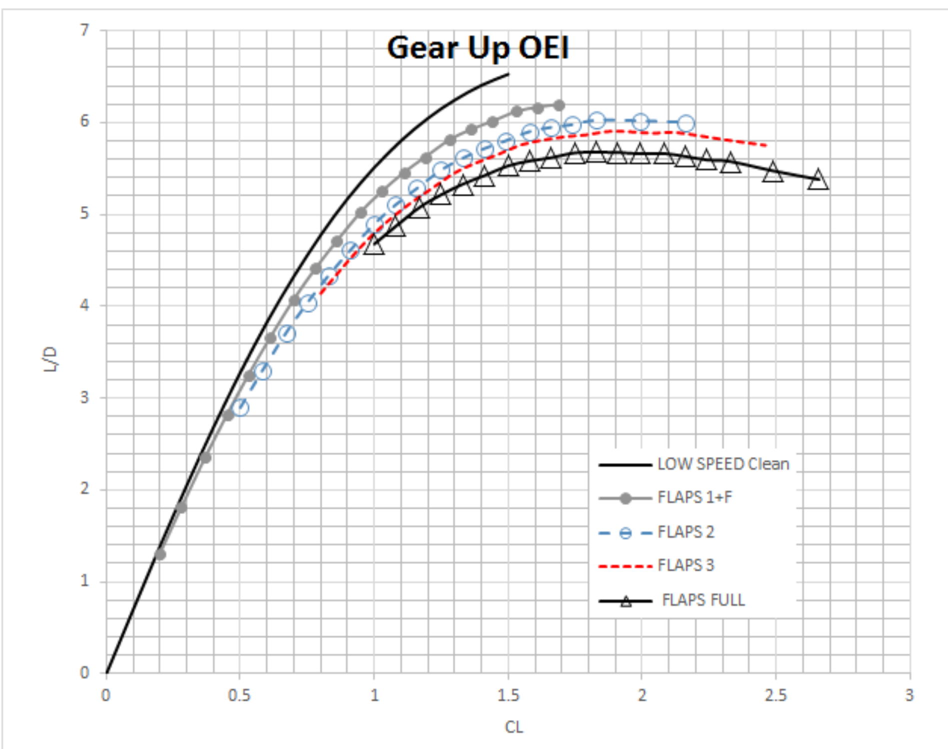


Figure 11. Drag Polars Inferred From A320 Published Climb Performance – OEI / Gear Up. Beard(2017)

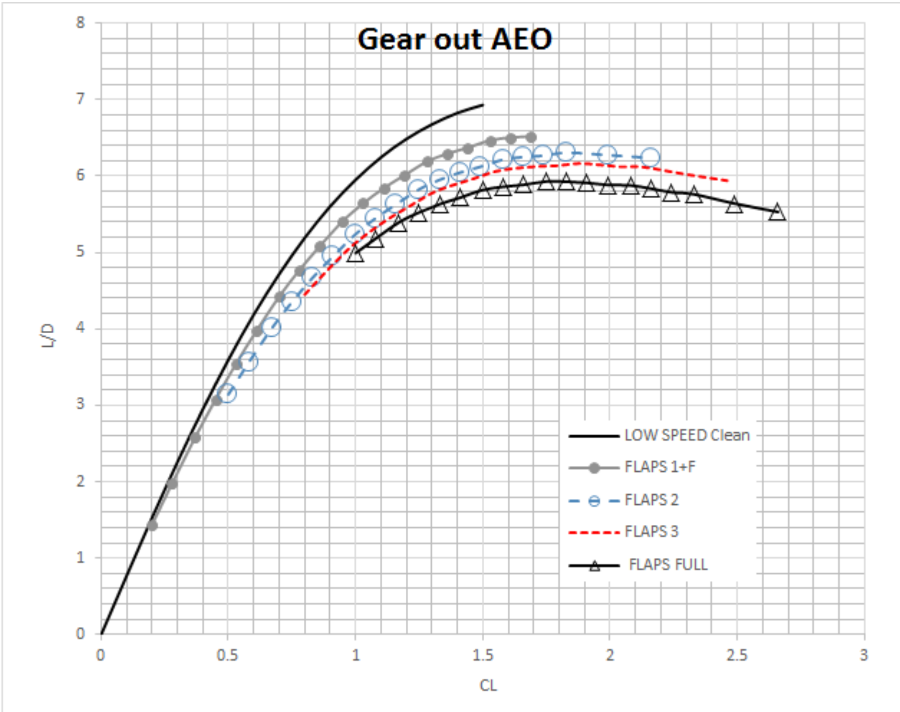


Figure 12. Drag Polars Inferred From A320 Published Climb Performance – AEO / Gear Out. Beard(2017)

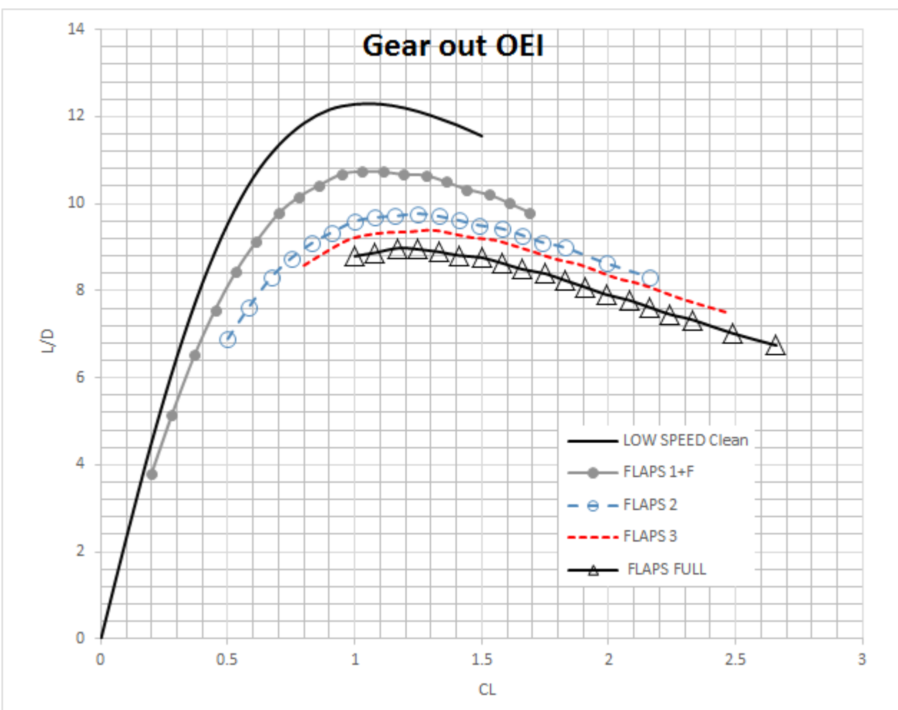


Figure 13. Drag Polars Inferred From A320 Published Climb Performance – OEI / Gear Out. Beard(2017)

The drag polars above (Figures 9 through 13) give insight in to the flight envelope flown for the multiple scenarios studied in this paper. It is shown here that that for most observed polars, particularly at FLAPS 3 and FLAPS FULL, L/Dmax peaks long before the vehicle reaches the stall CL. Most of the usable polar, therefore, will have the pilot fly on the 'backside' of the L/D curve.

In Power Side Blues, Pope (2014) talks about how flight on the 'backside' occurs when the aircraft operates in an "area of the performance envelope in which induced drag rises dramatically, necessitating considerably more power to maintain a given airspeed and altitude." Holding constant throttle, a pilot who commands a greater nose-up attitude will find a "region of reverse command" where the steady state sink rate will increase rather than decrease. Pulling back on the yoke exacerbates the problem.

The propulsion data used in this simulation was developed using NPSS, a numerical propulsion system simulation software package created by Ohio Aerospace Institute (2010). The model simulated the V2527 engine using the default two-shaft turbofan model compressor fan maps supplied by the software vendor, along with published values for reference bypass-ratio, fan-pressure-ratio and maximum turbine inlet temperature from Pratt and Whitney (2017). This model develops a realistic thrust-velocity and thrust-altitude lapse profile.

When an accurate dynamic simulation basis with well calibrated aerodynamic and propulsive performance data is combined, one can perform comprehensive trade studies. It is then possible to study how the aircraft preforms under different flight conditions.

CHAPTER 4

ANALYSIS

The research performed for this study involved using the simulation techniques outlined above to run various trade studies. The focus of the trade studies is to investigate the response of an aircraft when flown destabilized by being out of trim in angle of attack and pitch angle. Trimmed conditions imply that the aircraft is flown at 1g (lift is equal to weight) and climbing, in level flight, or descending at a constant indicated airspeed.

Angle of Attack Trades

Figure 14, below, shows an aircraft flown at V2+15 (155 KIAS), 170,000-lbm, with all engines operative, and FLAPS 2. Represented on the plot is the aircraft climbing in trim at constant indicated airspeed; impacts of flying the aircraft out-of-trim by 1°, 2°, and 3° in angle-of-attack is also shown.

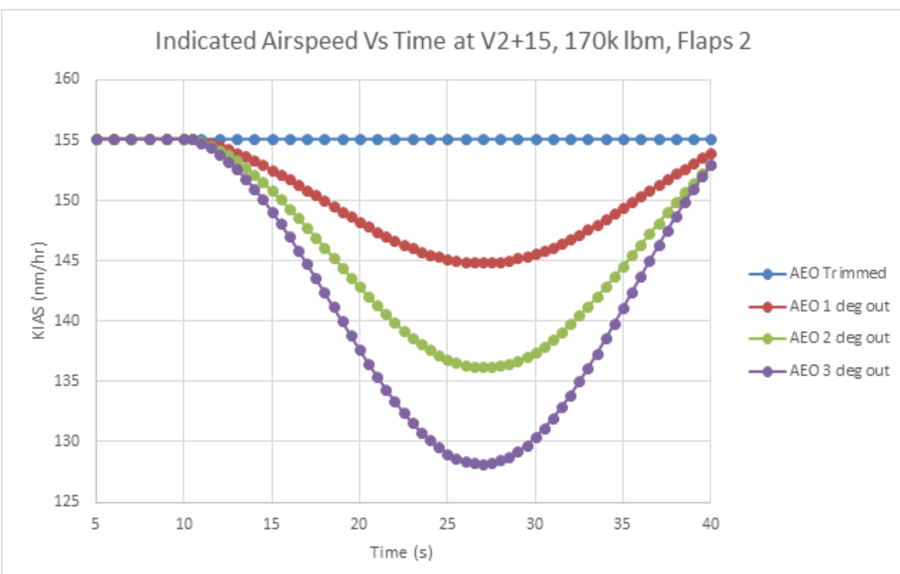


Figure 14. Speed-Time History - AEO Second-Segment-Climb With Destabilizing Pilot Inputs Beginning at T=10-sec

It is shown that flying out-of-trim by putting the aircraft at a slightly higher angle-of-attack will reduce speed rather quickly. When flown only 1 degree out-of-trim in angle-of-attack the aircraft will lose speed at only 0.64 knots per second. However, if the aircraft is out-of-trim by 3° the aircraft will lose speed at a rate of 1.55 knots per second.

What is odd here is the periodic nature of speed variation. Holding the angle-of-attack fixed in an "out-of-trim" condition will eventually result in the aircraft returning to its original airspeed approximately 30-seconds later.

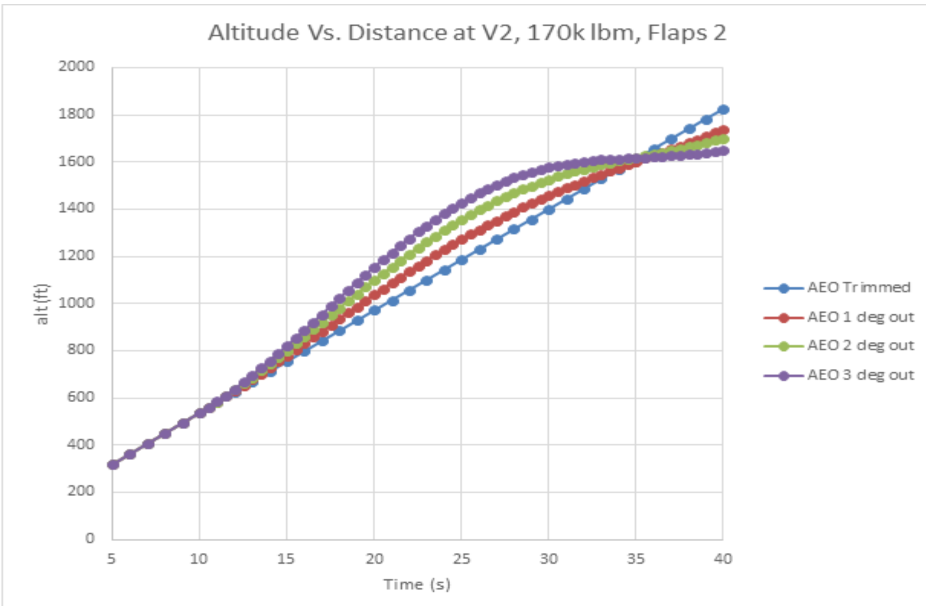


Figure 15. Altitude-Time History During AEO Second-Segment-Climb With Destabilizing Pilot Inputs beginning at T=10-sec

Looking at Figure 14 in conjunction with Figure 15 (the altitude-time-history) shows the overall response. When flown above the trim angle of attack, the aircraft first gains altitude more rapidly than it would if it were trimmed. Interestingly though as the aircraft sheds speed, it will begin to lose climb gradient, reducing the altitude below the flight path of the trimmed condition. The aircraft then appears to gain indicated airspeed as it loses rate of climb, at which point the aircraft begins to increase it rate of climb as airspeed increases. This causes an oscillation in indicated airspeed as well as altitude.

Interestingly the oscillations in indicated airspeed and altitude are not in phase with one another.

The coefficient of lift for the trimmed condition is about 1.47 while the coefficient of lift for 3° out of trim in angle of attack was as high as 1.72. Because constant angle-of-attack was commanded, the entire destabilized flight event occurs at constant CL. By looking at the drag polars all of the climbs observed in this trade, whether trimmed or not, it is shown that all flight is on the backside of the L/D curve.

The following trade was a similar scenario to the first trade except that the simulation begins at V2 and with an engine inoperative instead. The speed-vs-time history is shown in Figure 17 and the altitude-vs-time history in Figure 18. Prior to the 10-second mark, the aircraft is climbing at V2 with all-engines-operating. At 10-seconds, one engine suddenly fails.

