Breaking the Stall: System Dynamics Unveils Hidden Traps in Aviation Safety

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Abstract

Since the dawn of human flight, pilots have faced the often-fatal danger of stalls. Despite decades of research and advancements in engineering, safety systems, operational policies, and crew training, stalls remain a leading cause of fatal airline disasters. This paper introduces a System Dynamics model to bridge the gap between well-intended designs and real-life performance, capturing the complexities of pilot behavior in airplane cockpits. The model reveals an instability in the pilot-airplane system, explaining why pilots can inadvertently fall into the stall "error trap" and make erroneous inputs during recovery attempts. Additionally, the paper discusses pilot psychology during stalls, highlighting how human nature drives pilots into these error traps, causing them to ignore their training and the systems designed to protect them. The findings underscore the need for a major transformation in the airline industry's stall prevention strategy, which is projected to address the core challenges pilots face in stall situations effectively.

Introduction

Since the dawn of human flight over a century ago, pilots have been acutely aware of the often-fatal danger posed by a condition known as 'stall'. In an ongoing effort to enhance safety, the aerospace industry has dedicated decades to researching the causes and human factors involved in aircraft accidents, particularly stalls. This extensive research has led to improvements in engineering designs, the addition of safety systems, the implementation of operational policies, and the enhancement of crew training, all aimed at helping pilots avoid and recover from stalls. Despite these efforts, stalls remain one of the leading causes of fatal airline disasters, with numerous documented cases where pilots, contrary to their training and the multiple layers of protective policies and safety systems, made erroneous control inputs during a stall. For the industry, what looks good on paper does not translate into real-life scenarios.

To bridge the gap between well-intended designs and real-life performance leading to disasters, this paper introduces the practical application of System Dynamics to model the complexities of pilot behavior in airplane cockpits. This approach highlights the intricate psycho-technical challenges between humans and machines to reveal an instability in the pilot-airplane system. The identified system instability explains why pilots can inadvertently fall into the stall "error trap" and why the industry's efforts to save the pilot from disaster have been ineffective.

Finally, this paper describes the events leading up to a major transformation in the airline industry's stall prevention strategy and how it is projected to finally address the core challenges pilots face in stall.

Problem Statement

Over the 120+ years humans have been flying, the rate of accidents has steadily decreased to the point airline travel is now the safest mode of transportation. [1] In just the past 50 years, the fatal accident rate per each 1 million departures has decreased by 93%! [2] This remarkable improvement can be attributed to the aerospace industry's early adoption of systems thinking methodology to drastically improve the performance, efficiency, and efficacy of not only the aircraft, but also the other supporting programs in the airline industry's system-of-systems. Comprehensive and efficient airframe maintenance programs have been developed to ensure aircraft are operating at peak performance. A robust pilot training system is continuously updating the methods and tools used to produce qualified pilots. Enhancements have been made to the various operations systems, such as air traffic control, weather prediction services, and airline operators. But the most important feature in all these various aviation improvements is the steadfast focus on the industry's highest overall priority: safety. An important feedback loop in this effort is thorough analysis and publication of all airplane accidents, conducted by government agencies, such as the National Transportation Safety Board (NTSB) in the U.S. [1] We learn from our mistakes.

A heavy focus of aircraft safety efforts is human error, broadly and generally accepted across the industry to be attributing to 60% - 80% of all accidents, at least in some part. [3] In the Air Transport category, representing the major airlines, 41% - 65% of airline fatalities are attributed to a broad category encompassing when the pilot, flying with good intention, simply loses control of the airplane and crashes, called "Loss of Control Inflight", or "LOC-I". [4] [2] Numerous factors can lead to a pilot losing control of the aircraft, including winds, mechanical failures, weight & balance issues, icing on the airframe, and a condition called "stall", when an airplane wing suddenly stops producing lift. [5] As elemental as wing lift is to the proper operation of an airplane, the lack of lift, or stall, is estimated to be responsible for 43% of all airline LOC-I fatalities. [4] Unfortunately, in 46% of these stall fatalities, despite the industry's most rigorous safety systems, pilot training, and federal oversight, *the crew responded inappropriately*, making their situations worse. [4]

In 2022, a study of all U.S. commercial airplane stall accidents in the NTSB database, conducted by Oklahoma State University, found despite the improvements in aircraft, stall safety systems, and pilot training since 1964, the fatality rate of stall accidents has *increased* [6]. Figure 1 plots the stall fatality rate from 1964 through 2014 and shows pilots who find themselves in a stall in 2014 are approximately 66% more likely to suffer a fatality than pilots who stalled in 1964.

