Stall Avoidance on Plane ArduPilot (Rev 2) by FRANCIS NELSON HENDERSON Aug 28, 2014

Plane ArduPilots need only three (3) new easily available parameters in order to avoid stalling in any flight mode. First, a reference stall speed (Vs) is reliably computed on-line using aircraft weight and wing dimensions. Also needed is current aircraft weight, if different. That is all (Reference Vs, reference weight, and current weight).

The on-line Vs results for my airplane equals the measured Vs I observed on Mission Planner flight logs (28 mph). Following is the Link to a Stall Speed Calculator, its User Interface screen shot, and my airplane photo:

http://adamone.rchomepage.com/design.htm

On-line Vs calculations assume air density at sea level Standard Temperature and Pressure (STP).

Autopilots, like real pilots, need two (2) speed reference systems, True Air Speed (TAS) and Indicated Air Speed (IAS). Navigation functions (like waypoints or Inertial navigation) need True Airspeed (TAS); the piloting functions (like turning or landing) need IAS.

Andrew Tridgell's point is accepted, that slow speed stall avoidance relying solely on the air speed sensor could see too much variation in the measured speed. I've been out slowly driving my Pixhawk around the neighborhood with a GPS and airspeed sensor mounted 57 cm (22.5") above the roof of my car to see how the airspeed sensor behaves at slow speeds. I agree with Tridge.

However, I believe the new Extended Kalman Filter (EKF) is always giving its best opinion of speed using GPS in addition to airspeed sensor inputs. I suspect the EKF speed estimate is smoothed, hence better than the airspeed sensor alone. Therefore, I hold the hope the autopilot could still, by using the best information it has, attempt to avoid stall in its major flight modes.

Furthermore, I believe optimal flight mode parameters could be automatically derived at Mission Planner using the new Vs and weight inputs. This paper gives the formulas for automating calculation of some parameters tied to Vs. Example calculations are included. The creation of stall safe flight parameters is the first action towards stall avoidance.

Secondly, the autopilot could use the new reference stall speed information to avoid stalling the wing in all flight modes except manual mode. I return to in-flight Stall Avoidance later after parameter initialization.

In both cases much is derived from the new Vs input parameter and aircraft weights. Usually the current weight (Weight2) = the reference weight (Weight1) in which case stall speeds are equal. Otherwise, the one (1) g Vs at Standard Temperature and Pressure (STP) is immediately adjusted for any weight change using the following equation:

$$Vs(at\ weight2) = Vs(at\ weight1)\sqrt{Weight2/Weight1} \qquad (1)$$

This equation says that if you know the stall speed Vs (at Weight1), then the stall speed for another Weight2 can be determined by multiplying Vs(at weight1) by the square root of the new gross Weight2 divided by the original gross Weight1. The same principal applies in a balanced banked turn where the stall speed goes up (or down) in proportion to the square root of g's pulled.

$$Vs(banked) = Vs(level)/\sqrt{cos(bank\ angle)} \qquad (2)$$

For example, turning at 60 degrees bank (cos 60 = 0.5) results in 2 Gs. This is equivalent to doubling the weight. Once you know your level one (1) g stall speed, you can calculate it for a banked turn by doing the inverse: Multiplying Vs by the square root of the acceleration you must endure. Hence at 60 degrees bank, your stall speed increase by your level stall speed times the square root of 2, or 1.41. Say your stall speed at level is 28 knots. Maintaining altitude in a balanced turn at 60 degrees banking, it would then be 39 knots.

Bank Angle (θ) Degrees	G's pulled in turn	Stall Speed Increase
0	1.00	1.00
10	1.02	1.01
20	1.06	1.03
30	1.15	1.07
40	1.31	1.14
50	1.56	1.25
60	2.00	1.41
65	2.37	1.54
70	2.92	1.71

75	3.86	1.97
80	5.76	2.40
85	11.47	3.39

The above table suggest that if the turn radius is long enough and min/max speeds of entry are low enough to keep the bank angle (θ) shallow, then the banked stall speed does not increase much.

Mission Planner could set default parameters tied to the new Vs. These suggested defaults simplify parameter entry for new or rusty ArduPilot fliers. Here are the suggestions :

1. Minimum circular turn entry speed (V_{min}) = 1.5 Vs
2. Maximum circular turn entry speed (V_{max}) = 1.8 Vs
3. Target (avg) circular turning speed (V_{avg}) = 1.65 Vs
4. Waypoint straight line & turn speed (V_{wpt}) = 1.65 Vs
5. Landing approach speed (V_{lap}) = 1.3 Vs
6. Takeoff rotate speed (V_{tko}) = 1.2 Vs
7. Max circling bank angle (θ) = 35 degrees
8. Max waypoint bank angle (θ) = 45 degrees
9. Turn radius (r) = $r = V^2/g\tan\theta$
   g = acceleration of gravity = 9.81 meters/sec^2

