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NASA Dryden Flight Research Center

"Background and Principles of Throttles–Only Flight Control"

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Background and Principles of Throttles-Only Flight Control

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Abstract

There have been many cases in which the crew of a multi-engine airplane had to use engine thrust for emergency flight control. Such a procedure is very difficult, because the propulsive control forces are small, the engine response is slow, and airplane dynamics such as the phugoid and dutch roll are difficult to damp with thrust. In general, thrust increases are used to climb, thrust decreases to decend, and differential thrust is used to turn. Average speed is not significantly affected by changes in throttle setting. Pitch control is achieved because of pitching moments due to speed changes, from thrust offset, and from the vertical component of thrust. Roll control is achieved by using differential thrust to develop yaw, which, through the normal dihedral effect, causes a roll. Control power in pitch and roll tends to increase as speed decreases. Although speed is not controlled by the throttles, configuration changes are often available (lowering gear, flaps, moving center-of-gravity) to change the speed. The airplane basic stability is also a significant factor. Fuel slosh and gyroscopic moments are small influences on throttles-only control. The background and principles of Throttles-Only flight control are described in this paper.

Background and Introduction

The crew of a multi-engine aircraft with a major flight control system failure may use throttle manipulation for emergency flight path control. Differential throttle control generates yaw, which through dihedral effect, results in roll. Collective throttle inputs may be used to control pitch. Crews of DC-10, B-747, L-1011, and C-5A aircraft have used throttles for emergency flight control, ref 1.

To investigate the use of engine thrust for emergency flight control, the National Aeronautics and Space Administration's Dryden Flight Research Center (NASA Dryden) at Edwards, California, has been conducting a study including flight, ground simulator, and analytical studies. One objective is to determine the degree of control power available with engine thrust for various classes of airplanes. This objective has shown a surprising amount of control capability for most multi-engine airplanes, ref 2.

A second objective was to provide awareness of throttles-only control capability and suggested manual throttles-only control techniques for pilots. Dryden conducted simulation and flight studies of several airplanes, including the B-720, Lear 24, F-15, B-727, C-402, and B-747, refs 2&3. A third objective was to investigate possible augmented control modes that could be developed for future airplanes. An augmented control system that uses pilot flight path inputs and airplane sensor feedback parameters to provide appropriate throttle commands for emergency landings was developed. This augmented system was evaluated on a B-720 transport airplane simulation, ref 4, and a simulation of a conceptual megatransport, ref 5.

Recently, simulation studies and flight tests have been conducted to investigate the details of throttles-only control for the F-15 airplane, and to investigate the performance of a PCA (Propulsion Controlled Aircraft) augmented system. The PCA system was installed on the NASA F-15 research airplane. The objectives of the flight program were to demonstrate and evaluate PCA performance in up-and-away and landing approach flight, over the speed range from 150 to 190 knots at altitudes below 10,000 ft. There was also an option, if PCA performance was adequate, to attempt PCA landings.

The F-15 has since completed a 36 flight series of tests, including actual landings using PCA control. Recoveries from upset conditions including 90 deg bank at a 20 deg dive have also been flown. Altitudes to 38,000 ft and speeds up to 320 knots were flown. Six guest pilots have flown the PCA system.

The papers to follow present the principles of throttles-only flight control, flight tests of manual and augmented propulsion-only flight control for the F-15, the PCA design, development, and implementation, test techniques, and results, and pilot comments.

In this paper, the principles of throttles-only flight control are presented. These principles are rather simple but are not well-understood becuase the effects are so much smaller than normal flight control forces that they are often ignored.