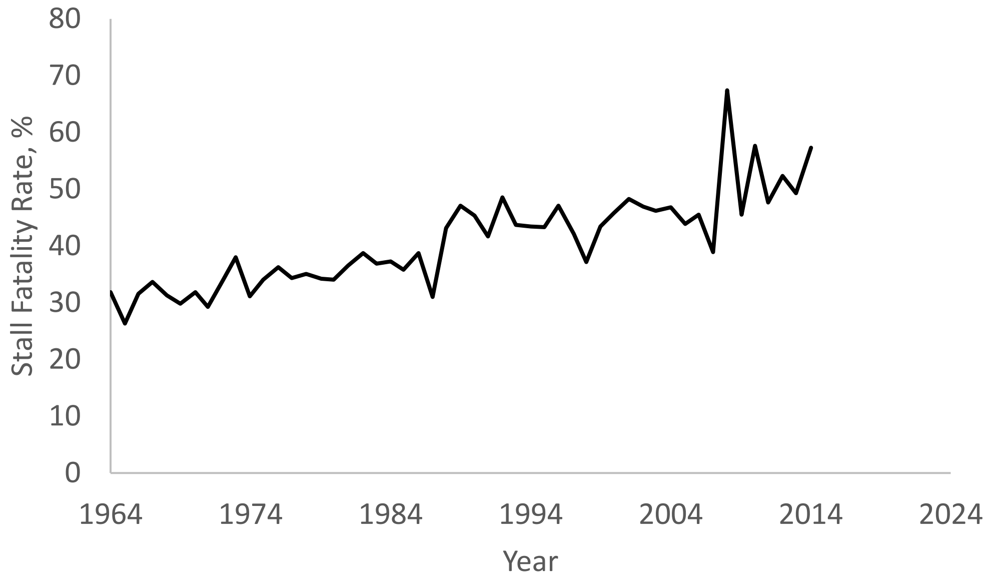

Figure 1: U.S. Commercial Aircraft Stall-Type Accident Fatality Rate, 1964 through 2014. (Copied directly from Reference [6])

For reasons explained later in this paper, it should also be noted the second leading cause of airline fatalities, 20%, is attributable to "Controlled Flight Into Terrain" (CFIT) [4], described as when the aircraft, in full control of the pilot, strikes the ground, mountain, or other obstacle.

Stall: When Airplanes Stop Flying

The cross section of airplane wings has a specific and highly engineered shape, called an airfoil, allowing it to generate lift when air flows over the surface. The amount of lift the airfoil, and therefore the wing, can produce is directly correlated to the angle at which the air impacts the surface, called "angle of attack". The higher the angle of attack, the higher the lift the wing generates until a critical angle is exceeded at which point the air flow suddenly separates from the wing resulting in a drastic and abrupt reduction in lift. [7] This sudden loss of lift is commonly called 'stall' and manifests as the airplane being unable to support its own weight falling towards the ground due to gravity.

At all costs, pilots should avoid stalling the airplane and must therefore prioritize maintaining the wing's angle of attack below the critical stall angle. However, the wing's angle of attack is invisible to humans and although a small number of airplanes can measure Angle of Attack (AOA) and display it in the cockpit, most do not. Regardless, pilots are trained to use a more easily observable state, airspeed, V, as a surrogate to angle of attack, α, using the following relationship between the two:

$$V = \sqrt{\frac{2W}{\rho S C_{L_\alpha} \alpha \cos\varphi}} \quad \text{(Eq. 1)}$$

Where:

V	airspeed, in ft/sec
W	weight of the airplane, in pounds
ρ	air density, in $slugs/ft^3$. Function of altitude and temperature.
S	wing area, in ft^2 (constant)
$C_{L_\propto}$	dimensionless derivative. Derived from experimental data and a function of airplane flap configuration.
$\propto$	angle of attack, in radians. This is the inclination angle at which the wing meets the air.
φ	angle of bank, in degrees or radians (left-right tilt of the wings controlled by the pilot)

The derivation of this equation can be found in Appendix A. From this point forward, this paper presents the pilot's perspective to stall by using airspeed, even though, angle of attack is a more direct and precise indicator to wing lift and stall. As can be seen from Equation 1, airspeed and angle of attack are inversely correlated: for a given airplane weight in trimmed flight, as angle of attack increases, velocity must decrease. As such, instead of ensuring angle of attack remains *below* the critical point, pilots manage their airspeed to keep it *above* the equivalent critical speed.

A pilot's challenge dealing with stall is as old as airplanes themselves. Even before the Wright brothers' famous first powered flight in 1903, several inventors experimented with human flight using unpowered gliders. One of the most well-known inventors in this field was Otto Lilienthal in Germany, personally piloting 16 different homebuilt glider designs in nearly 2,000 flights, jumping from hills and towers (see Figure 2). Not only is Otto known for his guilders, but unfortunately, he is also famous for being one of the first documented stall fatalities. On August 9, 1896, the speed of Otto's glider dipped below the stall speed, the wing lost lift, and Otto plunged 15 meters to his death. [8]

Figure 2: Otto Lilienthal Flying His Glider, 1893 [9]

Seven years after Otto's death, the Wright brothers successfully completed the world's first powered flight on December 17, 1903. Technically, this historic flight recorded in history books was the Wright brother's *second* attempt, the first being three days prior, on December 14, which ended in a crash. In Orville Wright's own words describing his brother Wilber's first attempt:

"…[the aircraft] was allowed to turn up too much. It climbed a few feet, stalled, and then settled to the ground…" [10]

Mankind's first attempt at powered flight only lasted 3 ½ seconds when Wilbur, immediately after leaving the ground, pitched up too aggressively, pushing the angle of attack past criticality, and causing the wing to stall. Luckily, Wilbur survived, unlike Otto.