When comparing the first two trades, losing an engine causes the out-of-trim destabilization to have a larger impact on speed loss. This is most likely due to the much lower lift to drag ratios flown when one engine is rendered inoperative; due to windmill drag. This causes the lift to drag ratio to decrease significantly. With a higher drag, once the aircraft comes out of trim and the forces do not balance each other, there is more drag that is going to be opposing the velocity vector, increasing the rate at which airspeed is lost.

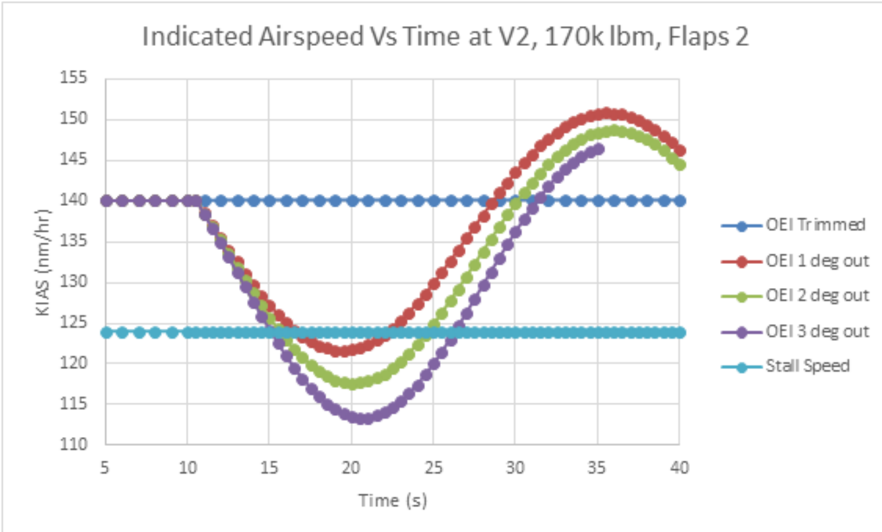


Figure 16. Speed-Time History During Second-Segment-Climb With an Engine Failure at T=10-sec

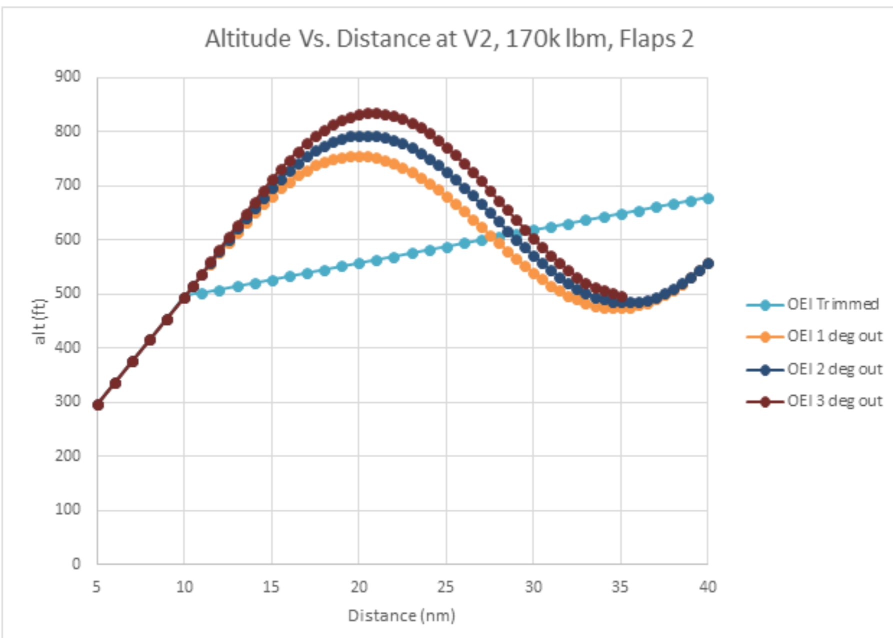


Figure 17. Altitude-Time History During Second-Segment-Climb With an Engine Failure at T=10-sec

From Figure 16, when flown out-of-trim by 1 degree in angle-of-attack the aircraft loses speed at a rate of 2.69 knots per second, reaching the stall speed after less than 7 seconds. When flown 3° out-of-trim the aircraft loses even more speed at a rate of 3.48 knots per second and reaches the nominal 1-g stall speed in just over 5 seconds.

Interestingly comparing this trade to the previous, the oscillations in airspeed, altitude, and lift are a lot closer to being in phase with one another. The period is noticeably shorter; ~20-seconds as opposed to ~30-seconds with all-engines-operating.

At the point the aircraft regains its original speed, it has also returned to the original altitude that it would have climbed to under a stable-trimmed scenario.

While the airspeed does dip below the posted stall speed, the aircraft doesn't stall. Recall that the entire excursion is flown at an angle-of-attack far below "stall." It is shown in Figure 18, that the point where the aircraft reaches its minimum airspeed, the wings do not support the weight of the aircraft. In other words, it is flying at a load factor of less than 1-g (0.73-g).

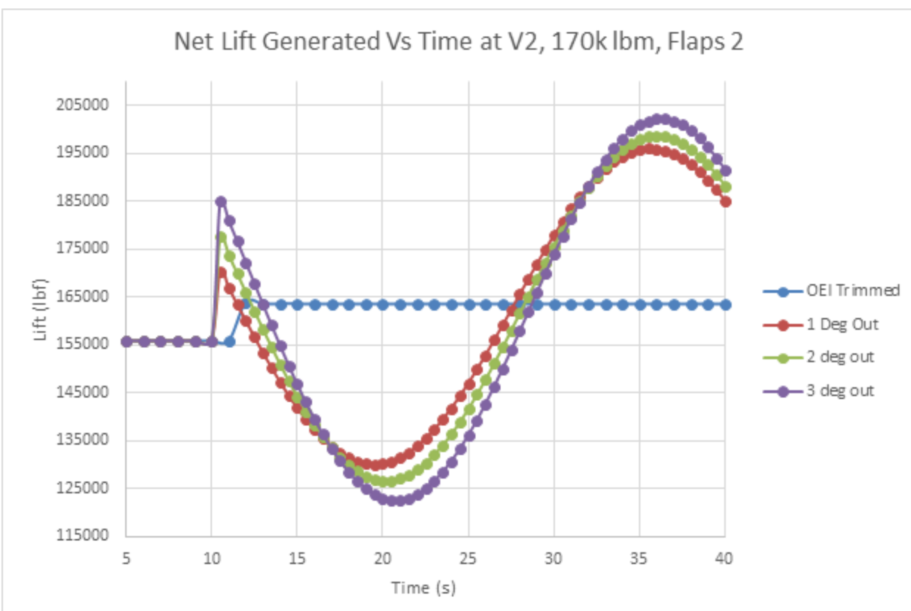


Figure 18. Lift-Developed - Time History During Second-Segment-Climb With an Engine Failure at T=10-sec

The fact that the lift developed is slightly less than the flight weight is another artifact of stabilized climb. Recall Figure 8, as the aircraft climbs at a significant flight path angle (γ) with all engines operating the vertical component of the thrust vector offsets a certain amount of weight.

It is interesting and confusing that the altitude oscillates about an increasing altitude (more visible in trade 1) and that the net rate of climb is positive even though the instantaneous rate of climb is positive and negative as you oscillate about the trimmed flight path.

The range of coefficients of lift for this trade were 1.86 for trimmed conditions to 2.11 for being 3° out of trim in angle of attack. For this trade, all of the coefficients of lift flown are interestingly on the frontside of the L/D curve.

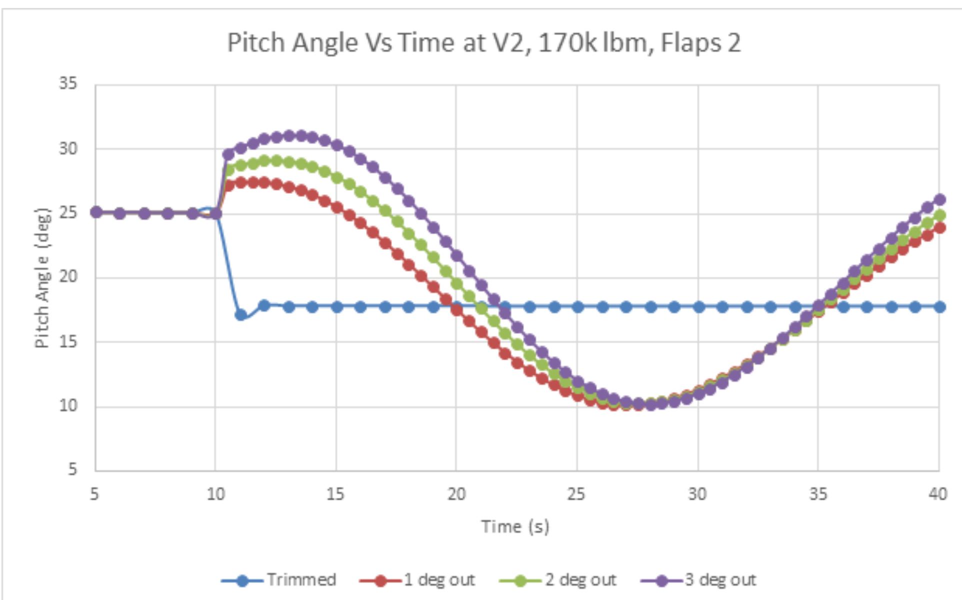


Figure 19. Pitch Attitude - Time History During Second-Segment-Climb With an Engine Failure at T=10-sec

Looking at Figure 19, the pitch angle of the aircraft over time, it is shown that it would be rather difficult to for a pilot to fly an out-of-trim constant angle of attack destabilized trajectory.

The following two trades were made modelling a final segment climb configuration with flaps clean, at the V4 speed, and 170,000 lbm.

Figure 20 shows the indicated airspeed for a trimmed aircraft climbing at constant indicated airspeed, as well as an aircraft climbing at constant angle-of-attack out-of-trim by 1° , 2° , and 3° with all engines operative. The rate at which the aircraft loses indicated airspeed 1 degree out-of-trim in angle-of-attack is 0.78 knots per second. However, when 3° out-of-trim in angle-of-attack the aircraft slows to a spall speed in less than 11 seconds while losing speed at 2.04 knots per second.

As seen before, the aircraft does not stall, but does quickly fall below the nominal 1-g stall speed.

The coefficient of lift flow for this trade were 0.96 (trimmed) to 1.26 (3° out of trim in angle of attack). Interestingly all of these coefficients of lift fall on the frontside of the L/D curve.

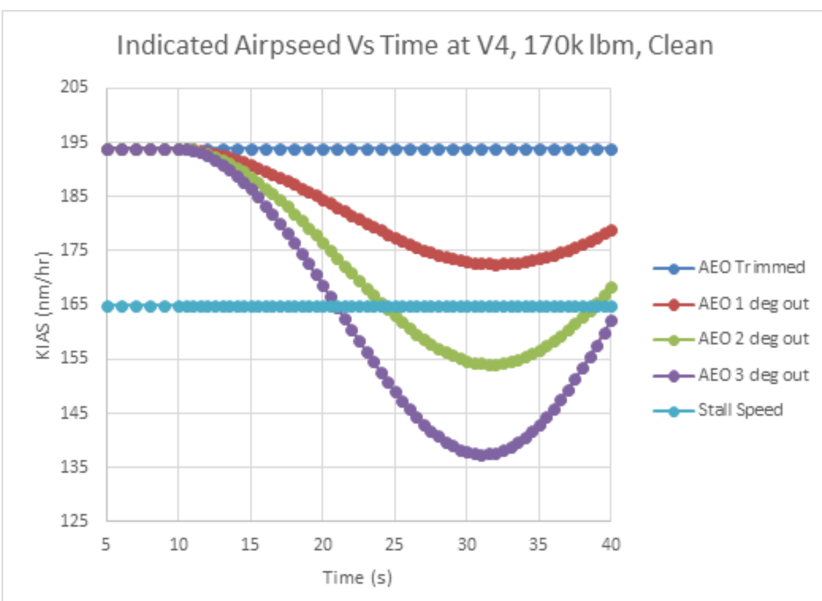


Figure 20. Speed-Time History During AEO Final-Segment-Climb With Destabilizing Pilot Inputs Beginning at T=10-sec

This trade was done similarly to the last one in that it is an aircraft simulated during final segment climb, with flaps clean, at 170,000 lbm, except this trade studies an engine inoperative.

Figure 21 is of indicated airspeed over time for an aircraft climbing trimmed at constant airspeed and an aircraft climbing out-of-trim by 1° , 2° , and 3° in angle-of-attack all of which have an engine inoperative. It is shown that when flown out-of-trim by 1 degree in angle-of-attack the aircraft will lose speed at a rate of 2.92 KIAS per second. If the aircraft is flown out-of-trim by 3° in angle-of-attack it will lose speed at a rate of 4.13 KIAS per second and reach a stall speed after 7 seconds.

Once again, the aircraft does not stall, but does quickly fall below the nominal 1-g stall speed. The aircraft regains its original speed after ~30 seconds.

The coefficients of lift flown at for this trade are 0.99 (trimmed) to 1.29 (3° out of trim in angle of attack). All of these coefficient of lift are on the front side of the L/D curve.

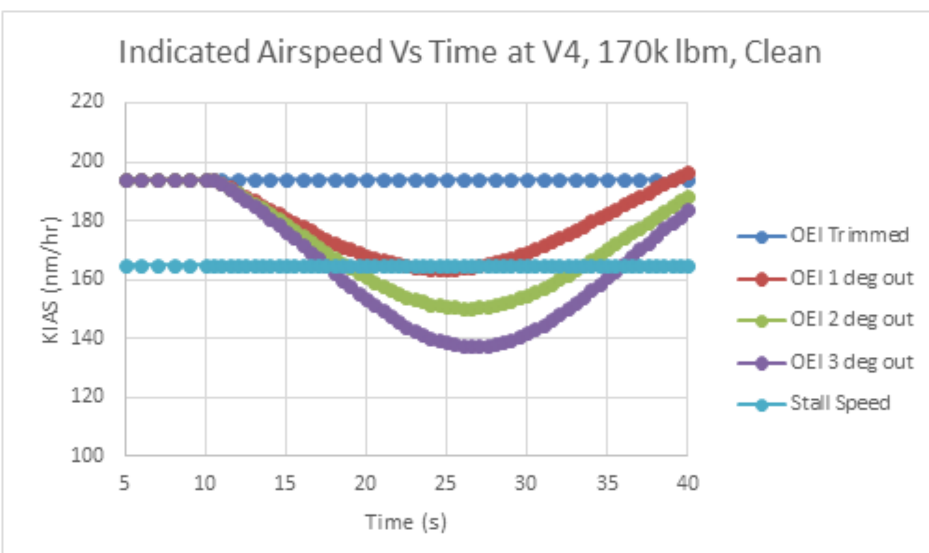


Figure 21. Speed-Time History AEO Final-Segment-Climb With Destabilizing Pilot Inputs Beginning at T=10-sec

Figure 22 shows the indicated airspeed for a trimmed climb at constant airspeed along with unstable flight caused by 1° , 2° , and 3° out-of-trim in angle-of-attack with all engines operative. The plots below show when flown in the landing configuration and out-of-trim by 1 degree the aircraft loses airspeed at a rate of only 0.57 KIAS per second. When the aircraft is flown out-of-trim by 3° the aircraft loses speed at a rate of 1.46 KIAS per second.

