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Manual Manipulation of Engine Throttles for Emergency Flight Control

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ABSTRACT

If normal aircraft flight controls are lost, emergency flight control may be attempted using only engine thrust. Collective thrust is used to control flightpath, and differential thrust is used to control bank angle. Flight test and simulation results on many airplanes have shown that pilot manipulation of throttles is usually adequate to maintain up-and-away flight, but is most often not capable of providing safe landings. There are techniques that will improve control and increase the chances of a survivable landing. This paper reviews the principles of throttles-only control (TOC), a history of accidents or incidents in which some or all flight controls were lost, manual TOC results for a wide range of airplanes from simulation and flight, and suggested techniques for flying with throttles only and making a survivable landing.

NOMENCLATURE

AOA	angle of attack, deg
ACFS	Advanced Concepts Flight Simulator
AGL	above ground level (radar altitude), ft
ARC	Ames Research Center
CAS	control augmentation system
CG	center of gravity
CGX	longitudinal center of gravity, percent of mean aerodynamic chord
CGY	lateral center of gravity
CGZ	vertical center of gravity
DEL	Direct Electrical Link mode of the F/A-18 FCS
DFRC	Dryden Flight Research Center
EPR	engine pressure ratio
EYD	engine thrust as yaw damper
FCS	flight control system
Fg	gross thrust
Fr	ram drag
FPA	flightpath angle, deg
GW	gross weight, lb
HDG	heading, deg
HUD	head-up display
ILS	instrument landing system
LaRC	Langley Research Center
PCA	Propulsion Controlled Aircraft

SCA	Shuttle carrier aircraft
TOC	throttles-only control
V	velocity, kn
VMAX	maximum velocity, kn (see fig 8)
VMIN	minimum velocity, kn (see fig 8)
VTRIM	trim velocity, kn (see fig 8)
WL	aircraft waterline

INTRODUCTION

In the last 30 years, several aircraft, including B-747, L-1011, DC-10, B-52, C-5A, and A300 aircraft have experienced major flight control system failures in which the crews have had to use manual throttles-only control (TOC) for emergency flight control. In most cases, a crash has resulted; the B-747, DC-10, and C-5A crashes claimed over 1100 lives (ref. 1).

To investigate the use of engine thrust for emergency flight control, a NASA/U.S. Department of Defense/Industry/University team has been conducting flight, ground simulator, and analytical studies. One objective is to determine the degree of control available with manual manipulation of engine throttles for various classes of aircraft. Tests in simulation have included B-720, B-747, B-727, MD-11, and MD-90 transport airplanes; a conceptual megatransport; C-402, C-17, F/A-18, SR-71, B-757 and F-15 airplanes; and, in flight, B-747, B-777, MD-11, T-39, Lear 24, F/A-18, F-15, T-38, and PA-30 airplanes. The pilots have used differential throttle control to generate sideslip, which through the dihedral effect, results in roll. Symmetric throttle inputs were also used to control flightpath. These tests have shown sufficient control capability for all tested airplanes to maintain gross control; both flightpath and ground track angle may be controlled to within a few degrees. These studies have also shown, for all airplanes tested, that, using manual TOC, it is exceedingly difficult to make a safe runway landing, (ref. 2). This is due to difficulty in controlling the oscillatory phugoid and dutch roll modes, weak control moments, and slow engine response.

To provide safe landing capability, engineers and pilots at the NASA Dryden Flight Research Center (DFRC) (Edwards, California) conceived and developed a system called Propulsion Controlled Aircraft (PCA), that uses only augmented engine thrust for flight control. A PCA system uses pilot flightpath command inputs and airplane sensor feedback parameters to provide appropriate engine thrust commands for emergency flight control. This augmented system has been evaluated on simulations of a B-720 transport (ref. 3), a conceptual megatransport (ref. 4), a C-17 military transport (ref. 5), an ACFS B-757 transport (ref. 6), and a B-747 transport (ref. 7). Flight and simulation tests of the PCA system have been flown on an F-15 fighter airplane (ref. 8) and an MD-11 transport airplane (ref. 1). All of these tests have been successful. As of 2004, however, there are no airplanes equipped with a PCA system, so major flight control failures that may occur and require the use of thrust for flight control must be accommodated with manual TOC.