System Dynamics of Flying

To help understand the complexities of human flight, a system dynamics model of a pilot flying an airplane is presented in Figure 3. The two main structures on the right side of the model represent the altitude and airspeed stocks for the airplane. The altitude stock stores the potential energy of the airplane and is filled by the wings producing lift in the up direction. Intuitively, it also follows the airplane must fight Earth's gravity, in the form of its own weight, draining the altitude stock. For an airplane trimmed for level flight, the wing lift equals the weight, and altitude is maintained at a constant value. The airspeed stock is the system's kinetic energy and is filled by the engines accelerating the airplane overcoming the drain of the air pressure drag.

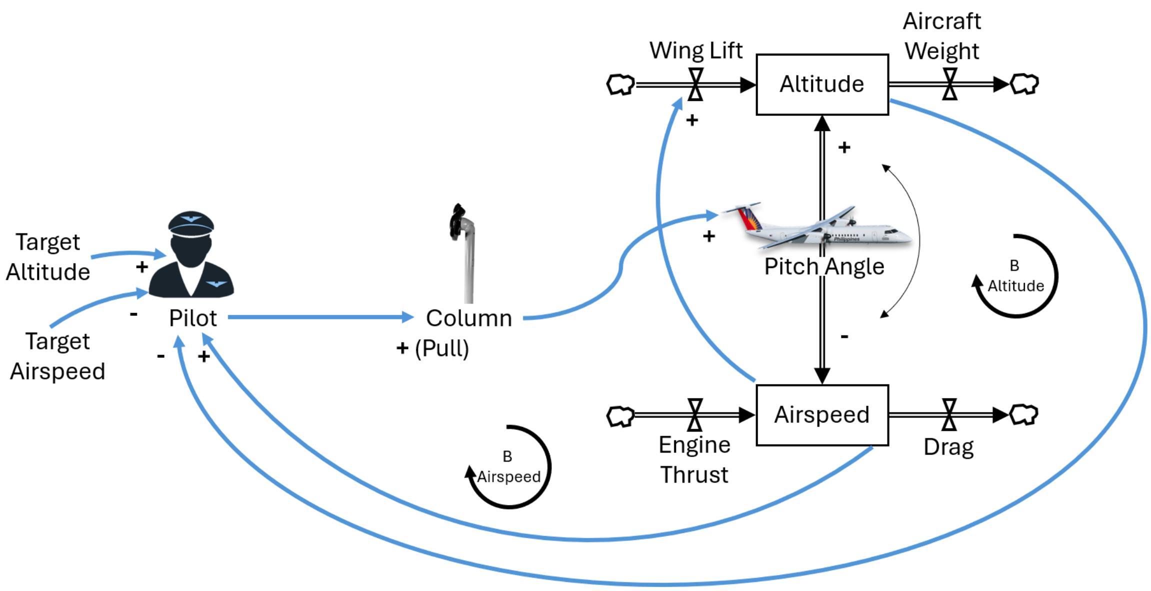

Figure 3: System Dynamics Model of a Human Flying an Airplane

Airplanes can also flow kinetic energy from the airspeed stock into potential energy in the altitude stock, and vice versa, depending on the pitch angle, or the physical up/down direction the nose is pointed. The airplane's pitch angle is manipulated by a small aerodynamic surface on the tail, called an elevator, controlled by the pilot making inputs to the column (also called a 'stick' or 'yoke') in the cockpit, as depicted in Figure 3. The pilot pushes or pulls on the column, changing the airplane's pitch angle, to control the direction and rate of energy flow between airspeed and altitude. The pilot makes these inputs to the column based on the airspeed and altitude levels displayed on flight instruments in the cockpit, thus closing the two respective balance loops.

For example, to increase altitude, the pilot pulls aft on the column, pitching the nose of the airplane up to flow kinetic energy from the airspeed stock. Conversely, if the pilot pushes the column forward to pitch the airplane nose down, potential energy is flowing from the altitude stock to increase airspeed. If needed, overall energy in the system is added or subtracted by changing the power from the engines (if it has engines!). Pilots spend their entire careers practicing and perfecting their skills in airplane "energy management." [11]

For airplanes, aside from being on the ground, the safest state is a full altitude stock. Having altitude allows the airplane to not only clear obstacles, but it is also the store of potential energy, a precious resource to convert to kinetic energy for maneuvering, as needed. Without it, the airplane loses the ability to build speed or maneuver away from collisions with the ground or mountains. As such, for pilots, maintaining a stock of altitude is an instinctive self-preservation mode and takes priority over airspeed. Mismanaging the level of the altitude stock leads to the second leading cause of air transport accidents, Controlled Flight Into Terrain (CFIT) [4].

The last remaining loop of the model in Figure 3 is a connection between the airspeed stock and wing lift, creating a problem for pilots of competing priorities. This loop represents Equation 1 above serving as a surrogate to the invisible angle of attack. When the airspeed stock drops below a critical threshold, the wing stalls, lift ceases, and the altitude stock rapidly drains due to gravity. Even energy transferred from the airspeed stock is not enough to prevent the airplane from falling from the sky. When stalls occur, the structure of the system dynamics model changes significantly, as presented in Figure 4.