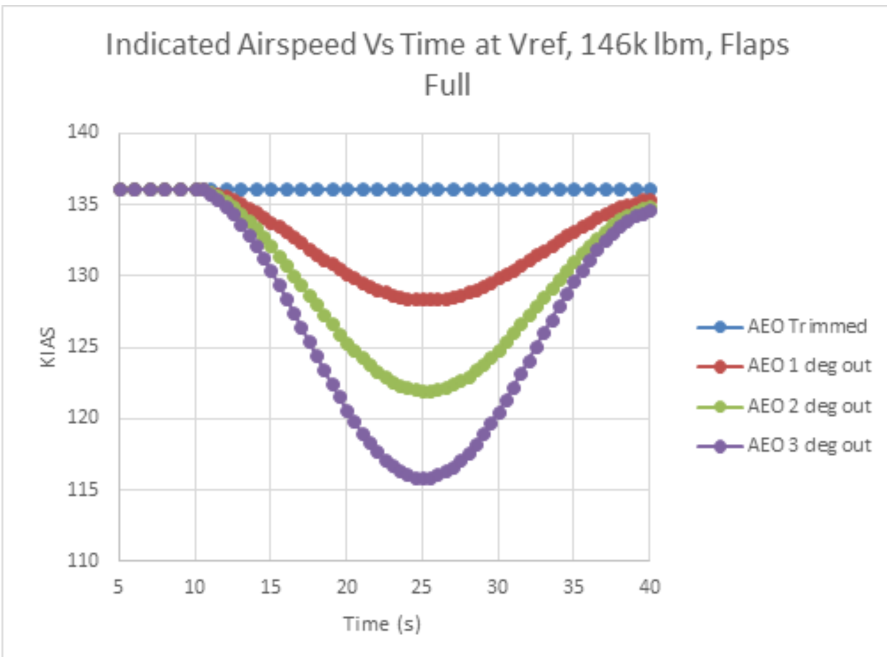


Figure 22. Speed-Time History AEO Balked-Landing-Climb With Destabilizing Pilot Inputs Beginning at T=10-sec

This next trade, similar to the previous was done in landing configuration with gear out, flaps full, at 146,000-lbm at the scheduled Vref speed for final approach. This trade was done for an aircraft trimmed and climbing at constant indicated airspeed along with out-of-trim conditions by 1° , 2° , and 3° in angle-of-attack all with one engine inoperative. Figure 23 shows that when out-of-trim by 1° the aircraft loses speed at a rate of 2.76 KIAS per second. When climbing 3° out-of-trim the aircraft loses speed at 3.57 KIAS per second and reaches a stall speed before 9 seconds.

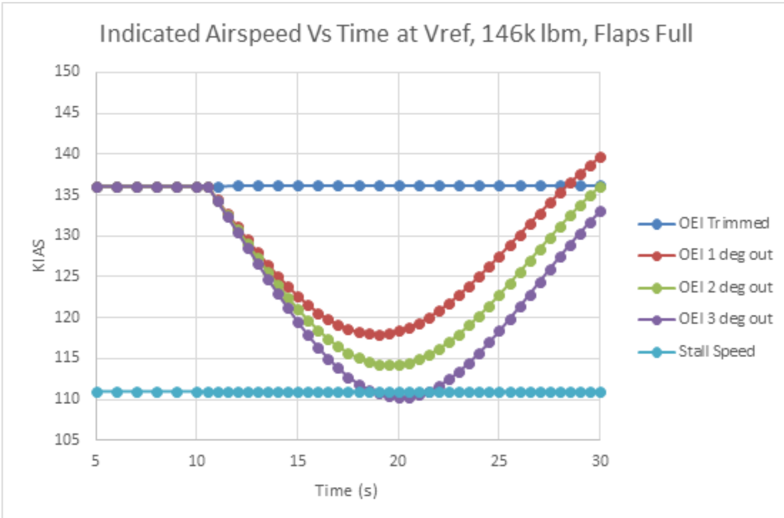


Figure 23. Speed-Time History AEO Balked-Landing - Climb With Destabilizing Pilot Inputs Beginning at T=10-sec

Takeoff Trades

The next trade looks in to the degradation in aircraft speed at different weights when flown out of trim in angle of attack and pitch angle. Table 2 shows the angle of attack and pitch angles at various flight weights.

Table 2. Trim Angles for an A320 at Various Weights

V2+15 KIAS Trimmed				
		145,000 lbm	160,000 lbm	175,000 lbm
Alpha (degrees)	AEO	11.22	11.65	11.94
	OEI	12.16	12.42	12.58
Pitch (degrees)	AEO	23.97	22.45	21.1
	OEI	15.14	14.57	14

From Table 2 it is shown that as the aircraft gets heavier, when an engine becomes inoperative, there is a smaller decrease in angle of attack and pitch angle between the two trim conditions.

Figures 24 and 25 report the indicated airspeed fluctuations over time during an engine failing and becoming inoperative at different flight weights, takeoff flap setting CONF 2, and climbing at an indicated airspeed of V2+15-KIAS. Figure 24 shows what would happen if the aircraft climbs one degree out of trim above the trimmed angle of attack for an engine inoperative. Figure 25 shows the response if the aircraft were to continue climbing at the trim pitch angle when an engine fails.

When comparing these two figures, it is shown that the lighter the flight weight, there is more impact on indicated airspeed during destabilized flight as a result of not being trimmed. This is due to lighter airplanes having less momentum and having their flight paths altered by weaker forces. It is also apparent when comparing the two plots that when the aircraft is flown out of trim in angle of attack, the indicated airspeed oscillates about the trimmed airspeed. However, when the aircraft is flown out of trim in pitch angle, the indicated airspeed diminishes and appears to stabilize on a new indicated airspeed.

From the plots it is shown that when an engine fails and becomes inoperative, flying the aircraft out of trim by 1 degree in angle of attack has similar degradation to indicated airspeed as holding the pitch angle for the trimmed aircraft climb when all engines are operative. At a flight weight of 160,000 lbm the aircraft loses indicated airspeed at a rate of 2.72 KIAS per second when flown out of trim by 1° in angle of attack and loses indicated airspeed at a rate of 2.3 KIAS per second when flown out of trim at the all engines operative trimmed pitch angle.

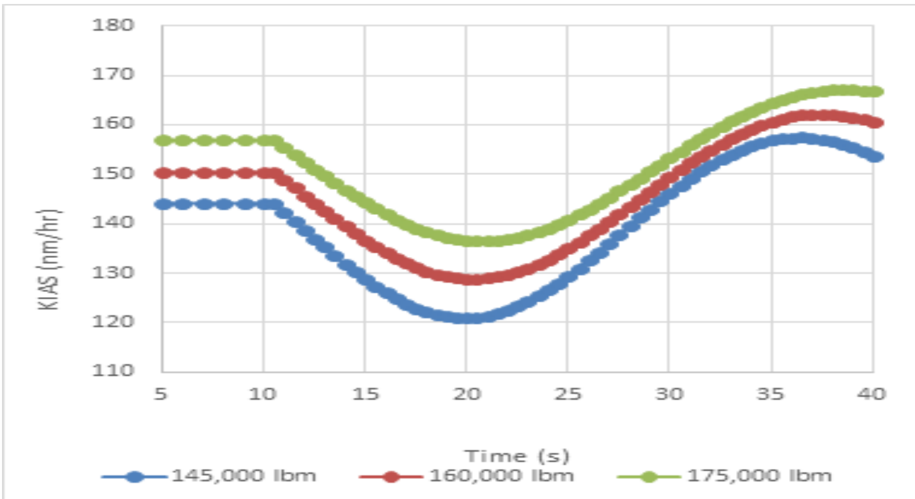


Figure 24. Indicated Airspeed Vs Time 1 Degree Out of Trim in Angle of Attack

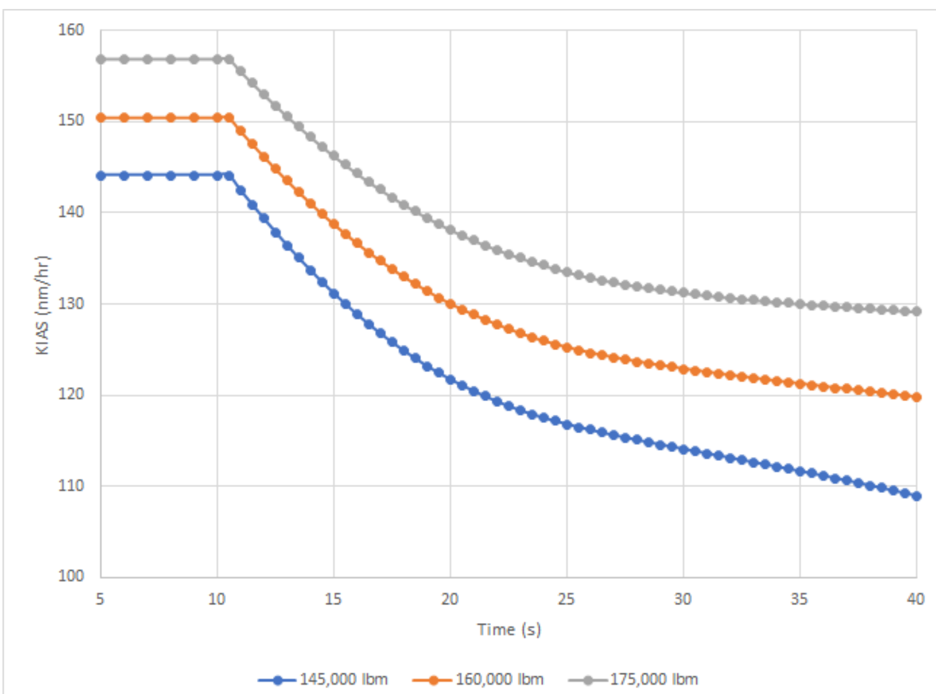


Figure 25. Indicated Airspeed Vs Time at the Trim Pitch Angle for AEO

Second-Segment Climb – Flight Path Impact of Out of Trim Climb

The following trades observe the effects of loss in climb gradients for various losses in indicated airspeed during second segment climb with flaps in the takeoff setting (flaps 2) and OEI. Figures 26, 28, and 30 show the altitude time progression at various weights flown at different airspeeds relative to the V2 speed for the given weight of the aircraft. Figures 27, 29, and 31 show the altitude distance progression at various weight flown at different airspeeds relative to the V2 speed for the given weight of the aircraft.

The plots make sense in that the heavier loaded airplanes have worse climb performance than the lighter ones. What is interesting though is that the heavy planes have less tolerance to being below the V2 speed than the lighter loaded airplanes. For example, the 175,000-lbm load would not permit for any climb performance at a speed of V2-15KIAS, however, the lighter loaded crafts were able to climb at V2-15KIAS.

The most interesting scenario to look at across the different weights is how far below the obstacle clearance height would you be if flown under the V2 speed. For the 145,000-lbm flight, if flown at V2, and assume the obstacle clearance height is 1,000-ft AGL, the aircraft will reach this altitude at about 3.15 nm and 88 seconds after wheels up. If flown 5-KIAS below the V2 speed, at 3.15 nautical miles, the altitude of the airplane is only at about 937-ft AGL. Given the laws in place, if flown 5 KIAS under the V2 speed, an aircraft will hit the obstacle in the flight path. This is increasingly worse in heavier aircraft. For the 175,000-lbm flight weight, the airplane will reach the obstacle clearance height of 1,000-ft AGL at a distance of 7.20 nm after 182 seconds all while flying at V2. If the same flight is flown 5 KIAS slower, the aircraft will be at a height of 824 feet when at the same distance.