Bank Angle Control

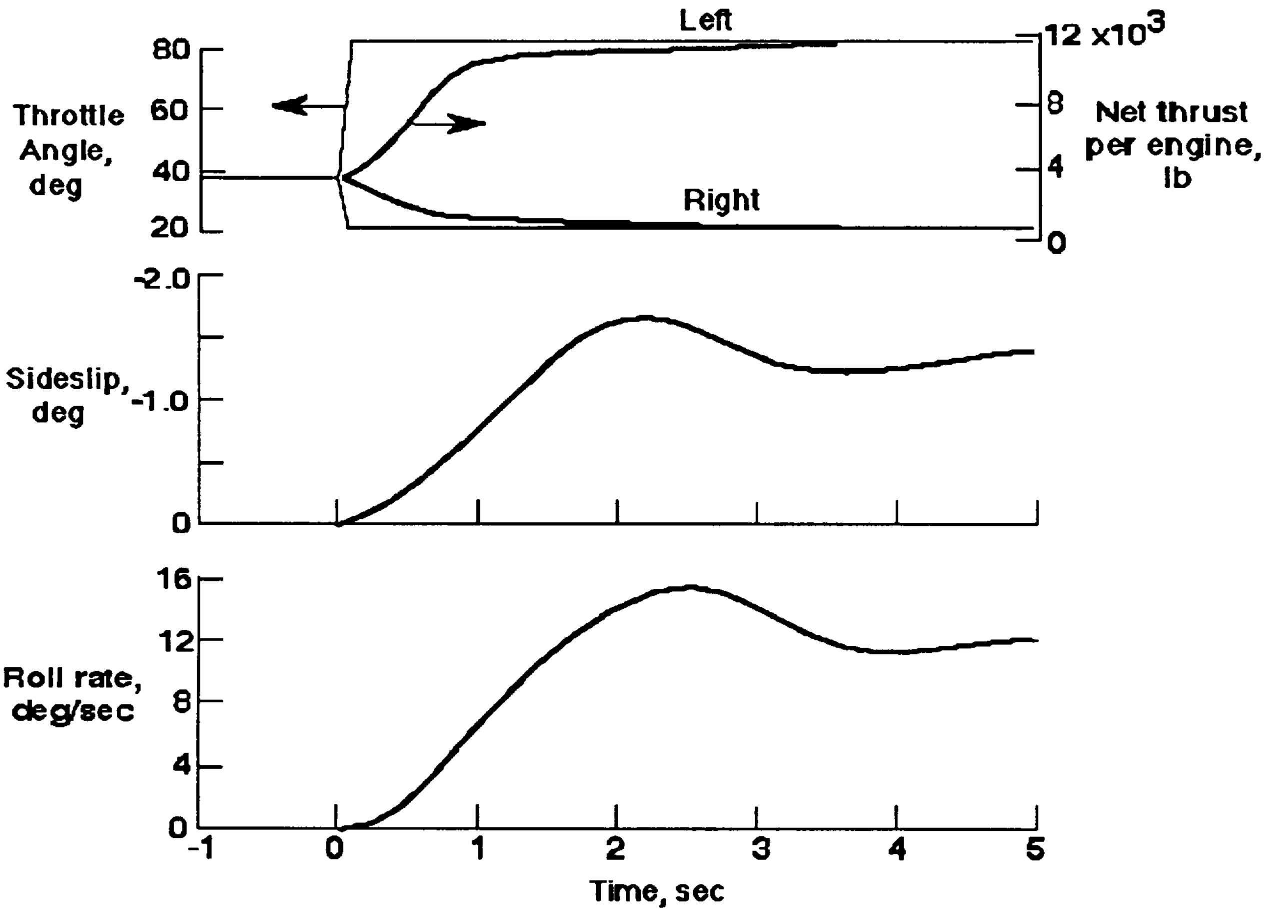
As shown below, bank angle is controlled by using differential thrust, which generates sideslip. The sideslip, through the dihedral effect present on the F-15 and most airplanes, results in roll rate. Roll rate is controlled to establish a bank angle which results in a turn and change in aircraft heading.

Full differential thrust for the F-15 yields a roll rate of about 15 deg/sec at a speed of 170 kts. Because bank angle is controlled by sideslip with throttles-only flight control, the turns are typically not properly coordinated.

