The Dynamics of the Turn

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Knowing the why of what can happen is the best stall/spin preventative

It has been said that the 180° turn is one of aviation's most difficult maneuvers. This is because a course reversal usually is contrary to plan and forces a pilot to admit defeat in the face of adversity.

But these are psychological reasons. The maneuver itself is relatively simple. Or is it? An astonishing number of fatal accidents occur annually because many pilots apparently do *not* appreciate the dynamics of a turning airplane.

Table I reviews two variables associated with turning flight that every student discovered while learning to fly. Unfortunately, however, many seem to have forgotten these early lessons. So it might be appropriate to review them before discussing advanced concepts.

As the angle of bank is increased during a coordinated turn, the load factor also increases, something easily detected by the gluteus maximus. But a larger G-load causes more than temporary discomfort of the pilot's posterior. It also burdens the wings with additional "weight." At two G's, for example, the wings must provide twice the lift required during level flight. This, in turn, requires a larger angle of attack, which increases drag, which reduces airspeed (unless additional power is applied).

It is interesting to note that an increased load factor results in the same airspeed loss (or requires the same amount of additional power) as if the airplane were loaded with the equivalent excess payload while in level flight.

For example, an airplane in a 40° banked turn encounters 1.31 G's. The resultant airspeed loss in such a turn is the same as if the airplane were 31% heavier while in level flight. Similarly, the airplane's climb capability is reduced. In other words, as bank angle steepens, the airplane becomes increasingly "heavier" and its performance suffers accordingly.

The lesson here is obvious. When maximum performance is required, don't turn.

Since aircraft weight effectively increases during a turn, it is logical to assume that stall speeds also would rise—which, of course, they do.

Table II illustrates the effects of varying bank angle and airspeed. Not surprisingly, rate of turn at any given airspeed increases as the bank angle steepens. But often not considered is that rate of turn decreases as true airspeed increases (for any given bank angle).

The effect of airspeed on turn rate is particularly distressing to pilots of the SR-71, which is probably the world's fastest airplane. When this remarkable machine is rolled into a 30° bank while cruising nonchalantly at 2,000 knots, the rate of turn is only .3 degrees per second. A 360° turn would take 19 minutes and the circle would have a diameter that stretches from Dayton, Ohio, across Indiana to Chicago. Now that's what is meant by having to plan ahead.

Although an extreme example, this indicates the need to initiate turns from base leg to final approach a little earlier when using unusually fast approach speeds and when checking out in high-performance aircraft. Failure to plan ahead can result in either overshooting final approach or having to roll into an excessively steep turn at a dangerously low altitude, one of many causes for the infamous stall/spin accident.

Most pilots realize that a standard-rate turn is 3 degrees per second. But this is only for relatively slow airplanes. Such a turn at 500 knots, for example, would require a 54° (1.7 G) bank angle. That's why a standard-rate turn in subsonic, jet-powered airplanes is only 1.5 degrees per second.

The variables of turning flight give rise to an interesting problem. Assume

Table I

Bank angle in coordinated turn	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
Load factor	1.0 G	1.02 G's	1.06 G's	1.15 G's	1.31 G's	1.56 G's	2.0 G's	2.92 G's	5.76 G's	infinite
Stall speed increase	0%	1%	3%	7%	14%	25%	41%	71%	140%	infinite

NOTE: Load factor = 1 ÷ cosine of bank angle,
and stall speed increase = square root of load factor

Table II

True Airspeed \ Bank Angle	10°	20°	30°	40°	50°	60°	70°	80°
50 knots	3.8°/s 1,259 ft	7.9°/s 610 ft	12.6°/s 385 ft	18.3°/s 265 ft	26.0°/s 186 ft	37.8°/s 128 ft	60.0°/s 81 ft	124°/s 39 ft
100 knots	1.9°/s 5,037 ft	4.0°/s 2,440 ft	6.3°/s 1,538 ft	9.2°/s 1,058 ft	13.0°/s 745 ft	18.9°/s 513 ft	30.0°/s 323 ft	61.9°/s 157 ft
150 knots	1.3°/s 1.9 nm	2.6°/s 5,490 ft	4.2°/s 3,461 ft	6.1°/s 2,381 ft	8.7°/s 1,677 ft	12.6°/s 1,154 ft	20.0°/s 727 ft	41.2°/s 352 ft
200 knots	1.0°/s 3.3 nm	2.0°/s 1.6 nm	3.1°/s 1.0 nm	4.6°/s 4,234 ft	6.5°/s 2,981 ft	9.4°/s 2,051 ft	15.0°/s 1,293 ft	30.9°/s 626 ft
250 knots	.8°/s 5.2 nm	1.6°/s 2.5 nm	2.6°/s 1.6 nm	3.7°/s 1.1 nm	5.2°/s 4,658 ft	7.6°/s 3,205 ft	12.0°/s 2,020 ft	24.8°/s 979 ft