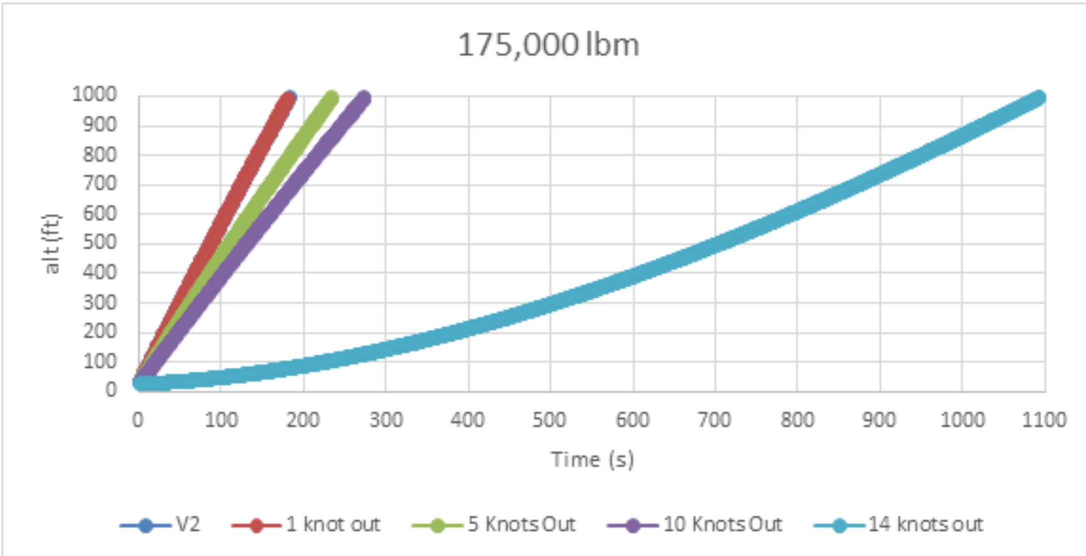


Figure 26. Altitude Vs Time for Flight Weight 175,000 lbm

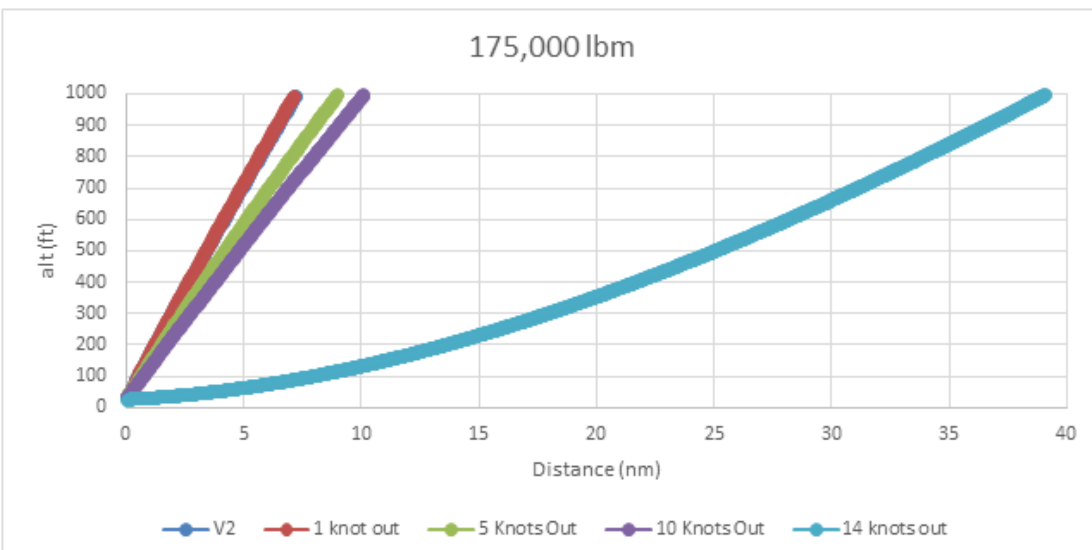


Figure 27. Altitude Vs Distance for Flight Weight 175,000 lbm

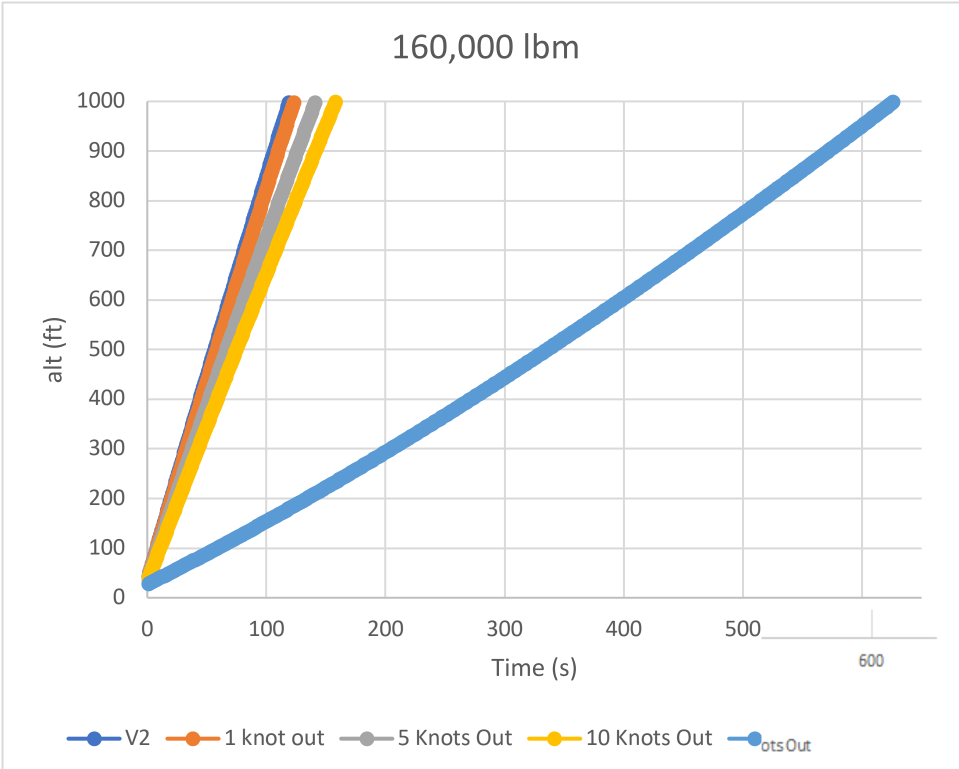


Figure 28. Altitude Vs Time for Flight Weight 160,000 lbm

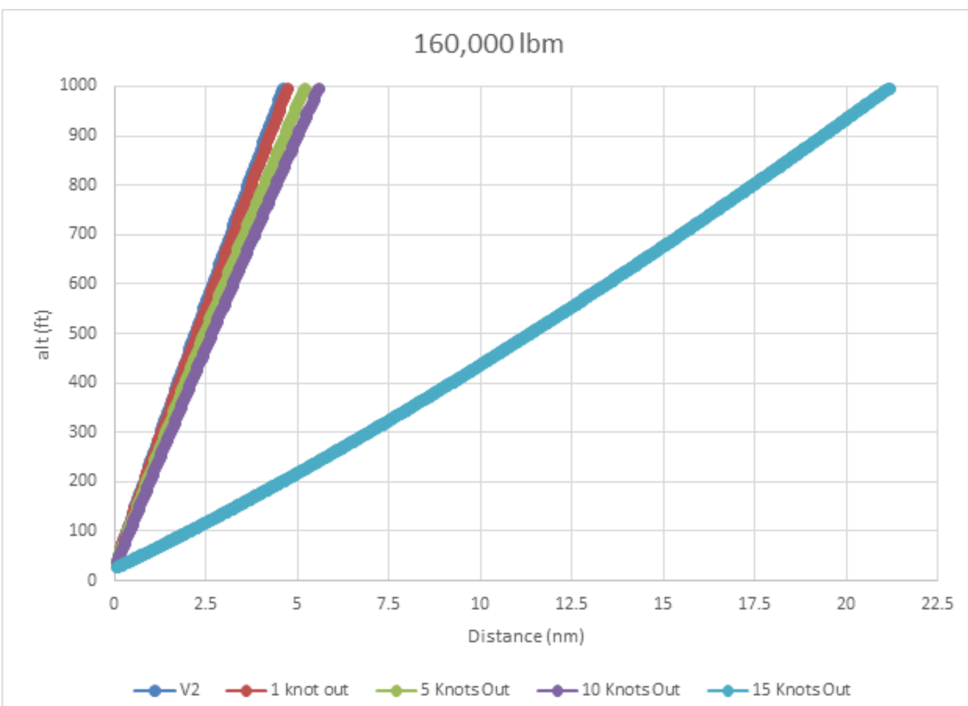


Figure 29. Altitude Vs Distance for Flight Weight 160,000 lbm

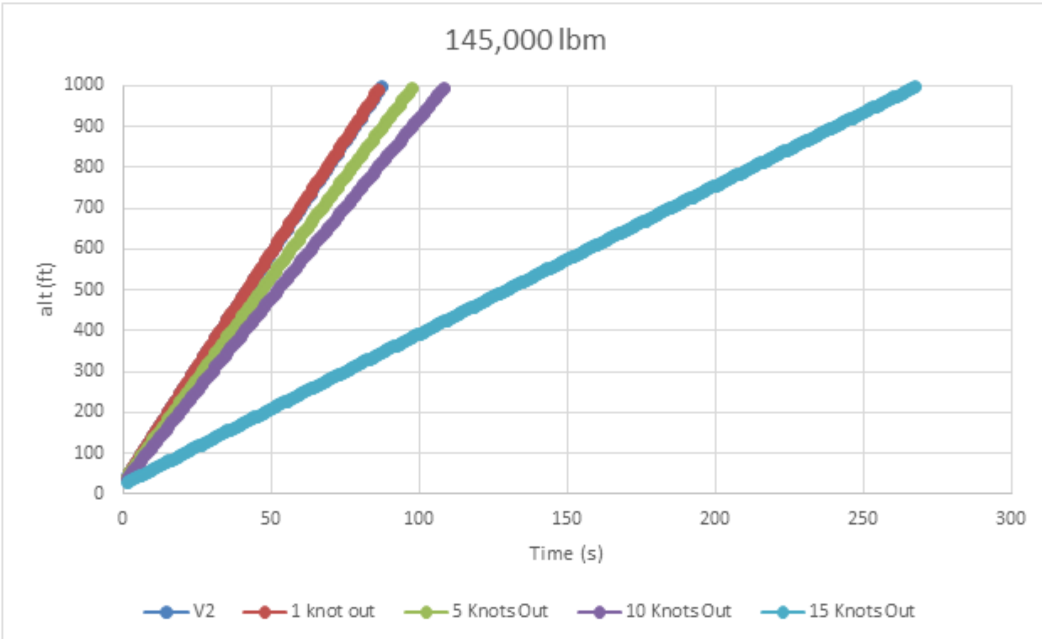


Figure 30. Altitude Vs Time for Flight Weight 145,000 lbm

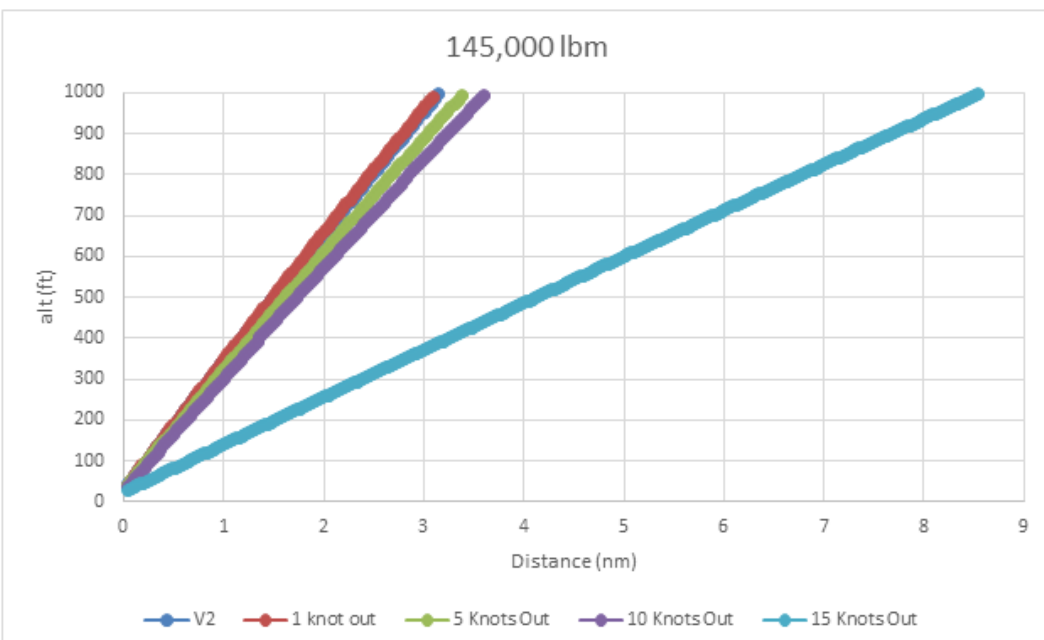


Figure 31. Altitude Vs Distance for Flight Weight 145,000 lbm

Third Segment Acceleration – Impact of Starting Level Acceleration from an Off-Speed Second-Segment Climb

The next trades in this study are to investigate the third segment acceleration consequences of losing speed during the second segment climb. The table below shows how long and how far it will take for an aircraft at various weights, with all engines operative, in the second segment climb flap configuration (CONF 2), at an altitude of 1,000-ft, to safely accelerate to its corresponding V4 speed. The plots below show acceleration time and distances to V4 starting from the corresponding V2 speed, V2 – 5KIAS, V2–10KIAS, and V2-15KIAS.

The acceleration distance and times in table 3 indicate that there is not a very significant difference in distance or time it takes to accelerate from various speeds near V2 to V4 with all engines operative. At light weight, 145,000-lbm, it only takes an additional 4 seconds and an additional 0.125 nm to accelerate from V2-15 KIAS to V4 compared to V2 to V4. Interestingly the flight weight that experienced the largest impact to acceleration time and distance was 160,000-lbm. This is likely due to the V2 speeds being set based off of stall, etc. For all cases, it makes sense that the heavier the plane and the further below the V2 speed it starts at, the longer and farther it takes to accelerate.

Table 3. Acceleration Times and Distances for AEO

	Airspeed (KIAS)	Acceleration Time (s)	Acceleration Distance (nm)
145,000 lbm	*V2* to *V4*	14	0.63
	V2-5 to *V4*	15	0.66
	V2-10 to *V4*	17	0.74
	V2-15 to *V4*	18	0.77
160,000 lbm	*V2* to *V4*	17	0.80
	V2-5 to *V4*	19	0.88
	V2-10 to *V4*	20	0.91
	V2-15 to *V4*	22	0.98
175,000 lbm	*V2* to *V4*	18	0.88
	V2-5 to *V4*	19	0.91
	V2-10 to *V4*	21	1.00
	V2-15 to *V4*	22	1.03

The next trade, like the previous, investigates the acceleration consequences to losing speed during second segment climb but with one engine inoperative. Table 4 below shows how long and how far it will take for an aircraft at various weights, with an engine inoperative, in the second segment climb flap configuration (CONF 2), at an altitude of 1,000-ft, to safely accelerate to its corresponding V4 speed. The plots below show acceleration time and distances to V4 starting from the corresponding V2 speed, V2 – 5 KIAS, V2 -10KIAS, and V2 - 15KIAS.

For the case with accelerations with one engine out, there is a little different of a story. The flight weight greatly effects the acceleration distance and time in that the heavier airplanes take more time to accelerate. It is also interesting to note that the heavier the airplane, the more it was effected by flying under speed. Interestingly, with one engine inoperative, the 145,000-lbm airplane can accelerate from V2-15KIAS to V4 by doing a level acceleration. However, the 160,000-lbm flight cannot perform a level acceleration from a speed lower than V2-13KIAS. The 175,000-lbm flight was un recoverable below V2-12KIAS. This means that the aircraft's only option to accelerate is to pitch the nose down below the flight path and dive to gain airspeed.

Table 4. Acceleration Times and Distances for OEI

		Acceleration Time (s)	Acceleration Distance (nm)
145,000 lbm	V2 to V4	55	2.42
	V2-5 to V4	61	2.64
	V2-10 to V4	67	2.83
	V2-15 to V4	79	3.22
160,000 lbm	V2 to V4	82	3.77
	V2-5 to V4	91	4.12
	V2-10 to V4	101	4.48
	V2-13 to V4	114	4.92
175,000 lbm	V2 to V4	134	6.43
	V2-5 to V4	148	6.97
	V2-10 to V4	165	7.62
	V2-12 to V4	193	8.64

Approach and Balked Landing Trades

Modelling A Stabilized Approach With All Engines Operating

The first item to investigate is the simulated A320 performing a scheduled final approach. All of the simulations were done at max landing weight for an A320 at 146,000-lbm. In order for this aircraft to descend 3° below the horizon (γ is -3°), at constant airspeed Vref= 135 KIAS, the PLA setting is set to a part power to stabilize flight. The horizon pitch angle should be approximately $\gamma+\alpha$ = +5.88° nose up.