Throttles-Only Roll Control

F-15, 170 knots

NASA 93-30

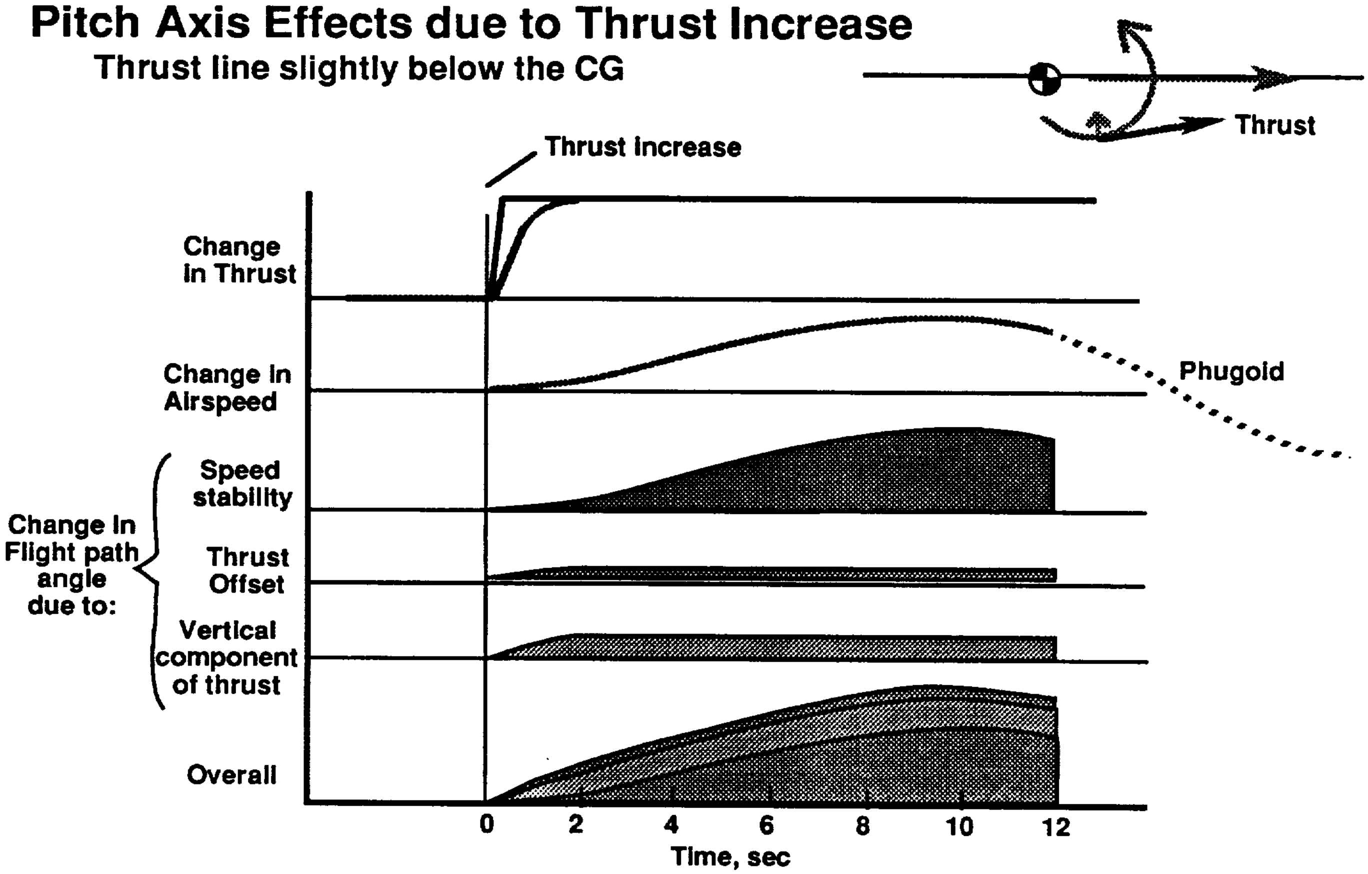


Principles of throttles-only control - Pitch axis

For pitch control due to throttle changes; several effects occur, as shown below.