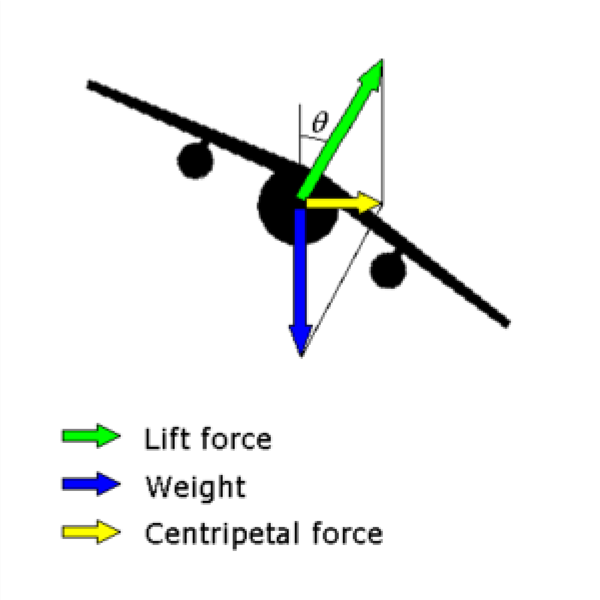
Advanced users could still override defaults in Mission Planner with edits. These might result in Mission Planner pop-up warnings about stall safety margins failing in a turn at edited speeds or radii.

Presently, the Mission Planner user could unknowingly, at a given speed, choose waypoint radii that are too short, that if obeyed, require violation of the maximum bank angle (θ) or could result in a stall from increased **g** loads in the turn. One needs to know the relationship between speed (V), balanced turn bank angle (θ), and radius (r) in order to choose correctly. Classical physics text books have the information, however Wikipedia has an excellent derivation cut and pasted below in italic:

http://en.wikipedia.org/wiki/Banked_turn

*When any moving vehicle is making a turn, the forces acting on the vehicle add up to a net inward force, mass * centripetal acceleration. In the case of an aircraft making a turn, the force causing centripetal acceleration is the horizontal component of the lift acting on the aircraft.*

During a balanced turn where the angle of bank is θ the lift acts at an angle θ away from the vertical, the lift vector can be resolved into a vertical component and a horizontal component. If the aircraft is to continue in level flight (i.e. at constant altitude), the vertical component must continue to equal the weight of the aircraft. The total (now angled) lift is greater than the weight of the aircraft so the vertical component can equal the weight while the horizontal component is the force causing the aircraft to accelerate inward along the radius of the turn.



Vector diagram showing lift, weight and centripetal force acting on a fixed-wing aircraft during a banked turn.

Because centripetal acceleration is:

$$a = \frac{v^2}{r}$$

Newton's second law in the horizontal direction can be expressed mathematically as:

$$L \sin\theta = \frac{mv^2}{r}$$

where:

L is the lift acting on the aircraft
θ is the angle of bank of the aircraft
m is the mass of the aircraft
v is the true airspeed of the aircraft
r is the radius of the turn

In straight level flight, lift is equal to the aircraft weight. In turning flight the lift exceeds the aircraft weight, and is equal to the weight of the aircraft (mg) divided by the cosine of the angle of bank:

$$L = \frac{mg}{\cos\theta}$$

where ***g*** *is the gravitational field strength. The radius of the turn can now be calculated:*

$$r = \frac{v^2}{g \tan\theta} \qquad (3)$$

$$\theta = arctan(\frac{V^2}{rg}) \qquad (4)$$

Equation (3) shows that the radius of turn (r) is proportional to the square of the aircraft's true airspeed. Alternatively using equation (4), bank angle (θ) may be calculated when radius of turn and true airspeed are given.

Selecting a stall safe Balanced Turn Radius is shown in Blue using equation (3):

Green fields are spread sheet Inputs	Acceleration of gravity		Vs Stall Speed
Blue fields are used at Mission Planner	9.81 Meters/sec2 (SI units)	28	mph
Pink fields are Km/hour units		45.2	Km/h
Purple fields are miles/hour	0.017453 Radians/Degree	12.5	Meters/sec (SI units)

		Speed Relative to Vs	Speed (mps)	Bank angle (θ) deg	Balanced Turn Radius (Meters)	Balanced turn G's	Stall Speed (mps)	Stall Margin (mps)	Stall Margin Factor
1. Minimum circular turn entry speed	(V_{min})	1.5 Vs	18.8	35	51.2	1.221	13.8	4.9	1.36 Vs
2. Maximum circular turn entry speed	(V_{max})	1.8 Vs	22.5	35	73.7	1.221	13.8	8.7	1.63 Vs
3. Target (avg) circular turning speed	(V_{avg})	1.65 Vs	20.6	35	61.9	1.221	13.8	6.8	1.49 Vs
4. Waypoint straight line & turn speed	(V_{wpt})	1.65 Vs	20.6	45	43.4	1.414	14.9	5.8	1.39 Vs
5. Landing approach speed	(V_{lap})	1.3 Vs	16.3				12.5	3.8	1.3 Vs
6. Takeoff rotate speed	(V_{tko})	1.2 Vs	15.0				12.5	2.5	1.2 Vs