Effect of True Airspeed and Bank Angle on Rate of Turn and Turn Radius

(Numbers in shaded boxes are rates of turn, numbers in boxes not shaded represent turn radius.)

$$\text{Rate of turn (degrees/second)} = \frac{(1{,}091)\ (\text{tangent of bank angle})}{(\text{true airspeed in knots})}$$

$$\text{Turn radius} = \frac{(\text{true airspeed in knots})^2}{(11.26)\ (\text{tangent of bank angle})}$$

that a pilot were flying through a very narrow canyon and had to make a minimum-radius, 180° turn without gaining or losing altitude. What technique should he use?

He knows that, for a given bank angle, the greatest rate of turn occurs at the slowest airspeed. He knows also that, for a given airspeed, turn radius decreases as the bank angle steepens. This suggests, therefore, that the canyon turn should be performed with a steep bank angle and minimum airspeed. But could this intrepid aviator complete the turn before stalling? Probably not.

In theory, the minimum-radius, or *maximum-performance*, turn is achieved by maintaining the airplane's maneuvering speed (V_A) and using the maximum possible bank angle without inducing either a stall or an excessive load factor. For aircraft certificated for 3.8 G's (which is *most* light planes), this is about a 75° bank angle. The resultant maneuver is a balance between structural and aerodynamic limits. When turning with a 75° bank angle, the load factor would be 3.8 G's (maximum allowable). Also, with any less airspeed or with additional bank angle, the airplane would stall. Quite obviously, this is a tricky, delicate maneuver.

Most light aircraft, however, are incapable of performing such a turn. At 3.8 G's, the airplane effectively weighs almost four times as much as when in level flight. To maintain altitude in such a configuration requires tremendous power, something lacking in many airplanes especially when operating at high density-altitudes. To attempt such a maximum-performance maneuver when near the ground, therefore, is to flirt with disaster.

When flying an *underpowered* airplane, such a turn can be performed only when a pilot is willing to sacrifice altitude. (Curiously, turn radius is *slightly* less when climbing or descending compared to an identical turn while maintaining altitude.)

Parenthetically, when flying through a narrow valley, it is usually best to fly along the downwind side. If a turn has to be made, it will be into the wind, which *decreases* turn radius. Conversely, a turn away from the wind *increases* turn radius and requires considerably more elbow room. Also, flying along the downwind side of a valley often places an airplane in orographically rising air which can improve cruise performance.

Many airplanes that lack sufficient power for maximum performance turns also are similarly underpowered during moderately steep turns at reduced airspeed. This is because of the increased induced drag that occurs as angle of attack is enlarged.

Consider an airplane climbing over an obstacle at full power and reduced airspeed. If the pilot enters a 45° banked turn, induced drag may double; in a 60° banked turn, induced