Shown in Figure 32 is what this scheduled approach might look like starting from 1000 feet above the ground until a few feet above the runway. Deducted from Figure 33, the rate of descent for this approach is about 675 ft/min.

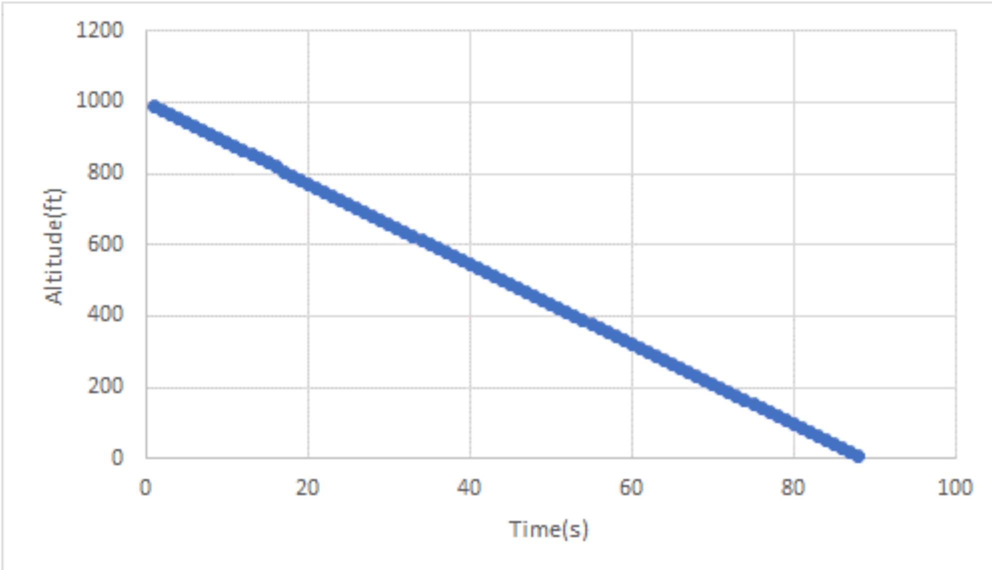


Figure 32. Altitude Time History for a Scheduled Approach

Normal Configuration Balked Landing

The next two plots (Figures 33 and 34) represent a scenario where the pilot follows the A320 flight manual for a balked landing. That is the pilot retracted flaps one step (from CONF FULL to CONF 3), maintained final approach speed, pitched the aircraft to establish a positive climb gradient, apply full power to the engines, and retracted the landing gear. The two figures below are indicated airspeed and altitude over time for when the pilots perform this balk scenario. The different lines represent the pilot pitching the aircraft to a trim condition that allows for climb at Vref, and when the aircraft is pitched to 12.5 +/- 2° horizon-attitude for all engines operating.

In order for the pilot to climb at a constant indicated airspeed prescribed in the manual, the SRS pitch command bar would have to be set to 22.4°. In the event of a balked landing the pilot would have to pull up the nose of the aircraft about 16.5° to maintain constant indicated airspeed when full throttle is applied. This provides a rate of climb of 2827.8 ft/min shown in Figure 34. If the pilot does not pitch to that angle, the aircraft will not climb as quickly and will gain some speed shown in Figure 33 below. Figure 34 shows that if the SRS pitch command bar is not set and the pilot pitches the aircraft to 12.5° horizon attitude, nearly 10° below the trim pitch angle for climb at constant airspeed, the aircraft will climb at only 2012.1 ft/min but increase speed at a rate of about 1.91 KIAS /s. Interestingly the aircraft seems to retrim to climb at a new stable condition with indicated airspeed around 170 KIAS and a constant climb gradient after about 30 seconds.

While the aircraft does not exhibit short-term speed stability, the trends are entirely safe. If pilots follow this procedure, after 30-seconds the aircraft is essentially at flap retraction speed.

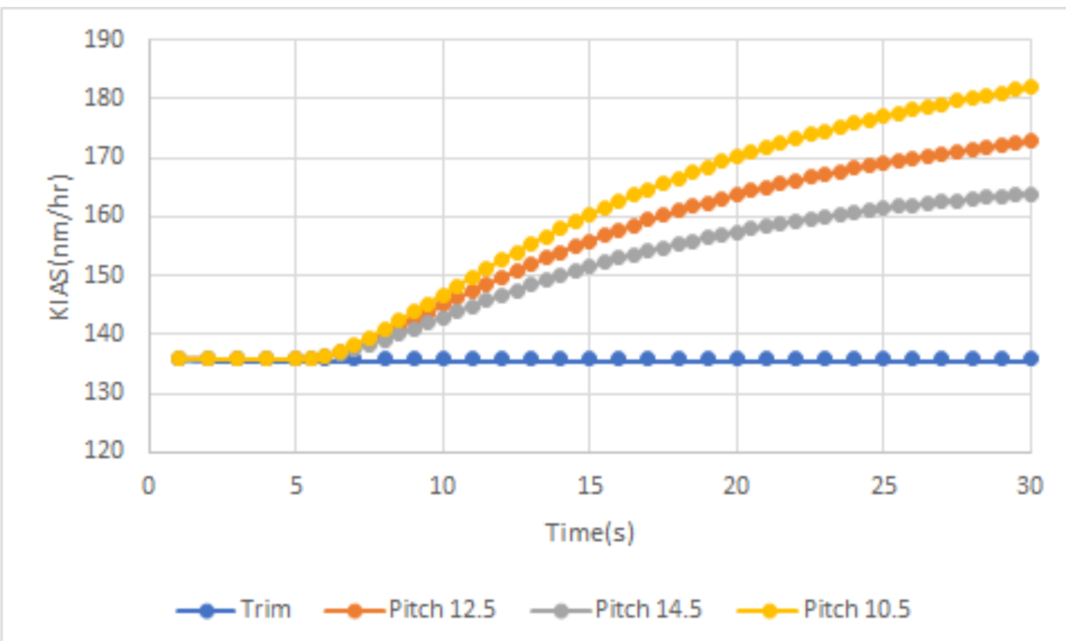


Figure 33. Indicated Airspeed Vs Time for CONF 3; AEO

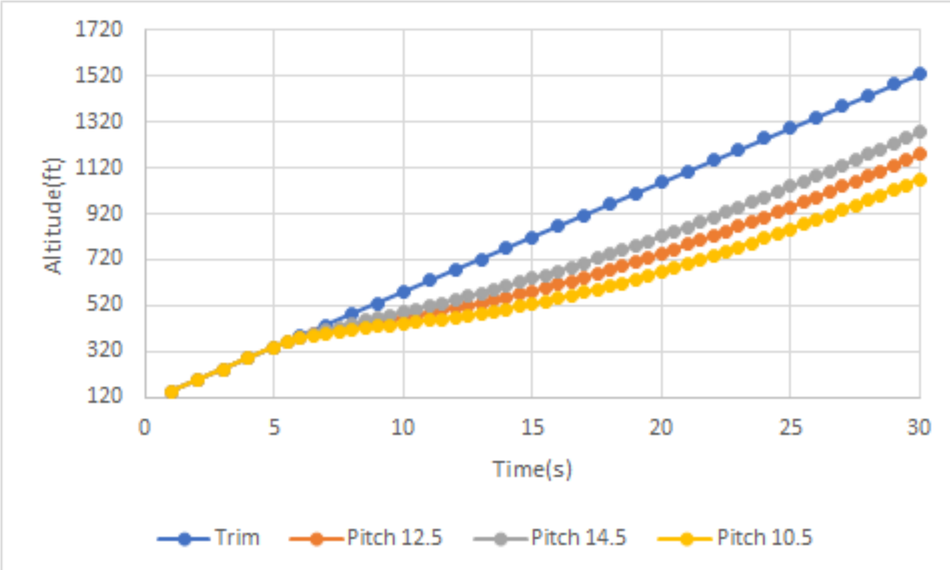


Figure 34. Altitude Vs Time for CONF 3; AEO

Balked Landing With Engine Failure at Beginning of Go-Around

This trade similar to the last observes the differences in pitch variation during a balked landing after retracting the flaps one notch to CONF 3, retracting the landing gear, and applying full thrust. However, for this trade the aircraft has lost an engine during the balk and now performs the balked climb with one engine inoperative. The two figures below are indicated airspeed and altitude over time for when the pilots perform this balk scenario. The different lines represent the pilot pitching the aircraft to a trim condition that allows for climb at Vref, and when the aircraft is pitched to 12.5 +/- 2° horizon-attitude. For one engine inoperative balked climb at constant indicated airspeed of Vref, the SRS pitch command bar would have to be set to 13.6°.

Interestingly if the pilot commands the aircraft to a pitch angle above this 13.6° trim condition, the aircraft will climb with better gradients for a short period while losing airspeed shown in Figures 33 and 34. Once the aircraft loses enough airspeed and re-trims at a lower speed, the aircraft is slightly above the trimmed flight path, but has a shallower climb gradient. This is the similar effect as seen in the previous trade.

Figures 35 and 36 (overleaf) show interesting results for what would happen in the event of the SRS pitch command bar not being set and the pilot pitching the aircraft to 12.5° horizon-attitude, slightly below the trimmed pitch angle allowing for climb at constant indicated airspeed. In that event if the aircraft is pitched slightly below the trim pitch angle for climb at constant indicated airspeed. Because the aircraft is destabilized it initially loses some indicated airspeed but then self trims, from being stable, at a lower speed and slightly shallower climb gradient. When comparing this to trade 1, when the aircraft is pitched below the trim angle as well, there is no speed loss due to instability with pitching the aircraft greatly below the trim pitch angle, there are losses when pitched only slightly below the trim condition. The rate of climb for the aircraft flying at constant indicated airspeed with one engine inoperative is 618.7 ft/min but only 456 ft/min when pitched a couple degrees below the trim pitch angle.

Under this procedure, the A320 will exhibit about 4 KIAS of speed sag (bottoming out at 132 KIAS) during the initial pull-up maneuver, followed by a slow return to Vref. Under no circumstances, even with an inadvertent pull-up to 14.5° horizon-attitude will the aircraft approach the CONF 3 stall speed (130 KIAS vs 114 KIAS). Neither will it sag below the CONF 2 takeoff obstacle clearance speed (130 KIAS). Thus, the A320 procedure and aerodynamic design of the flap system is inherently safe even in an OEI balked landing. However, the reader must note that other aircraft may not have as many intelligently chosen flap settings.

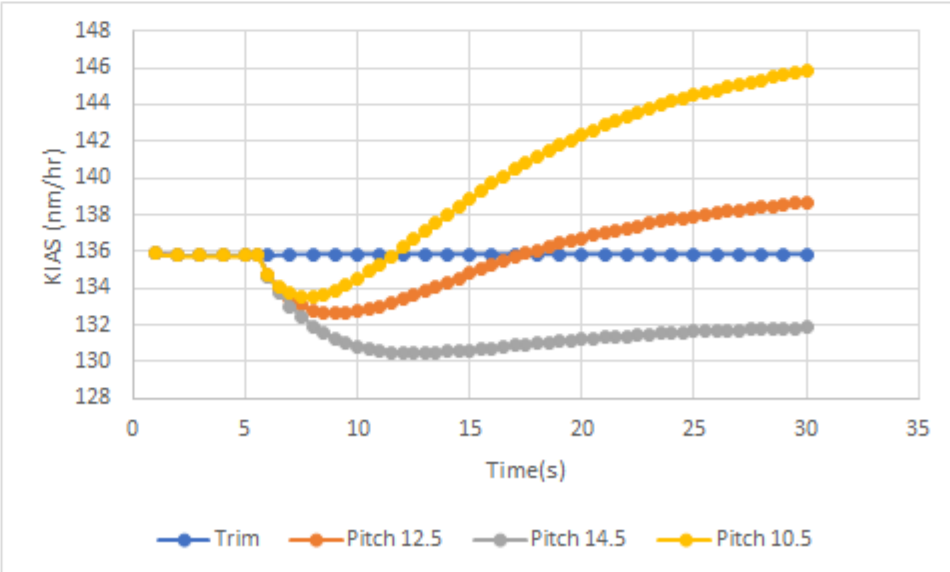


Figure 35. Indicated Airspeed Vs Time for CONF 3; OEI

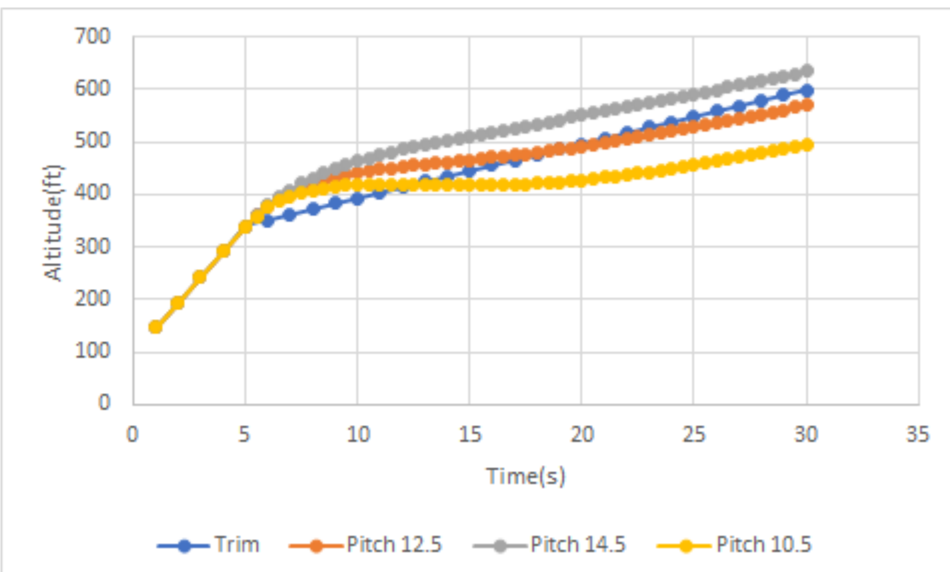


Figure 36. Altitude Vs Time for CONF 3; OEI

Balked Landing Holding Configuration Full Flaps

The following two trades are the same as the first two with the exception of the pilot not retracting the flaps one notch during the balked landing and attempts the balk with the flaps in the full configuration. The pilot maintained final approach speed, pitched the aircraft to establish a positive climb gradient, applied full power to the engines, and retracted the landing gear. The two figures below, Figures 37 and 38, are indicated airspeed and altitude over time for when the pilots perform this balk scenario. The different lines represent the pilot pitching the aircraft to a trim condition that allows for climb at Vref, and when the aircraft is pitched to 12.5 +/- 2° horizon-attitude for all engines operating. The pitch angle for a climb at constant indicated airspeed and all engines operative while in the CONF FULL configuration is 19.9°.