This paper presents a history of loss-of-flight-control accidents or incidents, the principles of TOC for a range of airplanes, a brief review of manual TOC simulation tests for the MD-11, B-727, B-720, B-747, B-757, megatransport, MD-90, SR-71, F-15, F/A-18, and C-402 airplanes, and manual TOC flight tests of the F-15, MD-11, T-39, T-38, C-17, B-747, F-15, and F/A-18 airplanes. Also presented are recommended techniques for manual TOC flight for airplanes with underslung and high-mounted engines. If, in an emergency, any flight control surfaces are still operating, obviously, those will be used; possibly throttles would be used for trimming out asymmetries or additional control as required. For the purposes of this report, it will be assumed, as in the worst case; that ALL flight controls are failed.

LOSS OF FLIGHT CONTROL ACCIDENT–INCIDENT HISTORY

There have been many accidents or incidents in which major flight control failures have occurred, and during which the crew either used or could have used throttles for emergency flight control (ref. 1). A brief description of seventeen of these is contained in appendix A. Table 1 summarizes the status of systems and controllers on several of the accidents or incidents discussed in appendix A. It is seen that the controls on the tail are the most likely to be lost; usually, all the engines were still operating, and often the wing surfaces (ailerons, spoilers, flaps) were still operating.

Table 1. Systems failed and operating for accidents and incidents in which engine thrust was or could have been used for control.

SYSTEMS REMAINING OPERATIONAL AFTER DAMAGE/FAILURE							
	Aileron Spoiler	Flaps	Rudder	Elevator	Stabilizer	Engines	Cause
Accidents							
UA DC-10	no	no	no	no	no	center out	fan disk/hyd
JAL B-747	no	yes	no	no	no	all OK	aft bulk/hyd
USAF C-5A	yes	yes	no	no	no	all OK	cargo ramp/hyd
USAF B-52H	yes	yes	no	no	yes	all OK	hyd leak/tail
Turkish DC-10	yes	?	no	no	no	all OK	door/cables/hyd
AA A300	yes	yes	no	yes	yes	all OK	lost vertical tail
USN F/A-18	no	no	no	no	no	all OK	hyd act leak
Incidents							
USAF A-10	yes	yes	no	no	no	all OK	AAA/cables
USAF B-52G	yes	yes	no	no	yes	all OK	hyd leak/tail
Delta L-1011	yes	yes	yes	yes	one side hardover	all OK	jammed stab
DHL A300	no	no	no	no	no	all OK	missile strike

PRINCIPLES OF TOC

The principles of TOC are presented in the following subsections. These apply to a stable airplane: an airplane in which stability is provided by natural rather than electronic means. First, the lateral-directional effects will be discussed, followed by a discussion of the longitudinal axis.

Lateral–Directional

The lateral-directional effects include thrust effects and lateral fuel slosh effects. These are described and discussed below.

Differential Thrust Effects

Differential thrust is effective in producing roll for all airplanes tested. Differential thrust generates yaw (sideslip) in the desired direction of the turn. In addition, rolling moments are developed from the dihedral effect. Swept-wing airplanes also have an additional rolling moment which is a function of twice the sweep angle and the lift. There may also be a rolling moment contribution from the vertical tail. All of these rolling moments are normally in the same direction as the yaw, and result in the airplane rolling in the direction of the yaw. Proper modulation of the differential thrust allows the airplane to roll to and approximately hold a desired bank angle, which results in a turn and change in aircraft heading.

An open-loop throttle step response from flight data for a large transport airplane (MD-11) is shown in figure 1 at 220 kn with gear down and flaps up. The 10° throttle split of the wing engines results in about 20,000 lb of differential thrust and a roll rate averaging 1.5 deg/sec. Note that the engine pressure ratios (*EPR*s) lag the throttle by approximately 1 sec, and that roll rate lags yaw rate. A lightly damped dutch roll oscillatory mode is excited by this throttle step, as seen in the roll and yaw rates.

An open-loop differential throttle step doublet from flight data on an F-15 fighter airplane is shown in figure 2. Even though the engines are located very close to the fuselage centerline, the thrust-to-weight ratio is high and a significant roll rate of approximately 6 deg/sec occurred. The F-15 has high dutch-roll damping, and the sideslip and roll rate are less oscillatory than for the transport airplane. The maximum roll rate for a full (maximum nonafterburning) differential throttle input at 200 kn is 15 deg/sec.