Figure 1

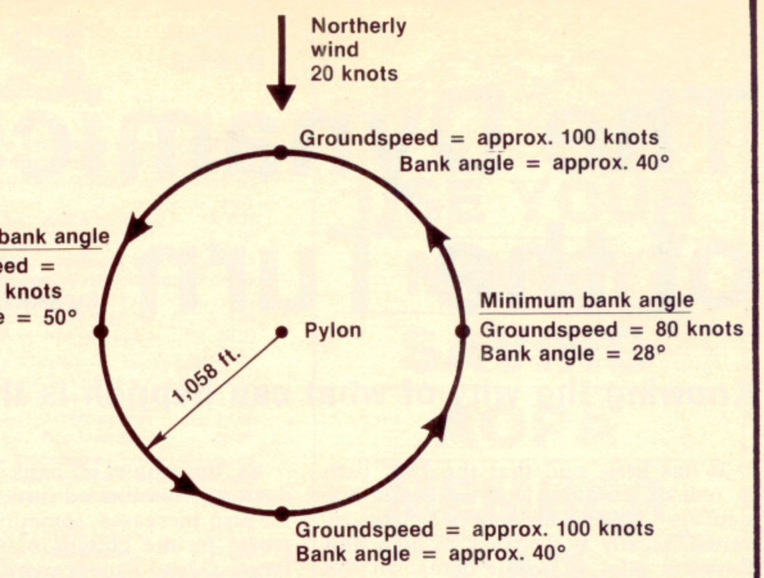
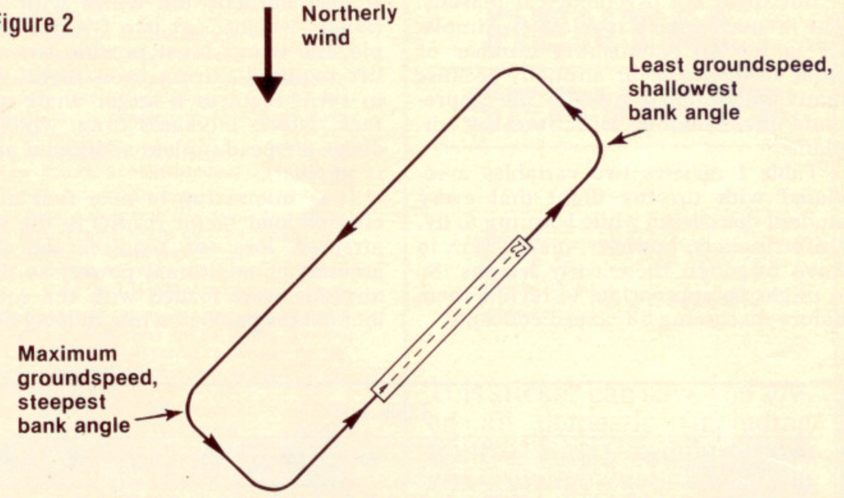


Figure 2



drag can more than triple. As a result, considerable power is required not only to climb, but simply to maintain altitude. Lacking sufficient power, the airplane simply may descend with the throttle wide open. This helpless sensation may not be as dramatic as a stall, but can be just as lethal. Raising the nose farther to arrest the sink rate worsens the dilemma and leads to a stall. The solution? Roll out of the turn.

Accident statistics reveal that such a stall accident most frequently occurs while departing high-elevation airports when airplane and engine performance may be marginal.

An approach accident of this type may occur when a pilot on base leg fails to recognize that the normal indicated approach airspeed converts to a much faster true airspeed when flying into a high-elevation airport. As a result, he peripherally senses an abnormally fast approach speed through the side window and subconciously reduces airspeed. Then, because he may still have a faster than normal groundspeed (because of the faster true airspeed), he may overshoot final approach and tighten the turn to line up with the runway. *Voila!* He has just met the admission requirements to join that elite society of flagging fliers. A missed approach isn't good for the ego, but it is much preferred to steep turns near the ground.

Stalls resulting from climbing and descending turns often create a unique brand of havoc: initially uncontrollable rolling moments that can lead to inverted flight and possible spinning. During a climbing, turning stall, the angle of attack of the outside wing is larger than that of the inside wing. As a result, the outside, or high wing stalls first and causes a rapid roll *opposite* to the direction of turn. Such an involuntary maneuver is called an "over-the-top" spin entry, which if unchecked results in a complete roll followed by a spin.

During a descending, turning stall, the angle of attack of the inside wing is larger than that of the outside wing. Consequently, the inside, or low wing stalls first and simply drops lower. Less dramatic than flipping on your back, but equally as dangerous, this is known as an entry to an "under-the-bottom" spin.

It must be noted that any attempt to correct either of these situations by applying "opposite" aileron control usually aggravates the crisis.

It is not easy to visualize why the outside wing in a climbing turn and the inside wing in a descending turn have larger angles of attack than their opposite wings. To understand this important concept, it is necessary to analyze the motion of an airplane about all three axes.