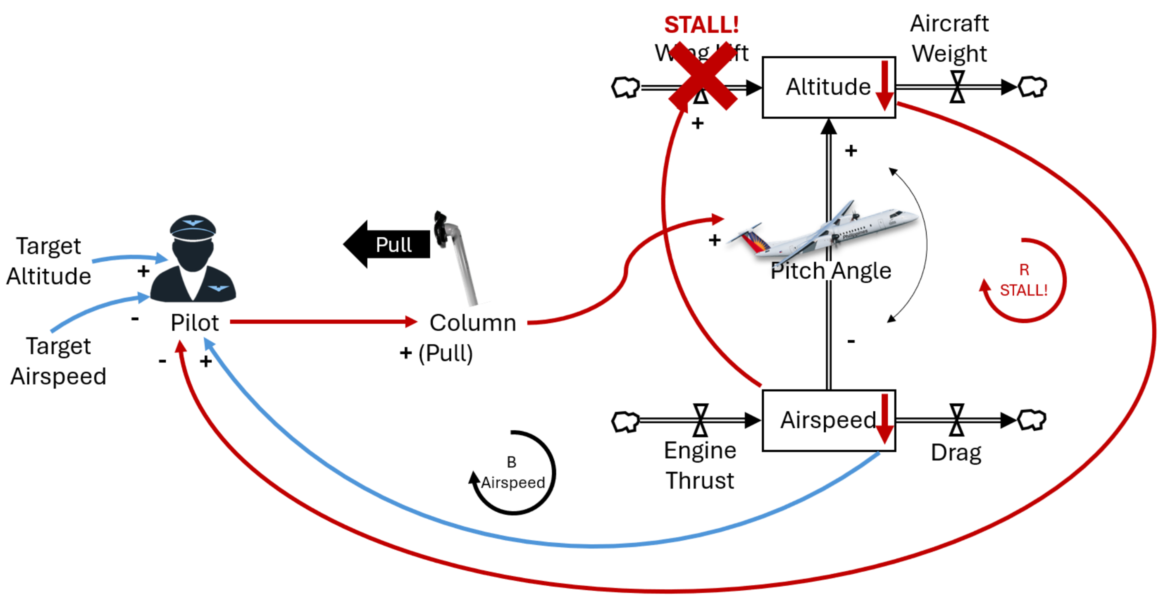

Figure 4: System Dynamics Model of an Airplane in Stall

The altitude feedback loop flips from a stable balance loop to an unstable reinforcing loop, as shown as red in Figure 4. Observing a fall in altitude activates the pilot's natural tendency, encoded in their "energy management" muscle memory, to pull aft on the column to recover in self-preservation. This reflex can be exaggerated when flying close to the ground where the pilot can see the ground and trees rushing up through the windscreen. But unlike in normal flight, pulling the column in a stall makes the situation worse and further decreases altitude, opposite to what the pilot is expecting. In any other emergency, the pilot's self-preservation tendency is to check and preserve their altitude stock, but when in a stall, attempting to use column to maintain altitude will result in a crash, usually fatal.

The Pilot Trap

Although a fundamentally well understood characteristic of airplane aerodynamics, stalls continue to be especially dangerous and a leading cause of fatal aircraft accidents [4]. The first reason is because stalls often catch pilots by surprise because "when" it will happen is difficult to predict. Below is Equation 1 rewritten for the critical point at which the wing stalls, $\propto_{Stall}$:

$$V_{Stall} = \sqrt{\frac{2W}{\rho S C_{L_\alpha} \alpha_{Stall} \cos\varphi}} \quad \text{(Eq. 2)}$$

Just by observing the structure of the equation, the airplane's stall speed is difficult for any human pilot to solve in real-time, especially since every variable in the equation, except for wing area, *S*, changes with time or flight condition. Furthermore, the nonlinear structure of the stall speed equation makes it difficult to predict how it changes with time. As Dietrich Dorner, a professor of Psychology at the University of Bamberg, states in his book, *The Logic of Failure*, when dealing with complex systems, people think in linear sequences [12]. In other words, human nature will cause pilots to make linear assumptions about the changes of a very nonlinear sequence.

The second reason stalls are so problematic for pilots is because the altitude feedback suddenly switches from a stable balanced to an unstable reinforcing loop. Pilots spend their entire flying careers using airspeed and altitude balance loops to perfect their energy management skills to the point where they become automatic in nature. Because it is a pattern they have seen thousands of times before, a pilot will see a drop in altitude and instinctively pull on the column to correct it. However, in the case of a stall, the pilot's natural tendency to pull on the column to arrest the decrease in altitude will make the problem worse, as illustrated in Figure 4. Reference [3] refers to this as a skill-based, or "doing" error because the pilot will react automatically without thinking. It goes on to say, "…these highly practiced and seemingly automatic behaviors…are particularly susceptible to attention and/or memory failures." [3]

Finally, recovery from stalls is a relatively simple action but difficult to execute. To restore lift on the wing, the airspeed must be increased back above the stall speed requiring the pilot to fight their natural altitude preservation reflex and instead do the opposite by nosing the airplane down. If the airplane is already falling towards the Earth due to a lack of lift, intentionally pointing the airplane towards their likely demise can be psychologically difficult for pilots. For these reasons, stalls can be thought of as an "error trap" because they are easy for pilots to fall into and difficult to escape.