Very similar to the previous trade, if the pilot commands the aircraft below the trimmed pitch angle, the aircraft will gain speed instantly because of how far down the nose is pointed, re-trim at an increased airspeed with a slightly shallower climb gradient below the trimmed flight path. Figures 37 and 38 show that when the aircraft is pitched to 12.5°, but now in the CONF FULL configuration, the aircraft gains speed at a rate of 1.58 KIAS per second, stabilizing a trim climb around 160 KIAS and a climb rate of 2739.3 ft/min. When the aircraft climbs at constant indicated airspeed the rate of climb is 2721.9 ft/min. This is an interesting observation because this shows that the aircraft was able to pitch the aircraft down below the trim pitch angle for climb at constant airspeed, accelerate and re-trim at a faster indicated airspeed and a better rate of climb. Although the climb gradient is better however, the flight path after 30 seconds for the aircraft that was pitched down is still below the flight path of the trimmed climb at constant indicated airspeed.

While the aircraft does not exhibit short-term speed stability, the trends do not imply any tendency towards stall.

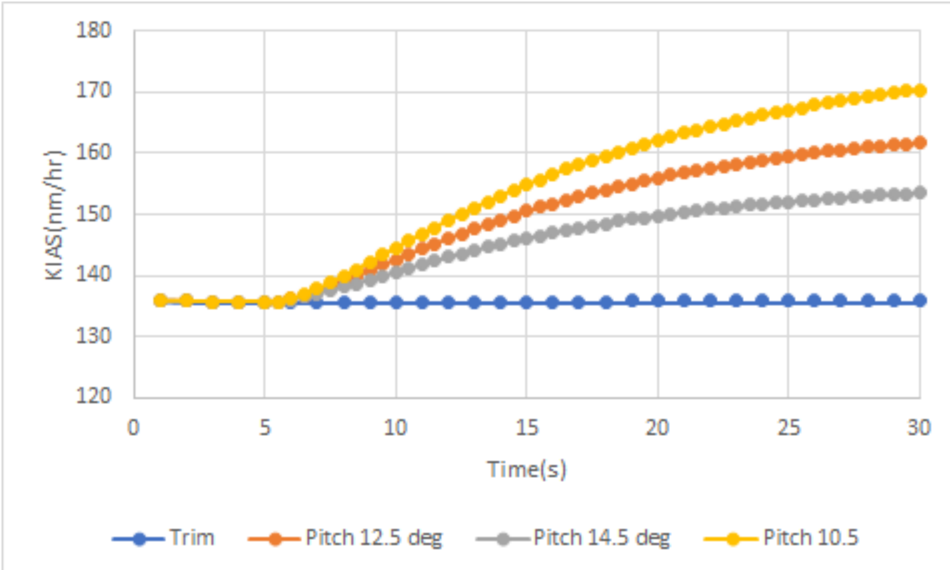


Figure 37. Indicated Airspeed Vs Time for CONF FULL; AEO

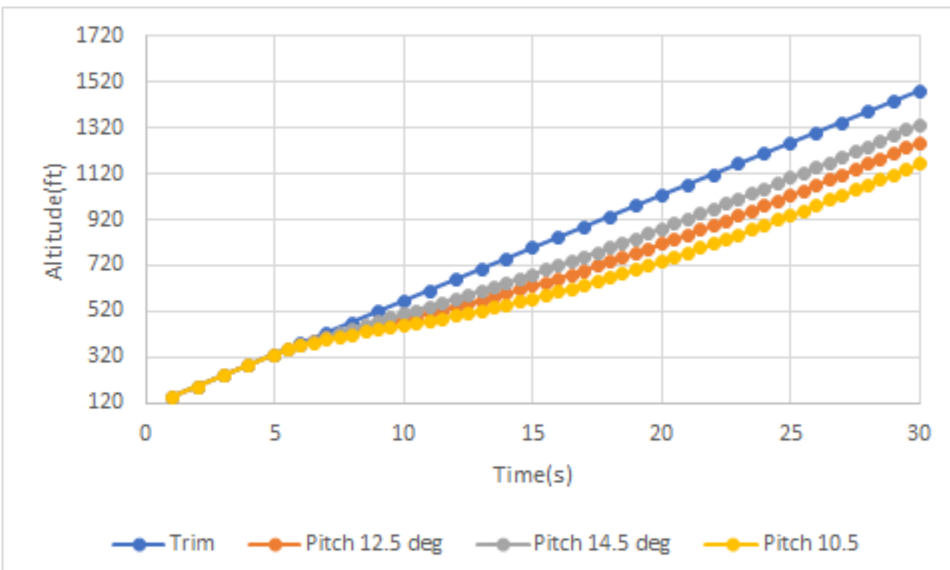


Figure 38. Altitude Vs Time for CONF FULL; AEO

Balked Landing at Full Flaps With Engine Failure at Beginning of Go-Around

The next trade now looks at the scenario when the pilot loses an engine during a balked landing, forgets to retract the flaps one setting and leaves the aircraft flaps in the full configuration, and pitches the aircraft to various angles. The pilot maintained final approach speed, pitched the aircraft to establish a positive climb gradient, applied full power to the engines, and retracted the landing gear. The two figures below, Figures 39 and 40, are indicated airspeed and altitude over time for when the pilots perform this balk scenario. The different lines represent the pilot pitching the aircraft to a trim condition that allows for climb at Vref, and when the aircraft is pitched to 12.5 +/- 2°. The pitch angle the pilot would have to command the aircraft to, in order for a climb at constant indicated airspeed, in this flight scenario was found to be approximately 11°.

Figures 39 and 40 fascinatingly show when the aircraft was pitched to 10.5°, only a half of a degree below the pitch angle for a climb at constant airspeed, the aircraft initially loses speed due to destabilized flight but then accelerates due to a nose down pitch. The aircraft then re-trims itself surprisingly around 1 knot faster than before. However, the climb gradient has diminished, and the flight path is below that of the trimmed climb after only about 20 seconds. Figure 39 also shows that if the aircraft is pitched even slightly above the trim pitch angle, it will lose speed rapidly, agreeing with previous trades.

If pilots follow the pitch procedure exactly, the A320 will exhibit about 6 KIAS of speed sag (bottoming out at 130 KIAS) during the initial pull-up maneuver. Pilots will need to depress the nose in order to regain Vref. However, the CONF 2 takeoff speed is 130 KIAS. Thus, this design and procedure is inherently safe even in an OEI balked landing. However, the reader must note that other aircraft may not have as many intelligently chosen flap settings.

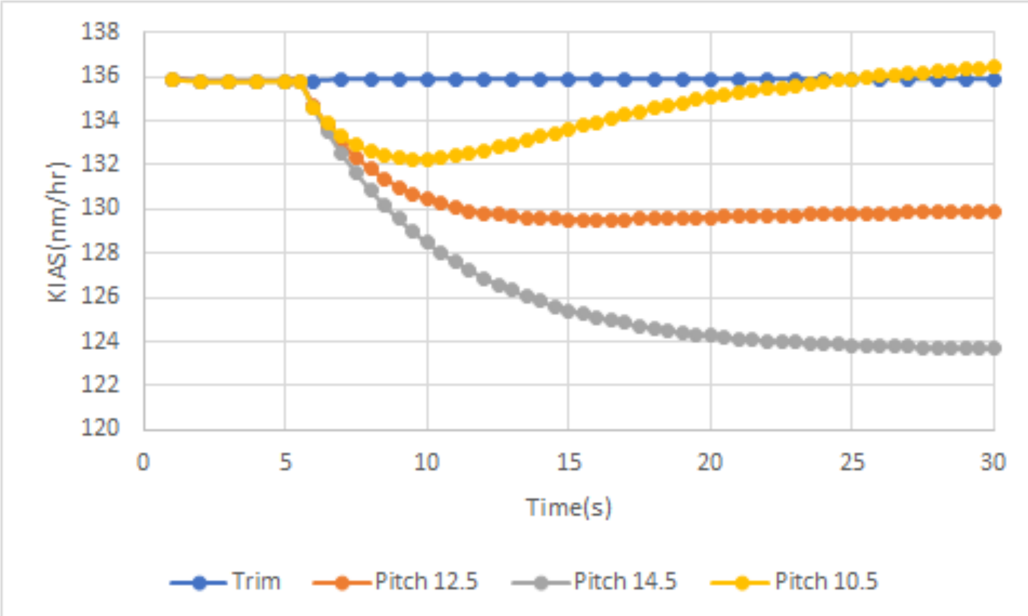


Figure 39. Indicated Airspeed Vs Time for CONF FULL; OEI

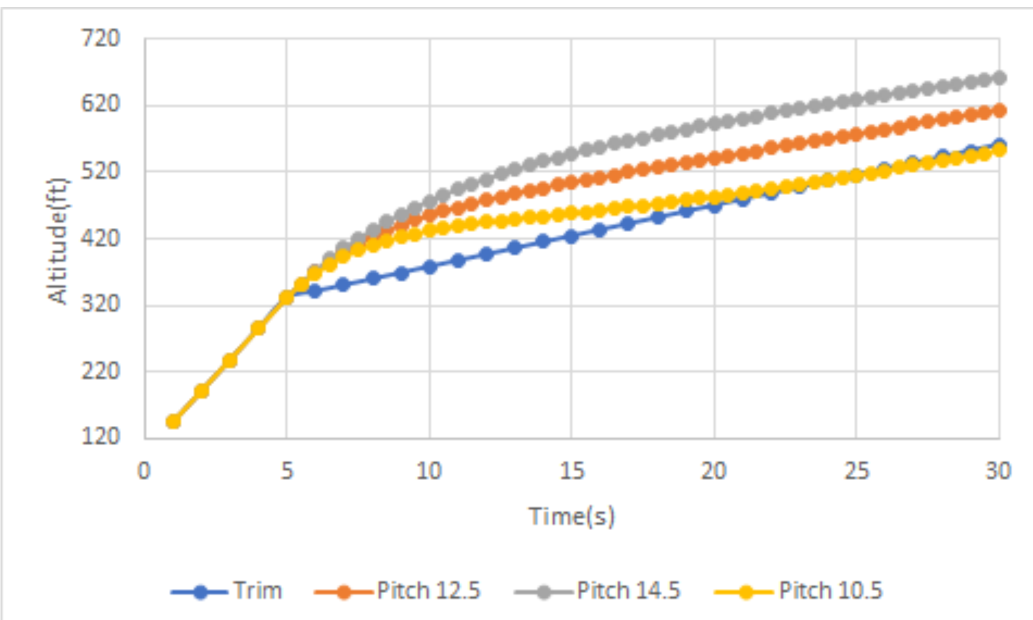


Figure 40. Altitude Vs Time for CONF FULL; OEI

Phugoid Trades

The following set of trades were investigated to see whether or not going out of trim in angle of attack or pitch angle are exciting phugoid like modes that Roskam talks about.

For this trade study, the simulation begins with the aircraft climbing at V2+15 KIAS (151-KIAS) and a flight weight of 160,000-lbm. This represents flight at a lift coefficient, CL ~ 1.57. The one-gee stall speed under these conditions is 120 KIAS.

Turning to Figure 9, the drag coefficient is estimated as CD ~ 0.16 for CONF 2 flaps gear-up and all-engines-operating. Thus, the aerodynamic efficiency is L/D ~ 9.8.

Following the Boeing equations [Eqn 25 and 26], one can determine that the approximate Phugoid period and damping ratio for this aircraft would then be $\omega_{Phugoid}$ ~ 35.16 seconds and $\zeta_{Phugoid}$ ~ 0.07. The aircraft is then expected to demonstrate a long period and very lightly damped Phugoidal motion.

Figures 41 through 44 shows the response of the aircraft that would be climbing at constant indicated airspeed (trimmed) as well as the response if the aircraft were to climb +0.5°, +1.0°, or +1.5° out-of-trim in angle of attack. Figure 41 is a time history plot of aircraft altitude; Figure 42 is a time history plot of airspeed, Figure 43 is a time history plot of horizon-pitch-attitude and Figure 44 is a time history plot of load factor. In all plots, the major gridline is set to a spacing of 35.16-sec to represent the estimated Phugoid period. In each simulation, the nominal angle-of-attack for AEO trimmed climb is α=11.7^o . Thus a +0.5-degree error is a climb at α=12.2^o ; a +1.0-degree error is a climb at α=12.7^o and a +1.5-degree error is a climb at α =13.2^o.

In Figure 41, it is shown that destabilization triggered from being out-of-trim due to an error in elevator setting (out-of-trim by various degrees in angle-of-attack) excites a clear Phugoidal mode (in time constant) for the first couple of oscillations. The relative motions exhibit a phase shift as time goes on. Interestingly all three responses for out-of-trim flight have the same period for the first couple of oscillations but diverge as time progresses.

When looking at Figures 41 through 44 together, one can see how the aircraft initially beings to ascend with an increased pitch angle and begins to lose indicated airspeed as soon as the aircraft is destabilized in angle of attack. As the aircraft decreases speed, it loses lift and eventually pitches down to descend and gain airspeed. As the aircraft gains speed, the lift goes up, pitching the aircraft up and returning it to the previous state. This process then repeats, just as Roskam describes the classical Phugoid response.

Of course, this behavior is incredibly unsettling to the pilot. The horizon attitude and airspeed swings wildly back and forth. At some points in this wallowing climb trajectory, the aircraft has a negative horizon attitude (pilot looking at the ground) and at other points the airspeed gauge will drop below the 1-g posted stall speed. If the stall warning horn is triggered by airspeed alone, it would sound. The reader should note that the aircraft is in no danger of actually stalling; as the airspeed dips below the 1-gee stall speed (120-KIAS), the load factor reaches its minimum value of well under 1.0. Of course, these wild oscillations are likely to provide substantial pilot inputs. A pilot attempting a pull-up at low airspeed will actually induce a stall, this is far worse than going along for the ride. The risk of further pilot induced oscillations is high.