In a flat, skidding turn with the wings level, for example, the aircraft is only yawing. But, in a coordinated turn while maintaining altitude, the airplane is yawing *and pitching*. In the extreme case of a 90° banked turn, the airplane is only pitching. But in a normal gliding or climbing turn, the airplane is yawing, pitching and *rolling*.

In a gliding turn, the airplane rolls inward, which causes the inside wing to have the larger angle of attack. Similarly, in a climbing turn, the airplane rolls outward which causes the outside wing to have the larger angle of attack.

Here's another way to look at it. During the descending turn, the inside wing is turning on a smaller radius, which means that it is descending in a steeper spiral than the outside wing. The air, therefore, must "rise" to meet the inside wing at a larger angle (of attack) than it does the outside wing. Similar logic explains why the outside wing has a larger angle of attack during climbing turns.

When an airplane is made to stall while turning *and* maintaining altitude, the bank angle should not change one way or the other. The exception occurs when one wing stalls before the other because both wings are not physically symmetrical.

The effect that wind has on turning flight while performing ground track maneuvers is not always appreciated. (Remember, flying a rectangular traffic pattern is a ground track maneuver.)

For example, assume that a pilot is attempting to fly a perfect circle around a pylon. Unfortunately, a strong northerly wind is doing its best to foil the pilot's plans. To fly a perfect circle during such a condition, bank angle must be varied during the 360° turn. At what part of the circle should the turn be the steepest? Where should it be the shallowest?

Most pilots believe that the steepest bank angle is required at the southerly part of the circle to prevent the northerly wind from blowing the aircraft away from the circular ground track. Similarly, the logic continues, the shallowest bank angle is needed on the northerly side to prevent drifting into the circle. This sounds logical, but is wrong.

Figure 1 shows a 100-knot airplane flying counter-clockwise about a pylon; a 20-knot breeze is blowing from the north. During no-wind conditions, a constant 40° banked turn would result in a circle with a radius of 1,058 feet. But because of the northerly wind, in this case, the bank angle must vary as shown in the diagram.

Notice that the steepest bank is required when flying downwind along the western edge of the circle, not at the southern edge. This is because *the steepest bank is required when groundspeed is at a maximum*. The airplane is flying so rapidly that the rate of turn must be increased to remain on track.

Similarly, the shallowest bank is required when flying upwind on the eastern side of the circle, not when flying crosswind at the northern edge. Groundspeed here is at a minimum. The airplane is flying so slowly that more time is available to turn a given number of degrees. Hence, a shallow bank angle is required.

The same logic applies when flying the traffic pattern. Notice in Figure 2 that, because of a northerly wind, the turn from downwind to base leg results in the fastest groundspeed and therefore requires the steepest bank angle (assuming that airspeed is held constant around the pattern). Similarly, turning onto the crosswind leg (after takeoff) results in the slowest groundspeed and suggests a shallower bank angle.

As we have seen, there are numerous circumstances that call for executing steeper-than-anticipated turns while at low altitude. And unless a pilot is very adept at such maneuvering *and* has a sufficiently powerful engine, such turning can be foolhardy indeed.

It is doubtful that there lives a pilot who hasn't lost altitude inadvertently while practicing steep turns. At altitude, this is not a serious problem. But when near the ground, there may not be sufficient time to apply the proper corrections.

Instructors teach three basic ways to arrest an undesirable sink rate when in a steep turn. One way is to raise the nose; another is to add power. If neither of these corrections is adequate, the third alternative is to decrease the bank angle and raise the nose or roll out of the turn entirely.

Unfortunately, rolling out of a turn to arrest an increasing sink rate usually is regarded as a sign of failure, an inability to control the aircraft. But when operating an airplane at the limits of its performance capability, rolling out of a steep turn may be the only *safe* way to maintain a healthy reserve of airspeed and power. If a steep turn gets out of hand, it is far wiser to recognize the limitations of plane and pilot than to horse back on the yoke and risk stalling or creating enough of a G-load to warp a wing. Rolling out of an undesirable situation is a safe, professional technique that allows the maneuver to be repeated at the pilot's leisure; stalling at low altitude can be terminal.

But since prevention is preferable to cure, learn to recognize and avoid situations that induce an apparent need to turn sharply. □