Stall Avoidance Strategy

The stall error trap is so silent and lethal, by the 1940's it was the cause of more than half of all aviation fatalities in the U.S [13]. Since the beginning of human flight, the aviation industry has embraced a stall avoidance strategy, leveraging policies, training programs, and technology to prevent pilots from falling into the trap.

The first defense against stall is to provide the pilot with recommendations on the safe airspeeds to use without fear of stalling. When an airplane is first certified by the manufacturer, it is rigorously tested throughout its entire operating envelope, to characterize all its performance, edges of maneuverability, and various stall speeds in Equation 2. From this data, recommended reference speeds, called "V Speeds" are prescribed and published in the airplane's Operating Handbook [14] to keep the pilot well within the performance envelop of the airplane and away from stall.

In 1944, the inventor Leonard Greene submitted a patent application for a stall-warning device. This invention, as lauded by the *Saturday Evening Post* in 1947, was viewed as "…the greatest life saver since invention of the parachute." [13]. Stall warning systems, now common on all airplanes today, use sensors to monitor the airflow over the wings and alert the pilot with a warning light and audible horn of an impending stall. Once notified of an imminent stall, the pilot is expected to make the appropriate control inputs to maneuver the aircraft towards safer conditions, namely push the column forward to lower the nose pitch angle and increase the level of the airspeed stock.

To further emphasize the warnings of impending stall and strengthen the call for immediate pilot action, airplanes may also activate a system called a "Stick Shaker" to physically shake the pilot. Comprised of an electric motor attached to the column spinning an unbalanced weight, the resulting vibrations felt by the pilot should be impossible to ignore [15]. Again, the unmissable physical shaking of the pilot is a signal to push the column forward to increase the airspeed stock.

The final action from the stall warning system is direct intervention. In the event a pilot ignores the warning lights, horn, and shaking, a system called a "Stick Pusher" uses a pneumatic ram to physically move the column forward. This system is designed to physically guide the pilot to push the column forward to increase the airspeed stock.

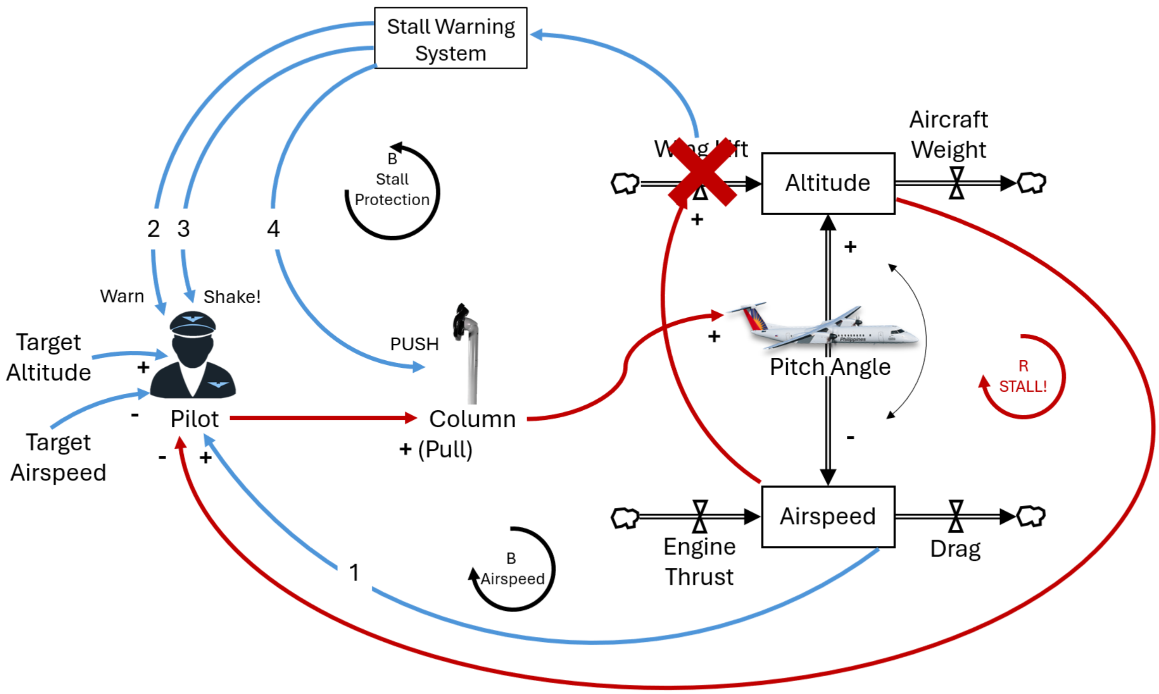

Figure 5: System Dynamics of the Airplane Stall Warning System

The Industry Standard in Stall Protection

To maximize the likelihood pilots can recognize, avoid, and prevent stalls, the airline industry does not rely on just one method, but has instead adopted James Reason's "Swiss Cheese" model of employing multiple layers of barriers against human error. [16] In this analogy, the holes in the slices of cheese are random in size and placement. If something passes through a random hole in the first slice of cheese, the holes in the subsequent slices are unlikely to line up and will block it. Likewise, in the airline industry's stall avoidance strategy using multiple layers of safety policies, systems, and training programs, if one fails to block a pilot error, the likelihood is high the next layer will.