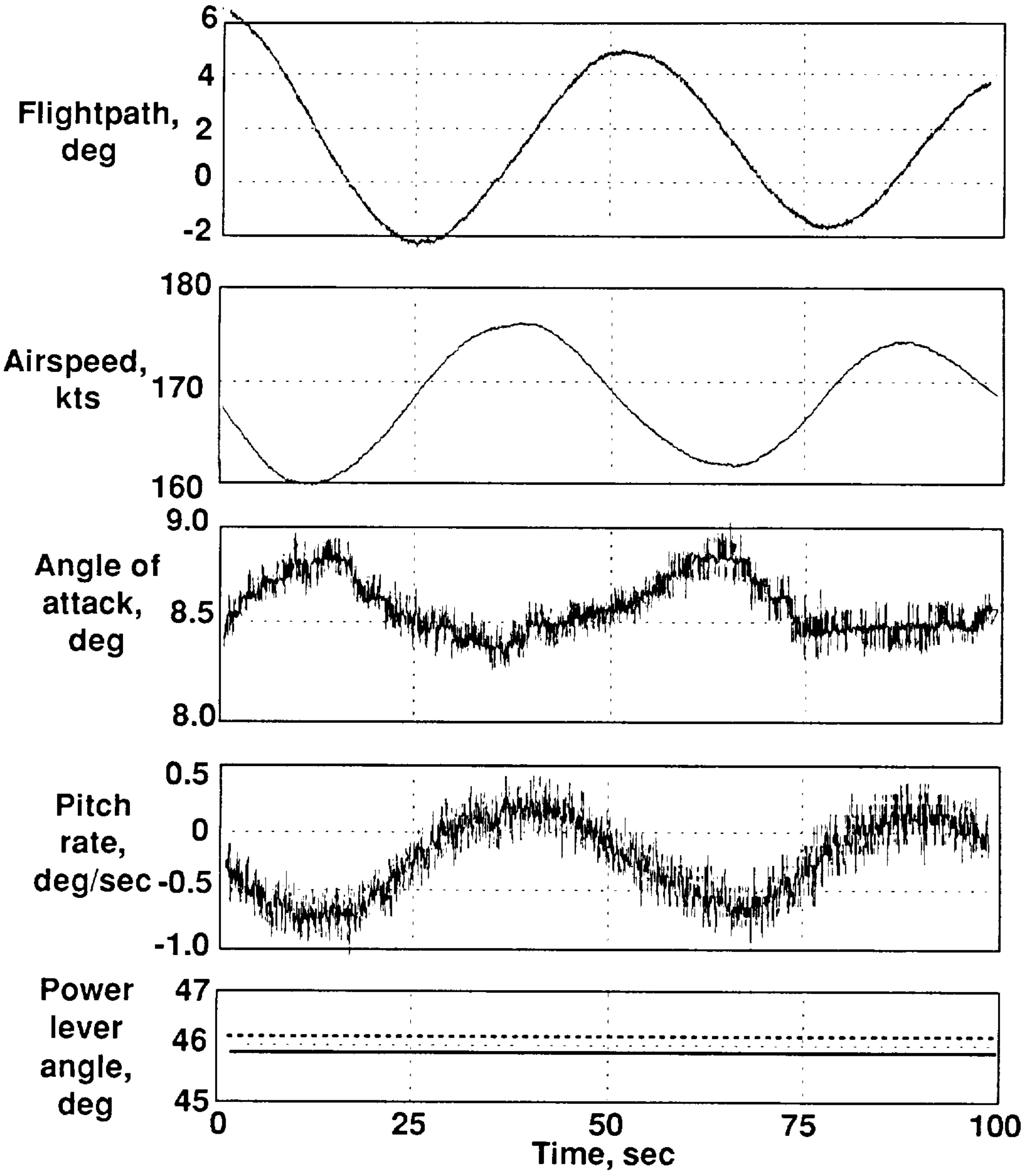
1. *Flight path angle change due to speed stability.* Most stable airplanes, including the F-15 exhibit positive speed stability. Over a short period of time (approx 15 sec), a thrust increase will cause a speed increase, which will cause a lift increase. With the lift being greater than the weight, the airplane will climb, which causes a pitch rate increase. (If allowed to continue for a longer period of time, this effect will be oscillatory, see "phugoid" on the next page. The degree of change to the flight path angle is proportional to the difference between the initial trim airspeed and the current airspeed, hence, the flight path angle tends to increase as speed increases.
2. *Pitching moment due to thrust line offset.* If the engine thrust line does not pass through the center of gravity (CG), there will be a pitching moment introduced by thrust change. For many transport aircraft, the thrust line is below the CG, and increasing thrust results in a desirable nose-up pitching moment, the magnitude being a linear function of the thrust change. This is the desirable geometry for throttles-only control, because a thrust change immediately starts the nose in the same direction as will be needed for the long term flight path angle change. The effect is more a function of change in thrust than in change in speed, and occurs near the time of the thrust increase. For the F-15, the thrust line passes within plus or minus an inch of the vertical CG, depending on fuel quantity, and this effect is small.
3. *Flightpath angle change due to the vertical component of thrust.* If the thrust line is inclined to the flight path, as is commonly the case, an increase in thrust will increase the vertical component of thrust, which will cause a direct increase in vertical velocity, ie, rate of climb, and a resulting increase in flightpath angle. For a given aircraft configuration, this effect will increase as angle of attack,(a) increases (ie, as speed decreases)

