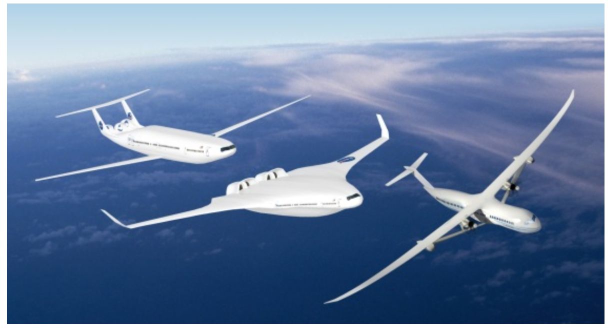
Avoiding Pilot-Induced Oscillations in Energy-Efficient Aircraft Designs

The aviation industry is vital to global economic well-being. In the U.S. alone, civil aviation provides more than one million jobs, a trade value of more than $75 billion, and a total contribution to the economy of almost $300 billion. Nevertheless, the aviation industry also has a negative impact on the environment and energy usage. In the U.S., air travel fuel use is 7% of fuel consumed for transportation, and jet fuel produces 65 million metric tons of CO_2 per year, or 4% of CO_2 emissions from energy usage nationwide.

To improve fuel efficiency and reduce environmental impact in the aviation sector, a variety of next-generation, energy-efficient aircraft design concepts are being explored. Many of these design concepts, however, rely on relaxed static or dynamic stability, which will likely lead to a resurgence in vehicle stability and control problems—particularly pilot-induced oscillation (PIO). Research in flight control of next-generation, energy-efficient aircraft to avoid PIO will be critical in enabling these new aircraft design concepts to operate safely in the future.



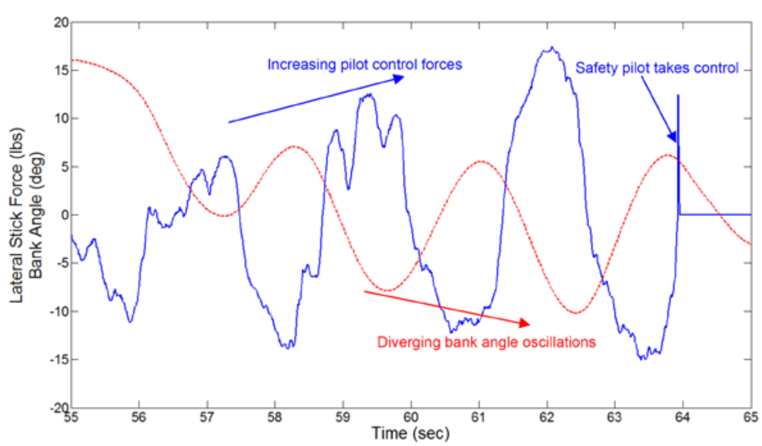
Aircraft design concepts for improved energy efficiency and environmental impact (Source: NASA)

Pilot-Induced Oscillation

A pilot-induced oscillation is a sustained or uncontrollable, inadvertent oscillation resulting from the pilot's efforts to control the aircraft. While PIOs can be easily identified during post-flight data analysis, often pilots do not know they are in a PIO—from their perspective the aircraft appears to have "broken."

When approaching instability, linear system performance degrades in a manner that is predictable to a pilot. As nonlinearities are introduced, however, gradual degradations can be replaced by sudden changes in aircraft behavior, resulting in the so-called "flying qualities cliff." With few warning signs provided by the aircraft as one approaches such a cliff, loss of control can easily occur. A common nonlinearity that is a major factor in PIO is control surface rate limiting. This phenomenon can introduce a delayed response. When the plane does not respond to the cockpit controls as expected, the pilot may move the controls more aggressively. The aircraft will ultimately overrespond, causing the pilot to reverse the control input and overreact again because of the delay. As this continues and develops fully into a PIO, the airplane response is essentially opposite of the pilot's command—for example, as the pilot commands a left bank, the airplane is in a right bank.