Fuel Slosh

Thrust effects can cause movement of fuel in fuel tanks. In general, the lateral effects will be unfavorable. The yaw force resulting from differential thrust would tend to force fuel outboard, in a direction to oppose the desired roll due to yaw. Of course, full tanks or nearly empty tanks will have smaller effects than when tanks are half full. These effects are usually small, but if possible, should be modeled in simulations. There was some evidence of this fuel slosh effect in flight tests of the F-15 airplane, as shown in reference 8 on page 70.

Summary of Maximum Roll Rate

Although roll acceleration due to differential thrust would be a better parameter than roll rate, that parameter was often not available; maximum roll rate, however, could be obtained on all airplanes tested. Figure 3 shows the maximum roll rate, developed from a full differential thrust input (no afterburning used on military jets), for several airplanes and simulations tested. Flight conditions were a speed of approximately 200 kn with gear and flaps retracted. The roll-rate parameter is an attempt to provide a simple way of evaluating the roll-rate response to thrust for an airplane. The numerator includes the maximum differential thrust multiplied by the lateral moment arm, and multiplied by the sine of twice the wing sweep angle to account for sweep effects. The denominator includes weight, span, and length, which approximate the effects of the moments of inertia. This roll-rate parameter produces an approximately linear relationship with measured roll-rate data and has maximum roll-rate data points ranging from 3–45 deg/sec.

Lateral Control with An Engine Out and a Lateral Center of Gravity (*CGY*) Offset

Figure 4 shows that if an airplane without flight controls and without an operating engine on one wing has the *CGY* offset toward the side with the operating engine, that engine's thrust can be modulated to develop yaw and a rolling moment to counter the moment from the *CGY* offset. With proper thrust modulation, it is possible to provide a degree of bank angle control. If thrust is reduced from a wings-level condition, the airplane will roll toward the operating engine. Conversely, if thrust is increased above that needed for wings-level, the airplane will roll away from the operating engine. The degree of lateral offset dictates the level of thrust required for wings-level flight, and hence also determines the average flightpath. The *CGY* offset may be obtained with fuel transfer or an asymmetric payload configuration. More discussion is given in reference 9 and appendix B.

Longitudinal Control Principles

Longitudinal, or pitch, control caused by throttle changes is more complex than lateral-directional control because several effects occur as shown in figure 5. Flightpath angle (*FPA*) changes may result from speed stability, the vertical component of thrust, the pitching-moment effects of thrust-line offset, the relative positions of engine inlets and nozzles, fuel slosh, and the phugoid oscillatory mode. Actual flight data from the MD-11 is shown in figure 6.

FPA Change Caused by Speed Stability

Stable airplanes exhibit positive speed stability. During a short period of time (approximately 10 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. The long-term effect is oscillatory (see the phugoid section below). Usually, the more forward the longitudinal center of gravity (*CGX*) is, the stronger the speed stability will be. In figure 6, the thrust increase causes a speed increase which causes an increase in *FPA* for the first 10 sec and another effect discussed below (the pitching moment effect of thrust) also causes an increase in *FPA*. As discussed below, the phugoid oscillation is excited which later causes speed and eventually *FPA* to decrease.

FPA Change Caused by the Vertical Component of Thrust

If the thrust line is inclined to the flightpath (as is commonly the case), an increase in thrust will increase the vertical component of thrust, which will cause a vertical acceleration and a resulting increase in *FPA*. For a given aircraft configuration, this effect will increase as angle of attack (AOA) increases. This effect is usually small.

Pitching Moment Caused by Thrust Line Offset

If the engine thrust line does not pass through the vertical center of gravity (*CGZ*), a pitching moment will be introduced by thrust change.

Thrust Line Below the CGZ. For many low-wing transport aircraft with engines mounted on underwing pylons (underslung engines), the thrust line is below the *CGZ*, and increasing thrust results in a desirable noseup pitching moment and subsequent AOA increase. Figure 6 shows this effect for the MD-11 using only the wing-mounted engines. Even with weak or nonexistent speed stability, adequate pitch control may be possible if positive pitching moment due to thrust exists.

Thrust Line Through the CGZ. For some airplanes, including many fighter airplanes, the engine thrust line passes approximately through the *CGZ*. Little AOA change or pitching-moment effect results from thrust changes.