For the F-15, the combined effects of the engine thrust is to produce a nose up pitching response that peaks at approximately 2 deg/sec for a throttle step from power for level flight (PLF) to intermediate power on both engines.



Phugoid

The phugoid is the longitudinal long period oscillation of an airplane. It is a motion in which kinetic and potential energy (speed and altitude) are traded. The phugoid oscillation is excited by a pitch, or velocity change, and will have a period of approximately a minute, and may or may not damp naturally. An example of an F-15 phugoid with the gear down and flaps up is shown below. The oscillation was excited by a step increase in thrust, which results in an oscillatory climb with very light damping. Although a very low amplitude phugoid is usually considered to be a constant angle of attack maneuver, if the amplitude is not small, there can be significant angle of attack variations resulting from pitch rate damping, as shown in this example. Properly sized and timed throttle inputs can be used to rapidly damp unwanted phugoid oscillations; these techniques are discussed in ref 2 and 3, and shown on the next page



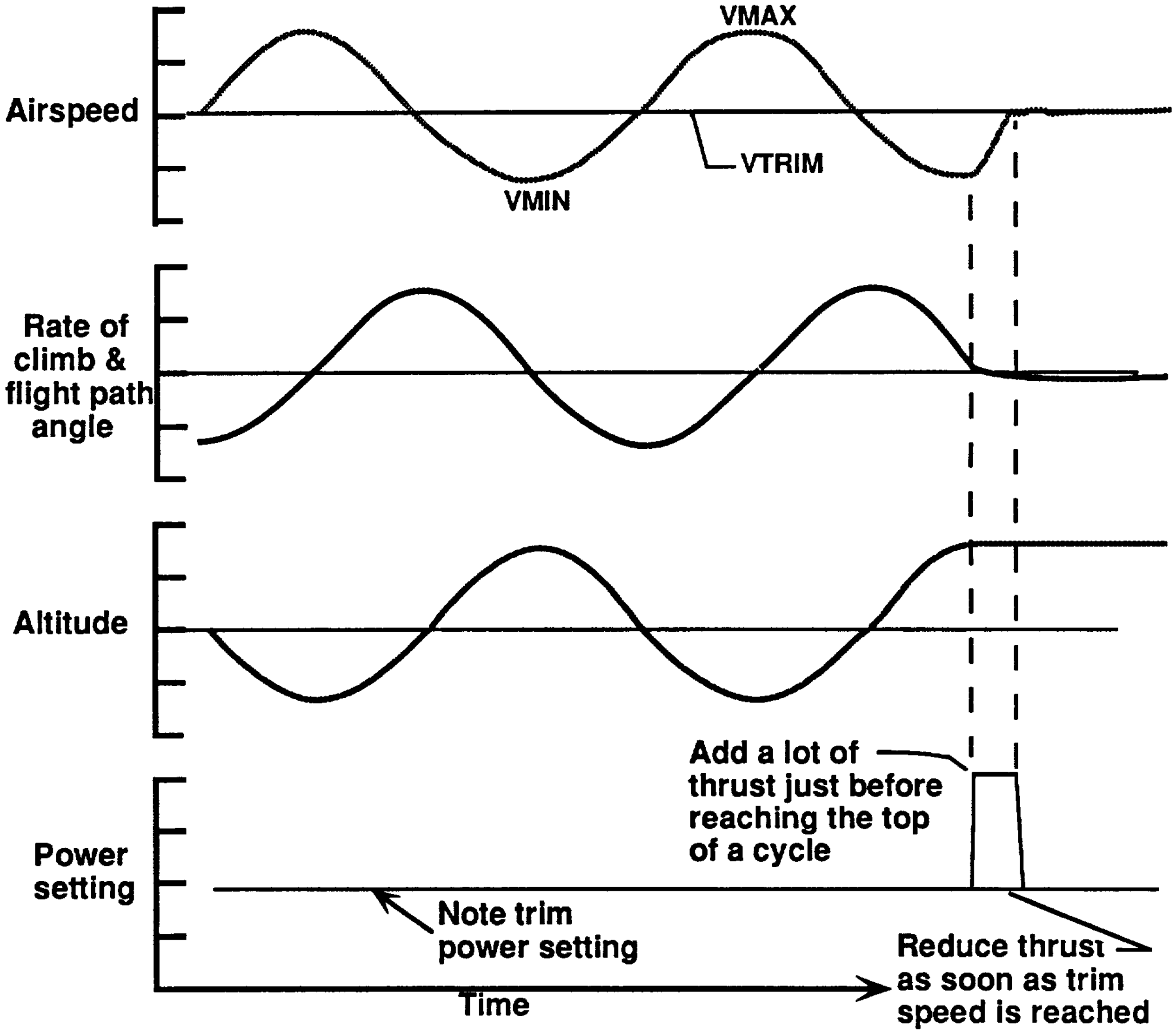
Manual Phugoid Damping Technique

The phugoid, a pitch oscillation in speed and altitude, may be damped with a properly timed and sized throttle input

Suggested technique for damping a phugoid oscillation

1. Determine trim speed from the average of VMAX and VMIN (set bug)
2. Observe trim power setting (EPR or %N1 or %N2) (set bug)
3. Just prior to reaching the top of a cycle, sharply increase power setting (to get speed back to the trim speed as the flight path is approximately level)
4. As soon as the speed increases to the trim speed, rapidly reduce power setting to trim