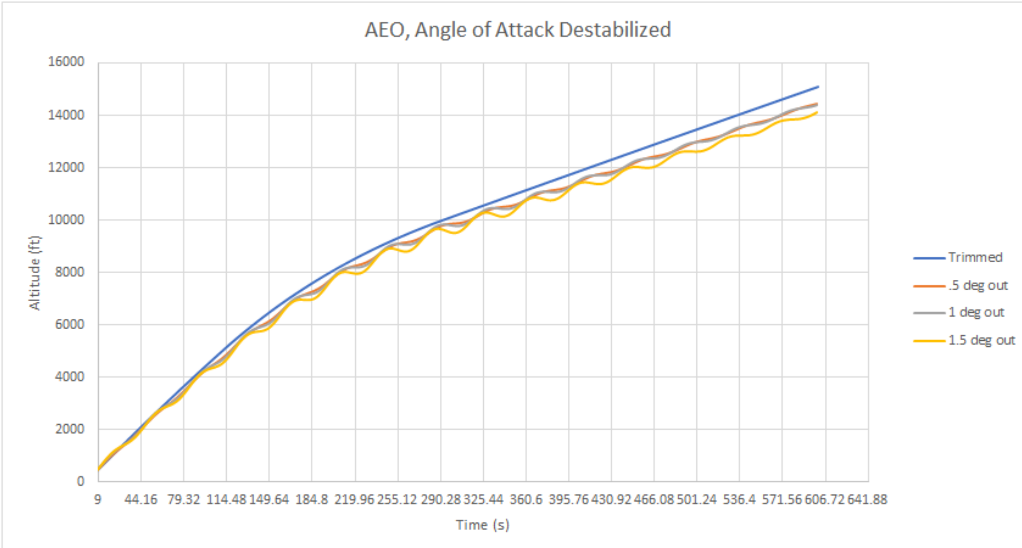


Figure 41. Takeoff Flight Path (AEO) with mis-trim in angle-of-attack (stick-fixed)

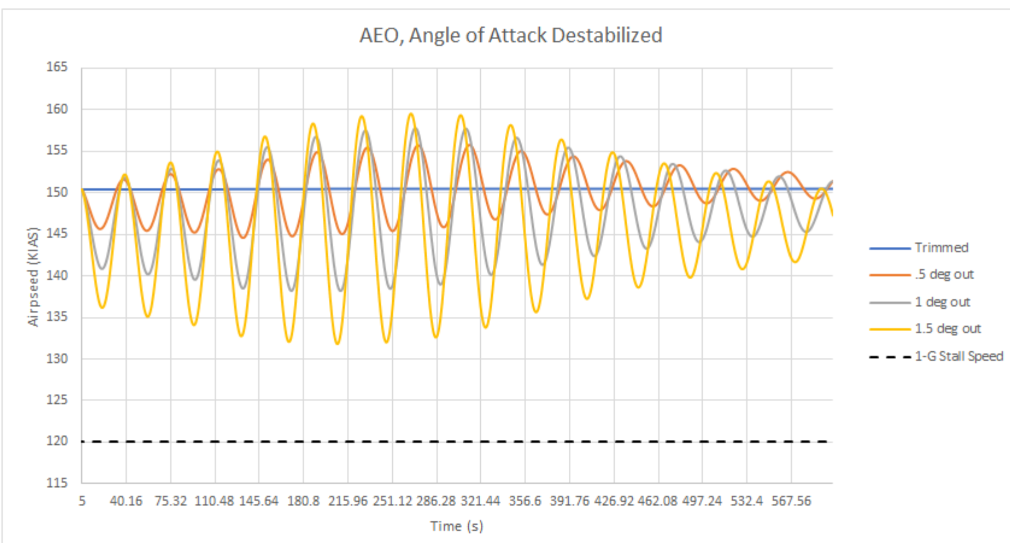


Figure 42. Takeoff Flight history (AEO) with mis-trim in angle-of-attack (airspeed variations)

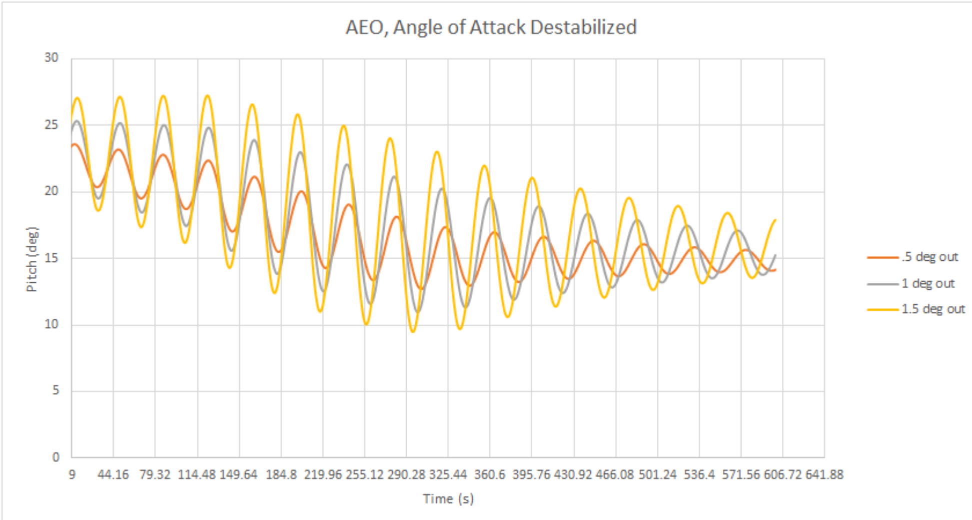


Figure 43. Takeoff Flight history (AEO) with mis-trim in angle-of-attack (horizon attitude variations)

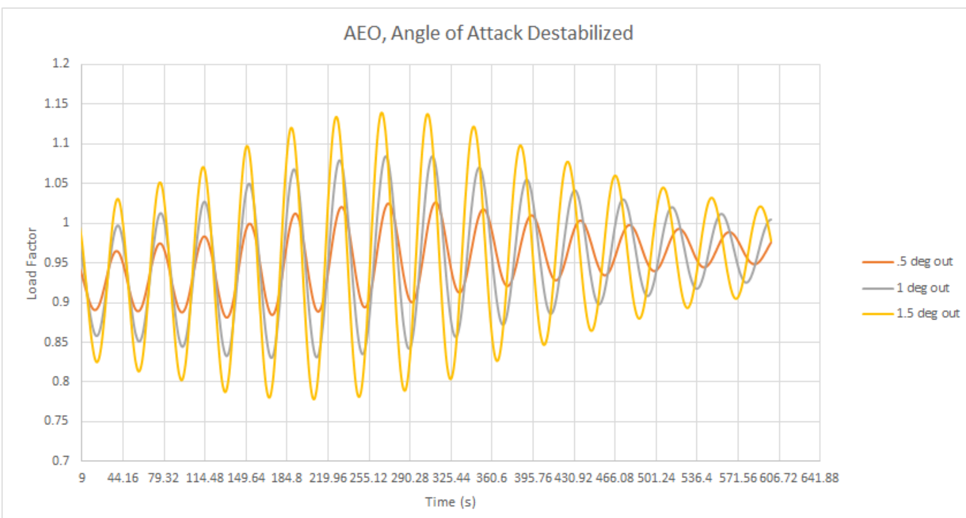


Figure 44. Takeoff Flight history (AEO) with mis-trim in angle-of-attack (Nz variations)

In Figures 45 through 47, a simulation of the alternative source for mis-trimmed flight; flight at a constant but inappropriate horizon attitude. If the horizon attitude is too high, there is a different means to a crash. Nominal flight is at an angle of attack α=11.7° and a horizon angle of ($\alpha+\gamma$)= 22.6°. A +0.5° mis-trim would result in flight at a horizon angle at $(\alpha+\gamma)=23.1^{o}$. Mis-trim by $+0.5^{o}$ would result in flight at a horizon angle at $(\alpha+\gamma)=23.6^{o}$.

The reader is invited to compare Figure 41 to Figure 45. Mis-trim from an inappropriate horizon-attitude includes an inherent mechanism for pilot feedback (the stick is continuously adjusted to maintain horizon-attitude). As such, the time history response is seemingly smooth and in no way resembles the Phugoid mode.

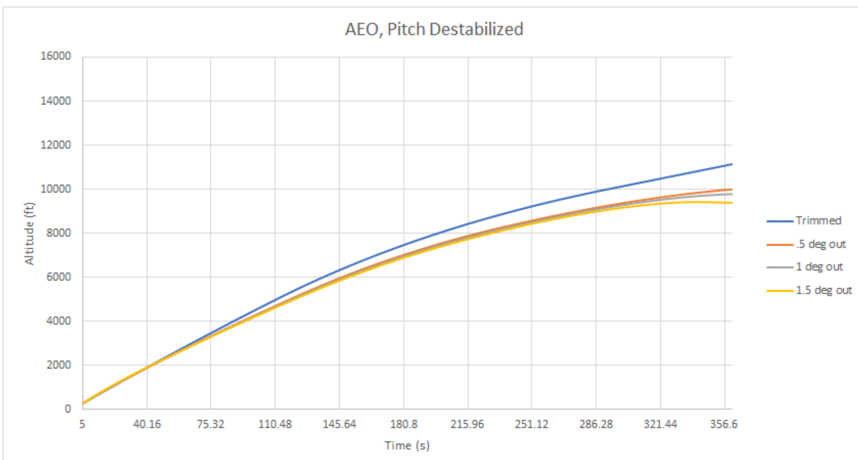


Figure 45. Takeoff Flight Path (AEO) with mis-trim due to flying constant horizon attitude

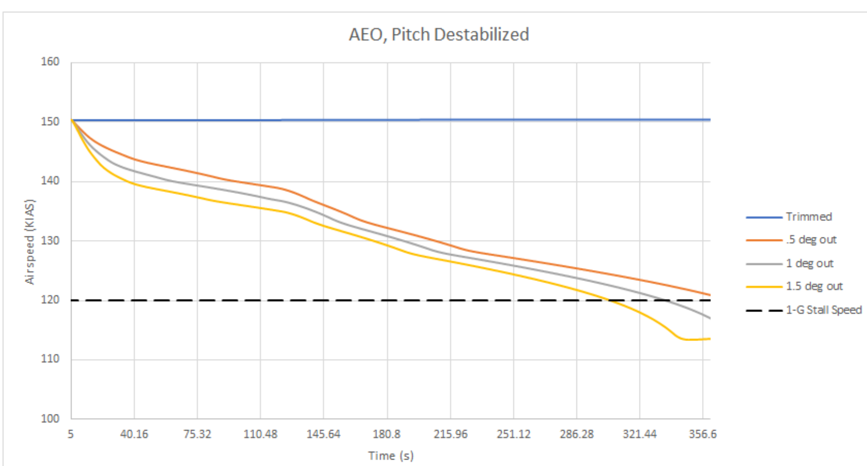


Figure 46. Takeoff Flight history (AEO) with mis-trim due to flying constant horizon attitude (airspeed variations)

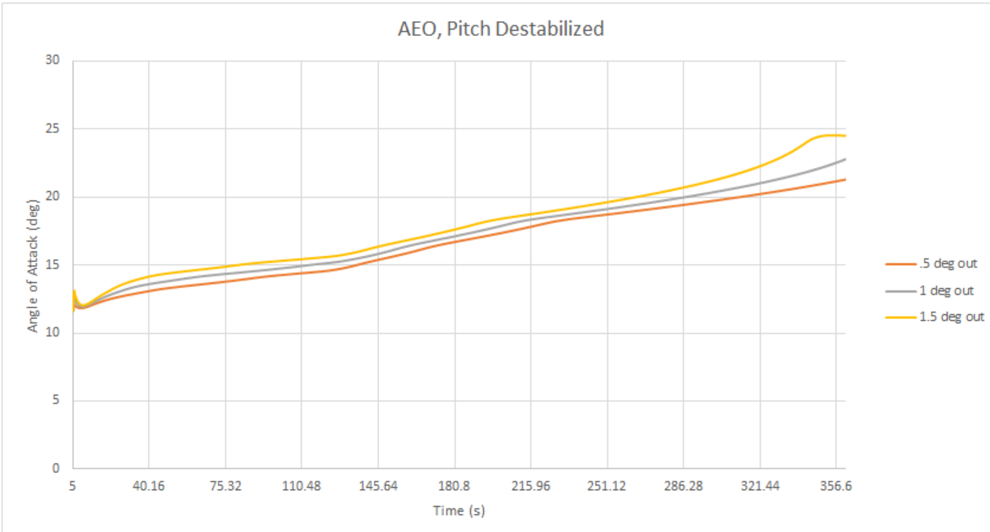


Figure 47. Takeoff Flight history (AEO) with mis-trim due to flying constant horizon attitude (angle-of-attack variations)

Figures 46 and 47 show an overall decline in airspeed with some slight "wobble" and a corresponding increase in angle-of-attack. About three minutes into the simulation, the pilot reaches incipient stall; the angle-of-attack cannot be increased further. Any further attempts to maintain horizon attitude would be met with a stick-shaker, stall warning horn. The good news here involves the time scale of the impending stall; three minutes at a typical climb rate of ~3000/ft to bleed off speed to reach stall. Because of the long period predicted here, it is unlikely that the dynamic problems from a foreseeable, but minor mis-trim in horizon attitude will become a safety hazard with all engines operating.

Now these simulations are repeated, but with flight with a critical engine inoperative.

Figures 48 and 49 show the response of an aircraft with one engine inoperative that is destabilized in angle of attack. The nominal angle-of-attack here is α=12.4°. With the reduced thrust and added drag of the windmilling engine, the overall climb performance is much weaker than before as is the energetics of the oscillatory flight. The period of the first couple of oscillations is closely predicted by the Phugoid approximation. The damping (probably due to the lower aerodynamic *L/D* from the windmilling engine) is much greater. As the nose-high trim attitude increases, the overall climb performance declines somewhat. The airspeed wobbles are much smaller than before, and in none of the simulations ever approached the 120-KIAS 1-gee stall speed of the aircraft.