Policies and Safety Systems

Figure 5 shows the human-airplane system dynamics model, in a stall condition, with all the Stall Warning System modes engaged. Labeling the existing airspeed balance loop with 1 indicates the addition of the recommended reference speeds in the airplane operating procedures. The balance loops labeled 2 and 3 are the stall warning informational feedback loops to the pilot. Adding information loops, in the form of lights, horn, and physical shaking, are the easiest methods for intervening in a system [17]. The stick pusher loop, 4, is the final escalation loop from the stall warning system injecting direct action into the system. This model represents today's standard for stall protection in the airline industry, using four balance loops to overpower, or block, the one stall reinforcing loop.

Certifying Pilots for Stall Avoidance

To earn a crew position with an airline, pilots must undergo years of training, earning various certifications and gaining flight experience, measured in "flight hours." [18] In the U.S., the final step is earning the FAA's Airline Transport Pilot (ATP) certificate by passing the *Airline Transport Pilot and Aircraft Type Rating Practical Test Standards* [19]. This standard outlines the expected level of competency a pilot must demonstrate and one of the tests is "Approaches to Stall" where a pilot must properly execute a stall recovery maneuver after the activation of the stall warning system. In this test, a pilot is instructed to trim the aircraft in flight, slowly and deliberately add back pressure to the column, and decrease airspeed in a controlled manor until the first stall warnings are activated. The pilot is then instructed to gently release the back pressure on the column, increase airspeed, and recover back to trimmed flight. The pilot is evaluated and graded on how well they execute this maneuver within the acceptable flight parameters.

The airline industry's multi-prong approach to preventing stall disasters includes multiple layers of policies, safety systems, and pilot training. On paper, this plan appears to be robust. To legally operate in U.S. federal airspace as an airline, the airplanes, safety systems, and pilots must be rigorously tested against this plan.

The Industry Standard in Action

Case Study #1: Colgan Air Flight 3407

On February 12, 2009, Colgan Air Flight 3407, with 4 crew and 45 passengers, was flying from Newark, NJ to Buffalo, NY on a Bombardier Q400, a state-of-the-art airplane with a full Stall Warning System. During this otherwise routine flight, the pilots were distracted by ice accumulation on the front windscreen, lost situational awareness, and missed their recommended references speeds (Loop #1 of Figure 5) allowing the airspeed stock to drop. When the aircraft approached the stall speed, the Stall Warning System activated the cockpit warning lights, audible horn, and shaker (Loops 2 and 3). The intent of the signals was to remind the pilot he was flying too slowly and needed to immediately push the column forward. Unfortunately, the pilot, despite his training and FAA certification, did not respond appropriately and the airspeed continued to drop until the wing stalled and the airplane rapidly lost altitude. At this point, the Stall Warning System escalated its response, and the stick pusher rammed the column full forward (Loop #4) [20].

All four balance loops in Figure 5 activated prompting and guiding the pilot to push the column forward to increase airspeed. Given the direct intervention from the stick pusher ramming the column forward, the pilot, at this moment, could have simply relaxed his grip on the controls and allowed the Stall Warning System to begin the stall recovery. However, the pilot instead fixated on the falling altitude pulling on the collum trying to save it, the *opposite* of what was required to recover from the stall. The pilot ignored the stall warning lights, horn, shaking, and fought the pusher by pulling with a force of 160 lbs. (712 N). The pilot fell into the error trap of the stall reinforcing loop of Figure 5: the higher the altitude loss rate, the more the pilot pulled on the column, deepening the stall, and further increasing the altitude loss rate. A total of 50 people died, 49 outboard and 1 person on the ground when the airplane crashed into their home.

Case Study #2: Air France Flight 447

Air France Flight 447 on an Airbus A330 with a Stall Protection System, was flying from Rio de Janeiro, Brazile to Paris, France on June 1, 2009, with 228 passengers and crew on board. While cruising at 35,000 feet above the Atlantic Ocean, the aircraft flew through a storm cell, accumulated ice on external cockpit instrument sensors resulting in the autopilot system deactivating. As the pilots manually controlled the airplane while clearing the ice they inadvertently pitched the airplane nose up and initiated a stall. The stall warning system activated as designed prompting the pilot to push the control stick forward to increase airspeed. However, the pilot instead did the opposite pulling the stick aft to recover altitude but deepening the stall. The pilot fought the stall warning system for four minutes as the airplane fell 35,000 feet into the ocean. There were no survivors [21].