1 meter/sec = 3.6 Km/h	3.6		(Km/h)				(Km/h)	(Km/h)	
1. Minimum circular turn entry speed	(V_{min})	1.5 Vs	67.5	35	51.2	1.221	49.7	17.8	1.36 Vs
2. Maximum circular turn entry speed	(V_{max})	1.8 Vs	81.0	35	73.7	1.221	49.7	31.3	1.63 Vs
3. Target (avg) circular turning speed	(V_{avg})	1.65 Vs	74.3	35	61.9	1.221	49.7	24.5	1.49 Vs
4. Waypoint straight line & turn speed	(V_{wpt})	1.65 Vs	74.3	45	43.4	1.414	53.5	20.7	1.39 Vs
5. Landing approach speed	(V_{lap})	1.3 Vs	58.5				45.0	13.5	1.3 Vs
6. Takeoff rotate speed	(V_{tko})	1.2 Vs	54.0				45.0	9.0	1.2 Vs

1 meter/sec = 2.23694 Miles/hour	2.23694		(mph)				(mph)	(mph)	
1. Minimum circular turn entry speed	(V_{min})	1.5 Vs	41.9	35	51.2	1.221	30.9	11.0	1.36 Vs
2. Maximum circular turn entry speed	(V_{max})	1.8 Vs	50.3	35	73.7	1.221	30.9	19.4	1.63 Vs
3. Target (avg) circular turning speed	(V_{avg})	1.65 Vs	46.1	35	61.9	1.221	30.9	15.2	1.49 Vs
4. Waypoint straight line & turn speed	(V_{wpt})	1.65 Vs	46.1	45	43.4	1.414	33.3	12.9	1.39 Vs
5. Landing approach speed	(V_{lap})	1.3 Vs	36.4				28.0	8.4	1.3 Vs
6. Takeoff rotate speed	(V_{tko})	1.2 Vs	33.6				28.0	5.6	1.2 Vs

Mission Planner parameter list setting are suggested using the above example (Vs = 28 mph):

TKOFF_ROTATE_SPD	=	15 mps
TECS_LAND_ARSPD	=	17 mps
ARSPD_FBW_MIN	=	19 mps
TRIM_ARSPD_CM	=	21 mps
ARSPD_FBW_MAX	=	23 mps
SCALING_SPEED	=	
LIM_ROLL_CD	=	45 degrees
WP_RADIUS	=	43 meters
WP_LOITER_RAD	=	62 meters
WP_MAX_RADIUS	=	0

I return now briefly to in-flight stall avoidance, however the subject is large enough that it deserves a separate paper. Here are thoughts going into the next paper.

First, I realize the auto pilot is mechanized using TAS. The physics rightly drives that choice because of the IMU and GPS sensors, and the navigation task. However, I believe stall avoidance will benefit from converting the best estimate of TAS back to IAS at Standard Temperature and Pressure (STP) so that all stall calculations are as if at one uniform air density. Ardupilot has all the input needed for converting back to an IAS equivalent using the barometer and temperature sensors during calibration before takeoff.

The desirable feature about IAS is that different altitudes (air pressure) and temperatures do not affect stall speed, or banked turn speed, or landing speed, if we use IAS. The TAS at which an airplane stalls is different at different altitudes for the same weight or **g** loads. However, the density change with altitude affects the IAS proportionally to the way it affects wing stall. If stall speed were measured at sea level, for example, and then several thousand feet above sea level, the lower density at the higher altitude would cause the airplane to stall at a higher TAS. However, the lower density reduces IAS to be the same as at sea level.

Second, I believe we have an estimated TAS better than is provided by the airspeed sensor alone. Let us use the best estimates we have.

Third, airspeed is not the single factor indicating an approaching stall. Wing **g** force loading also acts along with airspeed to cause or to relieve a stall condition. Small downward elevator may increase airspeed slowly, however down elevator is a nearly instant relief to **g** loads. It allows time for added engine thrust or turbulence (that could be the transient cause) to restore safe speed and wing loading.

Fortunately, the ardupilot z-axis accelerometer is measuring wing **g** loading directly and continuously. See equation (5) below:

The ratio of Weight2/Weight1 from equation (1) is equivalent to **g** acceleration. Therefore, Equation (1) can be rewritten to calculate rising (or falling) Vs from **g** loading.

$$Vs = Vs(one\text{-}g)\sqrt{g} \qquad (5)$$

If (Vs ≥ $V_{(\text{IAS measured})}$) then remedy stall

The above allows plane ardupilot software to continuously monitor for approaching stall conditions and to take preventative actions.

This paper and others about stall are submitted to www.diydrones.com – search Francis Nelson Henderson. The three papers plus Excel spread sheet are also posted at my web site.

http://www.inertial-solutions.us/pdf_files/Stall%20Speed.pdf

http://www.inertial-solutions.us/pdf_files/Learning%20and%20Using%20Lift-Drag%20ratio.pdf

http://www.inertial-solutions.us/pdf_files/StallAvoidance.pdf

http://www.inertial-solutions.us/downloads/TurningStallSpeed.xlsx