The phugoid oscillation should now be much smaller

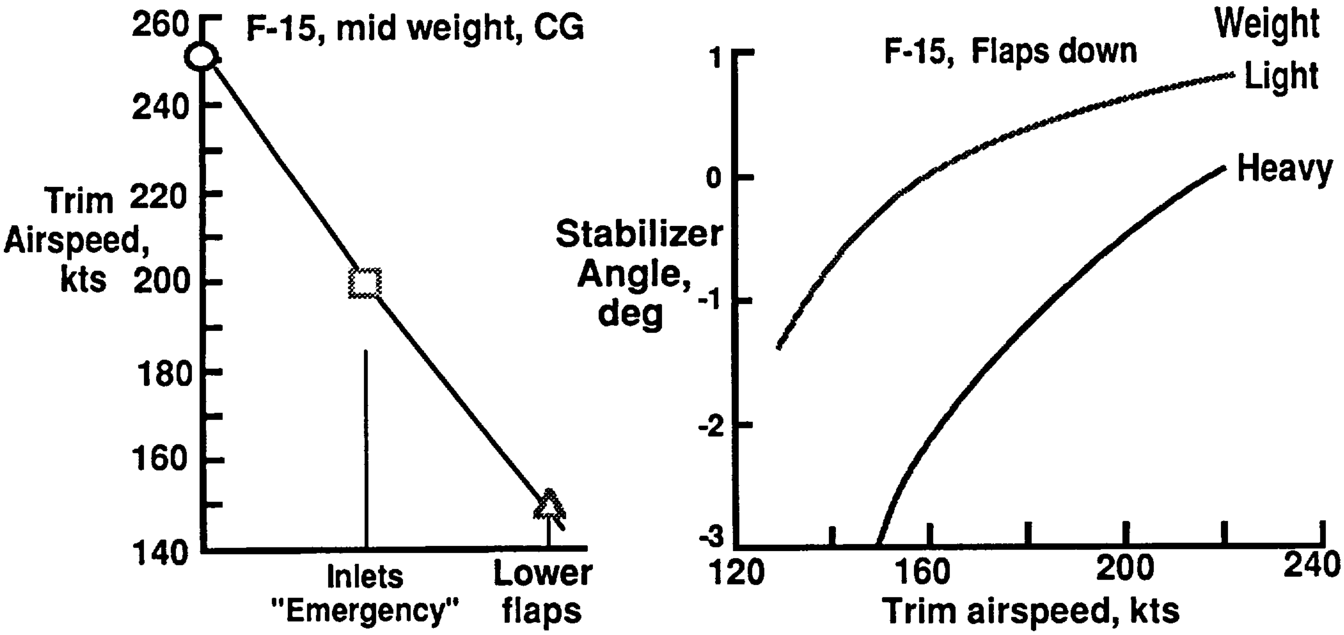


Speed control

Once the flight control surfaces of an airplane are locked at a given position, the trim airspeed of most airplanes is only slightly affected by engine thrust. Retrimming to a different speed may be achieved by other techniques, such as variable stabilizer control, center-of-gravity (CG) control, lowering of flaps, landing gear, and reducing weight. In general, the speed will need to be reduced to an acceptable landing speed; this implies developing nose-up pitching moments. Methods for doing this include moving the CG aft, lowering of flaps, extending the landing gear, or burning off or dumping fuel. Shown below are some of these effects for the F-15.

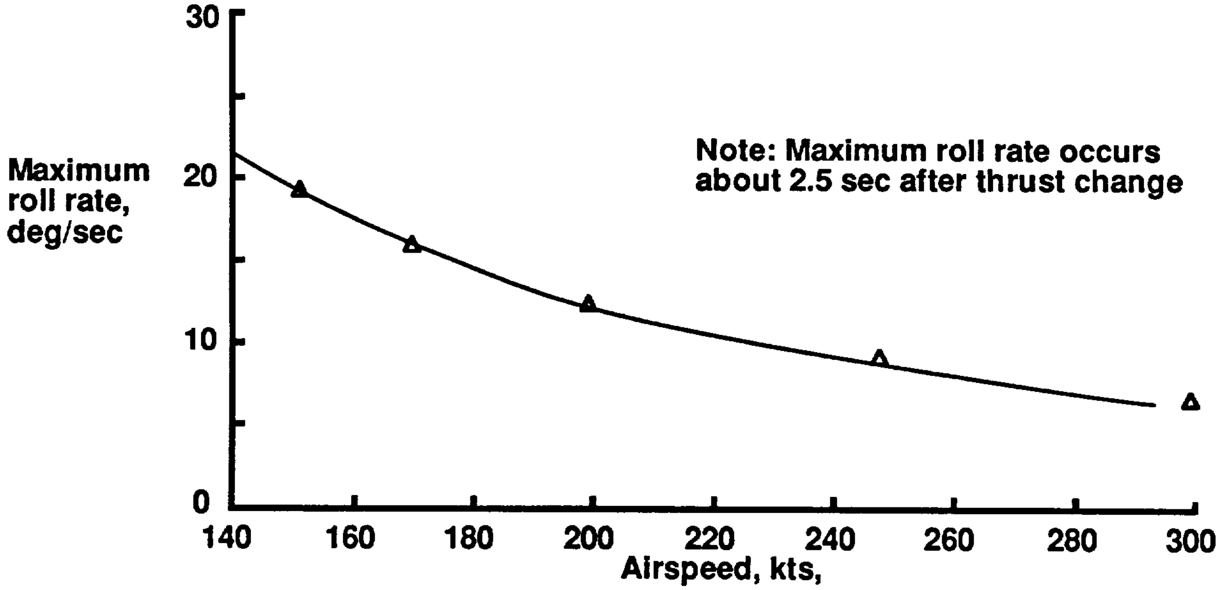
Trim speed is affected by changes in weight. As weight is reduced (such as by burning fuel), (assuming that the CG remains constant) the lift remains constant , so the airplane tends to climb. To maintain level flight, the throttle setting must be reduced to reduce speed until lift and weight are again in balance. For the F-15, flying at low speed and approaximately level flight, this effect reduces trim speed by approximately 1 knot every 1 to 2 minutes.

Other effective ways of slowing the F-15 include moving the air inlets to the full-up emergency position, and lowering the flaps. Landing gear extension on the F-15 has essentially no effect on trim speed. Center of gravity control using fuel transfer was studied for the F-15 and was feasible, but was not implemented due to funding constraints.