Case Study #3: AirAsia Flight 8501

AirAsia Flight 8501 departed Surabaya, Indonesia on December 28, 2014. The Airbus A320 carrying 162 passengers and crew was over the ocean on its way to Singapore when an amber caution message appeared on the main display in the cockpit. A minor issue, more of a nuisance, the pilots' focus shifted to clearing the message by resetting flight computers causing autopilot disengagement. While manually controlling the airplane, the pilots inadvertently pitched the nose up too high, lost airspeed, and tipped the airplane into stall. The stall warning system activated alerting the crew to push the stick forward to lower the nose and increase airspeed. Instead, the pilot did the exact opposite and immediately pulled the stick full aft and held it continuously, chasing the falling altitude until the aircraft impacted the sea. There were no survivors [22].

A single accident of this type could be dismissed as an outlier or simply cast into the ambiguous catch-all category of "pilot error." However, as shown in these three cases alone, the repeating behavioral pattern of the human doing the opposite of expected points to a more systemic flaw in the system. As mentioned above, these three case studies are part of the 46% of stall fatalities where the crew responded inappropriately making the situation worse. [4] In all three examples provided, there were no failures in the aircraft significant enough to cause a crash and each stall warning system did exactly as it was designed to do. But when the human pilot, also fully certified, is inserted as part of the loop, the overall system can become unstable.

The Fix Required an Act of Congress

The public outcry from the Colgan Air crash was so pronounced it prompted the U.S. Congress to pass the *Airline Safety and Federal Aviation Administration (FAA) Extension Act of 2010*. The result of this bill expanded the powers of the FAA and increased requirements for pilots, including [23]:

- Increasing the flight experience required to obtain an Airline Transport Pilot certificate from 250 hours to 1,500 hours
- Directing the FAA to update and implement new flight and duty times for pilots to reduce the effects of fatigue
- Requiring the FAA to ensure pilots are trained *how* to recover from a stall.

The final requirement was called *Upset Prevention and Recovery Training*, or *UPRT* and in 2012, the FAA issued an Advisory Circular recommending how pilots should be trained to recognize and recover stalls with the final rule released at the end of 2013. As mentioned earlier, prior to this rule change, the FAA's airline transport pilot practical test standards for the Approach to Stall competency check were briefed beforehand, controlled, predictable, and stable [24]. Furthermore, pilots were trained and tested on recovering the aircraft at the first warning of the *impending stall*, not from the stall itself. As such, in each of the case studies presented above, this competency did not translate to real-life practice where disaster occurred because the pilots were in an unstable flight condition, distracted by other unexpected events, and startled by the sudden occurrence of the stall, thus triggering their self-preservation reflex, inappropriate for stall recovery. UPRT training is different to legacy stall training by introducing a *scenario based training* methodology, exposing the pilot to more likely real-world elements, such as distraction, surprise, startle, and upset conditions. [25]

As should be expected, training stall recovery and other emergencies in the airplane is dangerous and impractical. The UPRT guidance incorporates high-fidelity and FAA approved flight simulators, see Figure 6 for an example. Beginning in late 2013, airline pilot training programs were directed to update their instructional material and retool their flight simulators to incorporate UPRT, to be completed by 2019 [26].

Figure 6: Airbus A320 Full Flight Simulator [27]

The practice of UPRT for pilots involves a mix of classroom, in-aircraft, and flight simulator training with a focus on proper recognition and recovery. In the safety of a ground-based flight simulator, pilots can learn to resist the self-preservation reflex to chase altitude and instead develop the muscle memory to follow airspeed and the stall warning loops [28]. This new approach directly confronting and then learning to overcome stalls effectively reduces the strength of the self-preservation reinforcing loop of Figure 5 so the balance loops can prevail.

As a reference, the U.S. stall-type fatality plot in Figure 1 is reprinted below in Figure 7 but with the remaining available years in the study included, namely the years after the introduction of UPRT in 2014.