*Thrust Line Above the CG*Z. For some airplanes, including many regional jets, business jets and seaplanes, the engine thrust line is well above the *CGZ*. This trait has the undesirable effect of causing a nosedown pitching moment for a thrust increase that is opposite in direction to that desired. When speed increases sufficiently for speed stability to overcome the pitching-moment effect, the *FPA* will increase, but this *FPA* increase usually takes 10–20 sec from the time the thrust is increased. Figure 7 shows an example of a throttle increase on the F/A-18 fighter airplane, which has the thrust line slightly above the *CGZ* at this condition. The thrust increase causes the AOA to decrease, causing a nosedown pitching moment that persists for 3–5 sec, depending upon airspeed, and causes the *FPA* to initially decrease, even though the long-term effect, not shown here, is a climb.

Phugoid

The phugoid mode, shown in figure 8, is the longitudinal long-period oscillation of an airplane. It is a constant energy mode in which kinetic and potential energy (airspeed and altitude) are traded. The airspeed oscillates around the trim velocity (*VTRIM)*, which is approximately equal to the average of the maximum velocity (*VMAX)* and the minimum velocity (*VMIN)*. The phugoid oscillation may be excited by a pitch, thrust, or velocity (*V*) change, or other disturbances. For large or dense airplanes, the phugoid mode is usually lightly damped. Properly sized and timed throttle inputs can be used to damp unwanted phugoid oscillations and keep the airspeed near the trim airspeed. These techniques are discussed below.

Relative Position of Inlet to Exhaust Nozzle

The relative positions of the inlet and the exhaust nozzle of each engine may be an important effect for TOC. The ram drag (*Fr*) vector acts through the centroid of the inlet area, which may not be coincident with the gross thrust (*Fg*) vector, which acts through the centroid of the exhaust nozzle. Figure 9 shows three possible arrangements of the inlet relative to the nozzle at low AOAs. As discussed in reference 1, if the inlet is above the nozzle, as shown in figure 9(a), a thrust increase produces a favorable pitching moment; examples are the B-2 propulsion system and the center engines of the L-1011, B-727, and Falcon 50. Podded engines, shown in figure 9(b), have a neutral effect, while airplanes with inlets below the engine nozzle, such as the F-16 and F/A-18, have an unfavorable pitchdown for a thrust increase, as shown in figure 9(c).

In addition, the *Fr* vector acts along the flightpath, thus rotating with respect to the airplane geometric reference system as AOA and sideslip change. The *Fg* vector typically acts along the engine nozzle centerline, thus maintaining its relationship to the airplane geometric reference system, as shown in figure 10 for the F/A-18 airplane. The result is that as AOA increases, the *Fr* vector tends to rise with respect to the *Fg* vector (provided the inlet is ahead of the nozzle) to a more favorable relationship. This is also true for the F-15 airplane, as discussed in reference 8.

Normal flight control system operation masks the above effects, to such a degree that crews may not be aware of them; simulations may neglect these effects. For fighter airplanes with highly-integrated propulsion systems, these effects may be quite significant. For transport airplanes with podded engines, these inlet-nozzle effects are small, but should not be ignored.

If an adverse position of the inlet relative to the exhaust nozzle exists, such as is the case on the F-16 and F/A-18 airplanes, the effect tends to decrease as speed decreases. This is due to the direct dependence of *Fr* on airspeed.

The above effects also occur in the yaw axis and may be important if the engines are close together, as is the case on fighter airplanes.

Fuel Slosh

Thrust effects can cause longitudinal movement of fuel in fuel tanks. In general, the longitudinal effects should be favorable; increasing thrust will move fuel aft, adding to the desired increase in AOA and *FPA*. Of course, nearly full tanks or nearly empty tanks will have smaller effects than when tanks are half full. These effects are usually small, but if possible, should be modeled in simulations.

Trim Airspeed Control

When the normal 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. In general the speed will need to be reduced to an acceptable landing speed, which requires developing noseup pitching moments. Methods for developing noseup pitching moments include moving the *CGX* aft, lowering flaps, increasing the thrust of low-mounted engines, decreasing the thrust of high-mounted engines, shifting fuel aft, or burning off or dumping fuel. Extending the landing gear often decreases trim speed (for low-mounted engines) because an increase in engine thrust is required. Examples of trim-speed control for transport airplanes will be discussed below.

Speed Effects on Propulsive Control Power

The propulsive forces (differential thrust 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 square of the speed.

Effects of *CGX* on TOC

The *CGX* affects TOC in that the speed stability is generally increased as the center of gravity (*CG*) moves forward. As the *CGX* moves aft, the static stability is reduced, and pitching moments due to thrust will cause a larger change in AOA. In fact, in simulations, a transport airplane with neutral longitudinal static stability but with engine thrust below the *CGZ* has been shown to be controllable in pitch.