An example flight test PIO is shown at right. The pilot is attempting a precision landing with an aircraft response that is dominated by a rate-limited control surface response. The rate limit nonlinearity results in a PIO that increases with each cycle as the pilot attempts the final runway centerline capture. Note that the peak oscillation of the aircraft response (red) is opposite of the peak oscillation of the pilot command (blue) and that both are increasing in amplitude until the safety pilot takes control. (Source: STI)



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PIO Susceptibility of Energy-Efficient Aircraft Design Concepts

Pilot-induced oscillations have plagued aircraft since the beginning of aviation. Even the Wright brothers believed stability and control was their most difficult challenge, and analysis has shown that their aircraft was susceptible to PIOs. To avoid PIO tendencies, the commercial aviation industry has adopted common aircraft design conventions—for example, for the fuselage shape; wing and tail size, shape, and location; and propulsion unit location. These conventions result in highly stable aircraft that compromise energy efficiency.

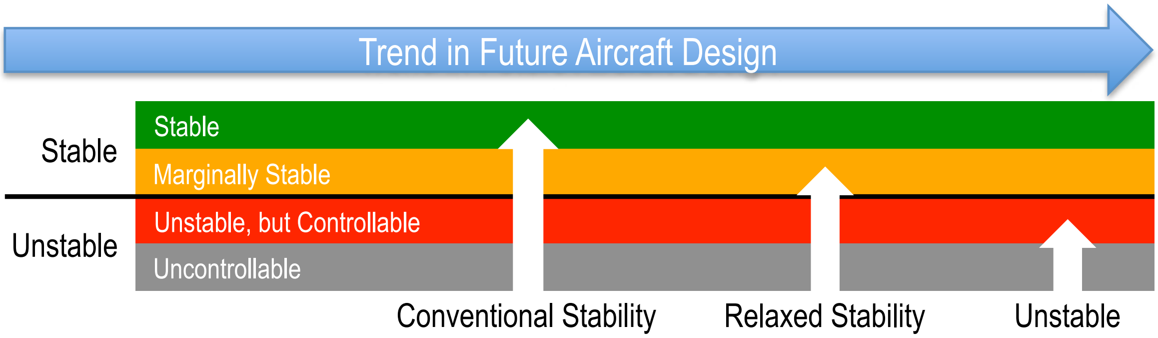
Future aircraft design concepts are beginning to deviate from many of today's common design conventions. Studies have identified relaxed static stability as a key technology for reducing fuel burn and cruise emissions. One design concept for a blended wing body (BWB) aircraft goes a step further with an unstable aircraft design augmented with closed-loop control to maintain stability, similar to modern fighter aircraft.

As the trend in aircraft design leads to marginally stable or unstable but controllable airframes, high levels of control power and feedback control augmentation are required to improve flying qualities and maintain closed-loop stability. In particular, best practices in PIO prevention recommend that an aircraft's actuation system exhibit sufficient rates and transient capability so as to avoid rate saturation of the surfaces. This poses a challenge for next-generation transport aircraft. For the BWB configuration, producing the power required to move the large control surfaces at a rate required for stability and control of the vehicle is technologically challenging.

Subject to traditional design practices, the strive toward energy efficiency and environmental compatibility in combination with the complexity of new designs will inevitably increase the susceptibility of future aircraft to PIO events. Technology is needed to mitigate the effects of PIO factors and allow aircraft to meet their potential in energy efficiency and environmental compatibility without abiding by constraining design practices.

Future Capabilities for PIO Avoidance and Recovery

- Sensors will need to measure data pertinent to PIOs.
- Using the data collected from the sensors, estimation methods will need to identify or predict the onset of unfavorable dynamics (i.e., the approaching flying qualities cliff).
- Control effectors will need to provide sufficient control power with a fast response while being lightweight, producing little drag, and not requiring significant actuator power.
- Pilot interfaces, including visual and aural displays and cockpit controls, will need to inform the pilot of the situation and recommend an appropriate course of action.
- Control laws will need to determine appropriate actions for the pilot or a safe-mode autopilot and/or compensation for the flight control system.
- Flight control computers will need to be fast enough to complete computations without introducing computational time delay.



Future commercial aircraft are expected to rely increasingly on relaxed stability and unstable designs to improve fuel economy and reduce environmental impact.