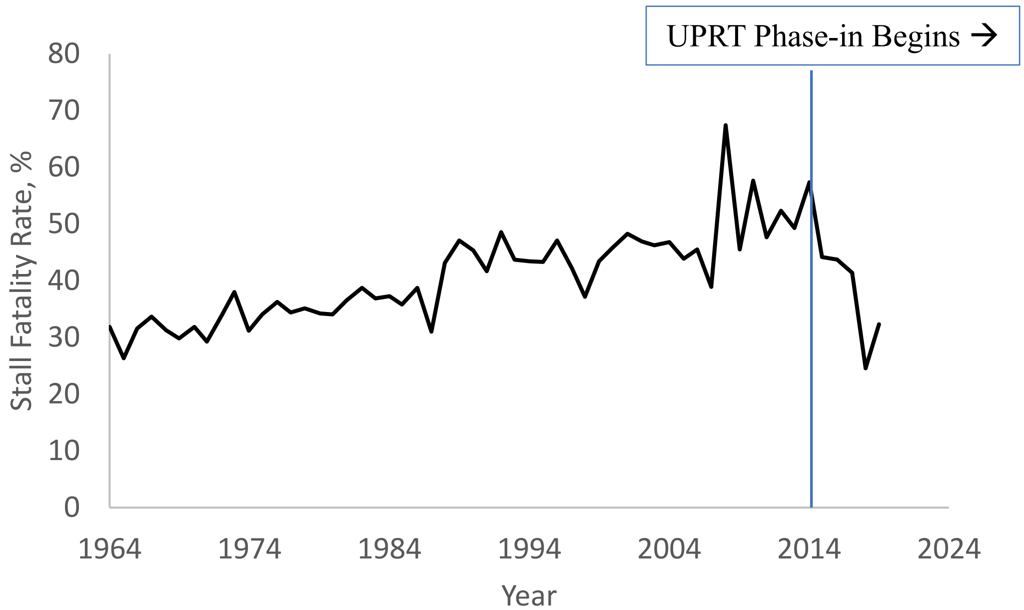

Figure 7: U.S. Commercial Aircraft Stall-Type Accident Fatality Rate, 1964 through 2020. (Copied directly from Reference [6])

The reader should be cautious assuming correlation means causation, but the reversal of the stall-type fatality rate trend since the introduction of UPRT in Figure 7 is notable.

Conclusion

This paper presented an application of system dynamics to model the complexities of humans piloting airplanes, both in and out of stalls. By using system dynamics, the unstable stall reinforcing loop is exposed explaining why it is easy for pilots to fall into the error trap. The aviation industry's policy of adding progressive safety systems to aircraft, as balance loops, to "cover up" the unstable reinforcing loop is shown to be ineffective, as observed in multiple real-life disasters. The new U.S. law passed in 2010 directing a new training standard for pilots, called UPRT, shifts the focus from covering up the instability to instead reduce the gain, or power, of the reinforcing loop by decreasing the pilot's self-preservation reflex.

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Appendix A: Solving the Airplane's Stall Speed

The airplane lift equation can be expressed as follows [29]:

$$L = \frac{1}{2}\rho V^2 S C_L$$

Where:

L	total airplane upward lift force, in pounds.
ρ	air density, in $slugs/ft^3$. Function of altitude and temperature.
V	Airspeed, in ft/sec
S	wing area, in ft^2 (constant)
C_L	lift coefficient, dimensionless. Function of *angle of attack*, α, and airplane configuration

The amount of lift generated by the wing, as represented by the dimensionless coefficient, C_L, is a function of its inclination angle relative to the flow of air. The relationship between lift and inclination angle, also called "angle of attack", α, is best described by the NASA Glenn Research Center in Figure 8.

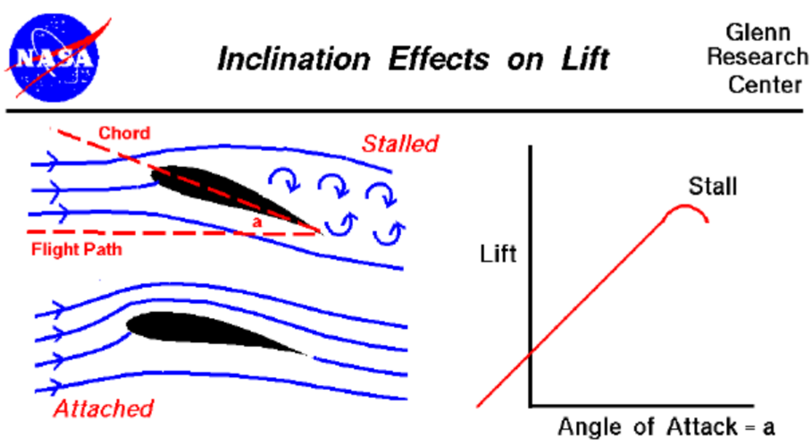

Figure 8: Inclination Effects on Lift (Copied Directly from Reference [30])

Within a limited range, the relationship between lift and angle of attack is linear with a slope commonly expressed by the dimensionless derivative, C_{L_α}. The lift coefficient term, from the above airplane lift equation, can now be rewritten as follows:

$$C_L = C_{L_\propto} \propto$$

Where:

$C_{L_\propto}$	dimensionless derivative. Derived from experimental data and a function of airplane flap configuration. This term is largely constant before the wing stalls, then decreases significantly and nonlinearly as the angle of attack continues to increase.

$\propto$ angle of attack, in degrees or radians. This is the inclination angle at which the wing meets the air.

Figure 8 also illustrates what happens when the angle of attack is increased past criticality causing the airflow to abruptly separate from the wing. This phase is called Stall and increasing the angle of attack beyond this point results in a sharp decrease in lift. This critical angle of attack at which stall occurs is $\propto_{Stall}$ and is derived experimentally from extensive testing of the airplane.

With the natural assumption wings produce lift, L, to support the weight, W, of the airplane, even when banked in a turn, φ, the relationship between the three can be expressed as [31]:

$$L = \frac{W}{\cos\varphi}$$

Where:

W weight of the airplane, in pounds

φ angle of bank, in degrees or radians

Substituting back into the lift equation, the airplane's stall speed can be solved as follows:

$$V_{Stall} = \sqrt{\frac{2W}{\rho S C_{L_\alpha} \alpha_{Stall} \cos\varphi}}$$