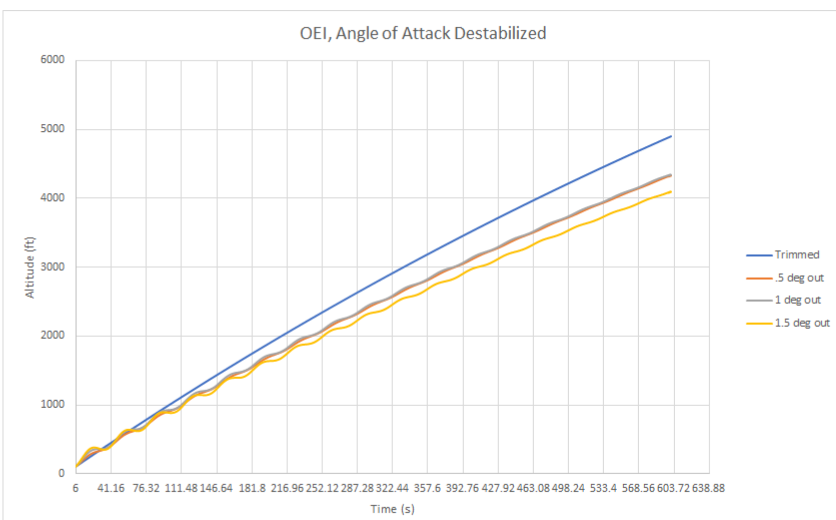


Figure 48. Takeoff Flight Path (OEI) with mis-trim in angle-of-attack (stick-fixed)

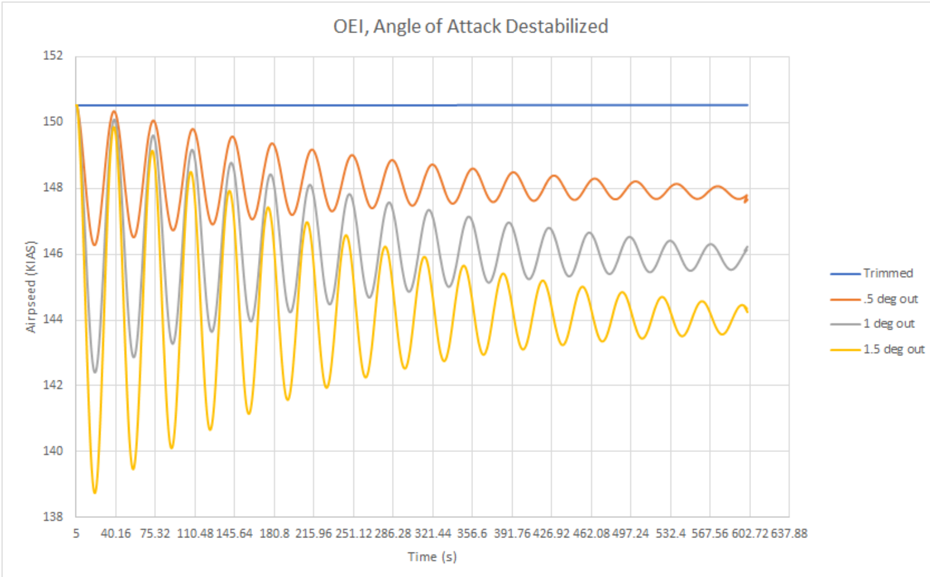


Figure 49. Takeoff Flight History (OEI) with mis-trim in angle-of-attack (stick-fixed) (airspeed variations)

In Figures 50 and 51, engine-inoperative flight at horizon attitude is simulated. It is immediately clear that these trajectories do not exhibit any sort of Phugoidal action.

If the pilot flies the aircraft to the AEO trimmed horizon attitude $(\alpha+\gamma)$ $=22.6^{o}$, the aircraft will rapidly decelerate beneath its 1-gee stall speed within ~25-seconds. As the aircraft decelerates, it will climb. Upon stall, if the pilot continues to attempt to maintain the nose-up attitude, the aircraft will eventually impact the ground. Thus, to recover from such an excursion, the pilot needs to reduce horizon attitude to regain airspeed.

Conversely, if the pilot flies the aircraft to the OEI trimmed horizon attitude $(\alpha+\gamma)$ $=14.7^{o}$, the aircraft will climb at constant airspeed. If the pilot files the aircraft to a slight mis-trim, for example a $+1.0^{o}$ mis-trim, will have the pilot attempt to maintain a constant horizon attitude $(\alpha+\gamma)=15.7^{o}$. Under such circumstances, the simulation shows a moderate airspeed loss of ~7 KIAS and an overall slight reduction in climb performance.

Such minor mis-trim is easy to correct by depressing the nose to a lower horizon attitude, whereby the aircraft would gain some speed.

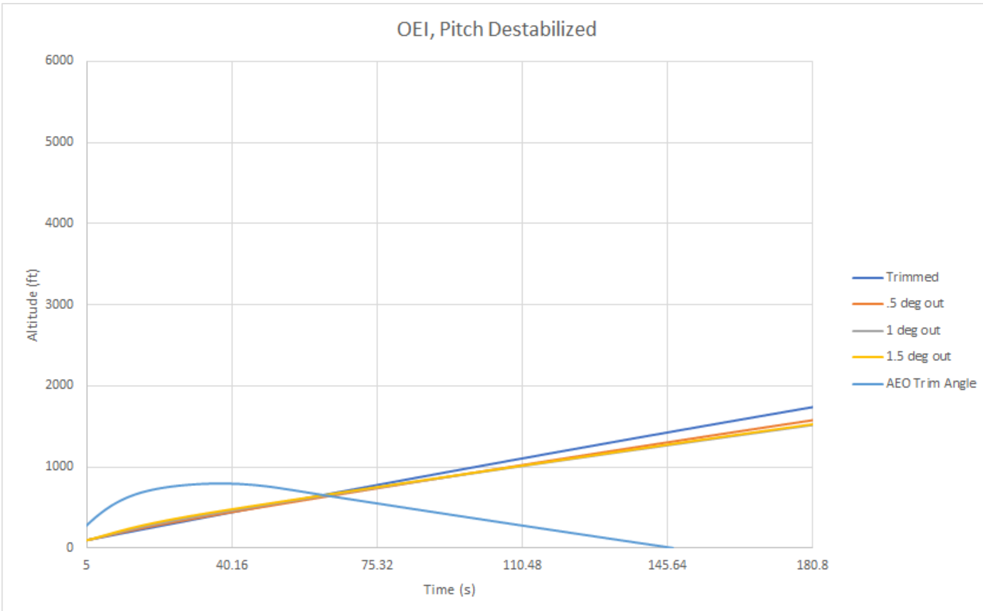


Figure 50. Takeoff Flight Path (OEI) with mis-trim due to flying constant horizon attitude

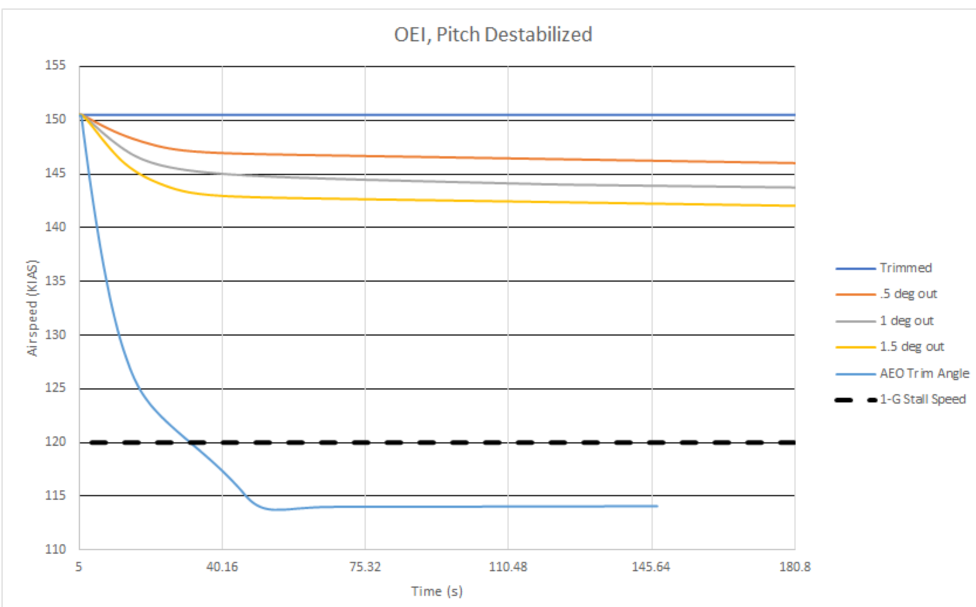


Figure 51. Takeoff Flight History (OEI) with mis-trim due to flying constant horizon attitude (airspeed variations)

CHAPTER 5

SUMMARY AND CONCLUSIONS

This study used a dynamic flight model, calibrated aerodynamic performance data, and calibrated five-column propulsion data to demonstrate performance of a narrow-body, twin-engine, commercial airliner. The trades show how quickly an aircraft loses speed by going out-of-trim by only a couple of degrees in angle-of-attack. In some flight configurations, it is shown going out-of-trim and causing destabilized flight can result in a loss of airspeed that can cause the aircraft to be at or below the nominal 1g stall speed.

In the event of an engine failure during the second segment climb, the pitch indicator may become very distracting and potentially dangerous. In a matter of seconds if the pilot does not attempt to pitch the nose of the aircraft down, it will lose airspeed very rapidly. At a flight weight of 160,000 lbm, an A320 will lose indicated airspeed at 2.3 KIAS per second if the pilot does not pitch the nose of the aircraft down at engine failure. This effect is most prominent in lightly loaded aircraft. If the pilots in command are distracted by the stall warnings and warnings coming from the engine failure, they may not realize to pitch the nose of the aircraft down if they look at the pitch indicator and notice the director is still aligned to the pre-determined pitch angle. In a matter of seconds, the airplane can lose 5 to 15 KIAS of indicated airspeed, bringing the flight speed dangerously close to stalling and falling out of the sky. It was shown that for heavier flight weights, the aircraft can withstand less deceleration before becoming un recoverable even to a level acceleration.

If an aircraft loses an engine during the second segment climb and the pilots recovered the airplane before it were to fall out of the sky, the pilots now should be concerned with clearing any obstacles in the flight path. Even if the airplane recovers from an engine failure quickly enough to avoid stall, the speed loss potential to being out of trim for even a couple of seconds can have a large impact on obstacle clearance. For various weights flying under speed by even as little as 5 KIAS indicated airspeed can reduce your climb gradient greatly. If speed is lost during a maneuver or during an engine failure that results in a speed even slightly below the V2 speed, the aircraft is in danger of not clearing obstacles. If speed is lost to where the aircraft is around 15 KIAS below the V2 speed, the aircraft will likely not be able to climb at all, causing the aircraft to be stuck at a certain altitude.

Takeoff is a very complicated maneuver to be performing and very difficult to do entirely trimmed, especially given the pitch indicators the pilots use to pitch the aircraft up and down. If the aircraft is above the trimmed pitch angle it will lose speed, depending on the flight weight and status. Even if the aircraft is able to perform the takeoff without losing an engine and crashing, the performance drawbacks shown in acceleration times and distances from pitching the plane out of trim slightly can be impactful. More research into destabilized flight could prove useful for safety during emergencies such as an engine inoperative as well as reducing emissions and operation costs. A more precise way for pilots to pitch the aircraft to the proper angle can also improve safety during emergencies as well as improve fuel consumption.

The results presented above show that if the pitch command bar is not set properly or the pilot commands the aircraft to a pitch angle that is not the pitch angle for climb at constant airspeed, the climb performance and airspeed of the aircraft is significantly affected. In the event of an engine failure during a balked landing, the pilot performing the maneuver is likely to lose situational awareness and have difficulty pitching the aircraft to the right angle for climb, different than the pitch angle if all engines were operative.

The trades above also give insight in to how a pilot can most effectively perform a balked landing climb. From comparing the trades of climbing at the same indicated airspeed but different flap settings, the configuration with less flap was able to climb faster, implying the pilot would want to clean the flaps up as soon as possible to CONF 2 for best climb performance. It is also shown that flying either slightly above or below the pitch angle for climb at constant indicated airspeed will either increase or decrease your flight speed, but both will lower your climb rate once stabilizing. This means that for a pilot to fly effectively they will want to fly a constant airspeed climb without having to re-stabilize from going out of trim. Interestingly though, if pitched far enough below the pitch angle that allows for trimmed climb at constant indicated airspeed, the aircraft will accelerate and re-stabilize at an increased flight speed, and an increased rate of climb. There is an optimal amount of pitch below the trim that allows for an acceleration and an increase in climb performance after stabilization because it was shown as the aircraft increasingly pitched towards what would be a level altitude acceleration, the climb performance decreased. If the pitch is too low though, it will just accelerate the aircraft and trim in a condition. It is also interesting to notice that the corresponding V2 speed at the landing weight is about 6 knots slower than the reference speed, implying that the pilot can retract the flaps to CONF 2 and begin climbing in that configuration without having to accelerate.

From these observations it is reasonable that for a balked landing to be most efficient the pilot should retract flaps to CONF 2 and begin climbing at a pitch angle for climb at constant indicated airspeed. However, it is also shown that if the pilot pitches to an angle above that for climb at constant indicated airspeed, airspeed will be lost rapidly. If too much airspeed is lost the pilot will be unable to retract the flaps safely, hindering the performance. If the pilot retracts the flaps at too low of an airspeed, the aircraft could potentially stall and fall out of the sky. The risk of pitching above the intended pitch angle for climb at constant indicated airspeed is especially high when an engine failure occurs during a balked landing. This highlights the complexity of attempting a balked landing, the vague instructions given in the flight manuals, and the performance consequences that can even be dangerous if the balked landing climb is performed improperly.

Turning to the angle of attack trades, the initial reaction of the airframe to a trim-error is to change airspeed, attitude and altitude. If a pilot is unable to distinguish the source of the out-of-trim flight, his reactions to attempt to damp the motion may prove to exacerbate the situation.

From the simulations presented, that aircraft destabilized by seemingly minor constant-angle-of-attack trim errors will develop Phugoid-like oscillatory response in climb. This can be a wild ride; although the aircraft does not stall, the magnitude of Phuogoidal oscillations increases and the relative damping decreases as thrust levels increase. A pilot trying to hold controls fixed will not actively suppress this mode; but they will eventually damp out.

At the same time, constant-horizon-attitude flight with small trim errors produce slow variations in speed and climb performance that are easy to mitigate. Large errors in horizon-attitude, for instance pitching to a familiar attitude for AEO climb but flying with a failed engine, can result in a swift drop in airspeed leading to stall.

In either case, the initial reaction of the airframe is to change airspeed while continuing to climb. If a pilot is unable to distinguish the source of the out-of-trim flight, his reactions to attempt to damp the motion may prove to exacerbate the situation. These trades may lead some to believe that flight dynamics tending towards an accidental stall due to major horizon-attitude error is a byproduct of pilot training and flight manuals that call out horizon attitude cues on the artificial horizon. If a pilot attempts to "ride out" a horizon-attitude error, it is shown in several simulation runs with both AEO and OEI that result in airspeed loss that ends in stall.

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