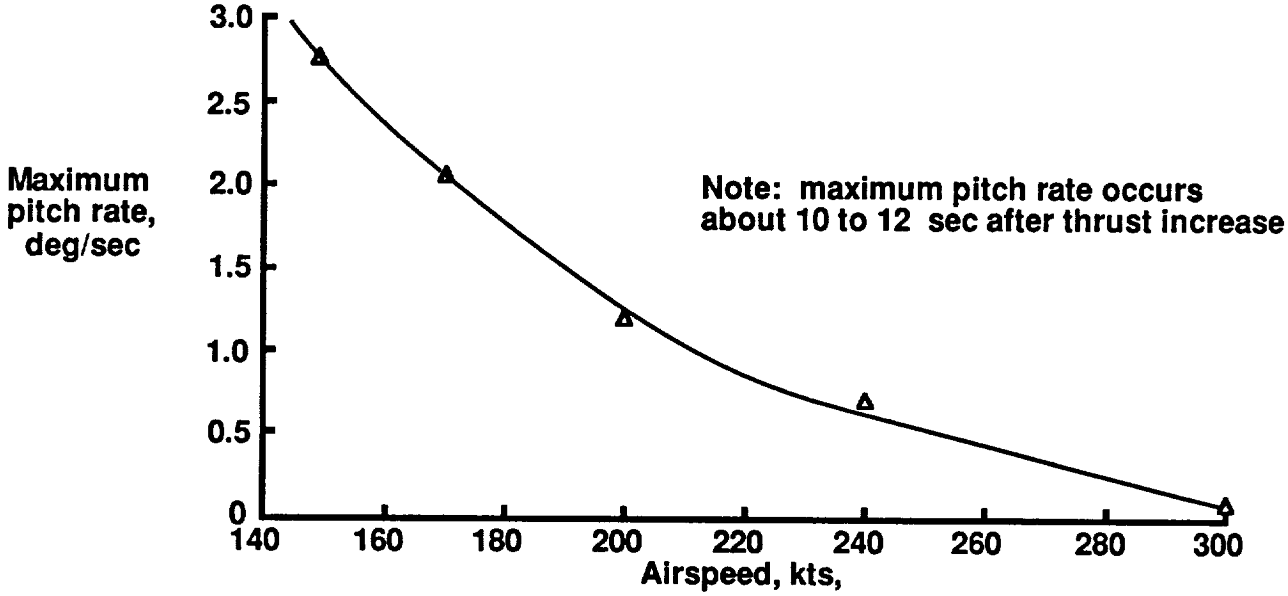


Speed effects on propulsive control power

The propulsive forces (differential thrust for yaw for lateral control and collective thrust for flightpath control) tend to be relatively independent of speed, whereas the aerodynamic restoring forces that resist the propulsive forces are proportional to the dynamic pressure, which is a function of speed squared. This relationship results in the propulsive control power being approximately inversely proportional to the speed. The figure below shows these effects for the F-15. The maximum roll rate for a full differential thrust step varies from 8 deg/sec at 300 kts to 18 deg/sec at 150 kts. The maximum pitch rate, occurring approximately 8 sec after the throttles were stepped from power for level flight (PLF) to intermediate, varies from 0 at 300 kts to 2 deg/sec at 170 kts.



Note: Maximum roll rate occurs about 2.5 sec after thrust change



Note: maximum pitch rate occurs about 10 to 12 sec after thrust increase

Airplane Stability

The flight controls-failed stability of an airplane is an important consideration for throttles-only control. Large transport airplanes typically have good basic static stability. Yaw dampers may be used for increasing the dutch roll mode stability, but good pitch, roll, and yaw static stability is usually built in. This stability remains if the flight control system should be lost. For fighter airplanes, the airframe may have lower levels of static stability, with adequate stability being achieved with mechanical and/or electronic stability augmentation. Thus in the case of flight control system failure in a fighter, the basic short period stability may be considerably reduced, and the control requirements for a PCA system will be more difficult. (The previous comments do not apply to the long-period phugoid stability which will likely be a problem for both fighter and transport aircraft)

References for PCA Background and Principles

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