Speed Effects on TOC

As discussed above, the TOC control power is inversely proportional to the square of the airspeed. But control power is not the only issue. Speed may also affect damping and thrust required, and certainly has an effect on landing roll. In general, increasing speed improves dutch-roll damping. Decreasing speed below the speed for minimum drag increases the thrust required, which provides more thrust that can be modulated for control. Decreasing speed (at constant weight) also increases AOA, which often has a favorable effect on the vertical component of thrust and improves the relationship between inlet *Fr* and engine *Fg*. A high approach speed may spell trouble in the flare, where a long float or balloon may occur once ground effect is entered. If speed can be controlled following a major flight control system failure, it may be wise to select a speed that is the lowest consistent with adequate dutch-roll damping and an adequate margin above pre-stall buffet. If the airplane is damaged, the published approach speeds may no longer be appropriate.

All of the above discussion is based on subsonic flight speeds. In the transonic regime, as speed (and Mach) increases, the center of pressure tends to move aft. In this speed range, increasing thrust will still cause an increase in speed and hence lift, but it may result in an aft shift of the center of pressure that will cause a nosedown pitching moment that will more than offset the speed stability. TOC flight may not be possible in the transonic speed range, depending on the characteristics of the airplane. At Mach numbers above 0.7, the F-15, B-747 and MD-11 airplanes were stable in pitch, but the C-17 simulation was unstable in pitch. Lowering the landing gear may be considered to reduce Mach number.

Surface Float with Hydraulics Off

With the hydraulic system failed, a surface will typically float to the zero hinge moment condition. For the rudders and elevators of many aircraft, in trimmed flight, this position is essentially the trail position, while ailerons usually float trailing edge up. Simulator and flight tests on the MD-11 indicated that a total hydraulic failure would cause the ailerons to float trailing edge up, the amount depending on speed. Similar results are shown for the C-17 and B-747. Rudder float would have a negligible effect on trim speed but would reduce directional stability somewhat, possibly increasing the yaw due to differential thrust, which could be a favorable effect. Elevators are usually trimmed to near zero force, hence elevator float would have a small effect. The stabilizer is usually moved with a jackscrew actuator which, in case of hydraulic or electrical failure, remains fixed due to friction. The effects of floating surfaces are difficult to predict analytically, and therefore simulations based on anything other than actual flight data may not be accurate.

Summary of Predicted Longitudinal and Lateral Thrust Control Power

Figure 11 shows the combined pitch-rate and roll-rate parameters for several airplanes. The pitch-rate parameter includes the thrust moment arm multiplied by the difference between the trim and maximum thrust; thus this represents the pitch rate due to thrust increase and not thrust decrease. The roll-rate parameter is the same as that shown in figure 3. The best control power configurations are in the upper right section, but it has been shown that the MD-11 and F-15 airplanes, using the PCA system, have sufficient control power for safe landings. The worst control capability configurations lie to the left with very low roll parameter or at negative values of the pitch parameter. Other considerations that may be important but do not appear on this plot include aircraft dutch-roll and phugoid damping, the relative location of the inlet and exhaust, engine response, and availability of equipment such as instrument landing system (ILS) displays, flight director displays, and autothrottle systems.

AIRPLANE TESTS FOR TOC

Use of propulsive forces for flight control has been tested on many airplanes in simulation, and several airplanes have been tested in flight. The pilots used in these evaluations are presented in table 2.

Table 2. TOC pilots and affiliations.

A.	NASA chief PCA pilot
B.	NASA chief PCA engineer
C.	Boeing chief B-747 pilot
D.	United Airlines DC-10 check captain

Airplanes Tested in Piloted Simulators

Several airplanes have been tested for TOC using piloted simulators. These include transport airplanes (the B-720, B-727, B-757, MD-90, MD-11, B-747, and C-17), a conceptual megatransport, the light twin C-402, and fighter airplanes (the F-15 and F/A-18), and the SR-71.

B-720 Commercial Jet Transport

The Boeing Company (Chicago, Illinois) 720 airplane (ref. 3) is a four-engine transport designed in the late 1950s. The airplane has a 35 deg swept wing mounted low on the fuselage and four turbojet engines mounted on individual pods below and ahead of the wing. The airplane is equipped with a conventional flight control system incorporating control cables and hydraulic boost. The airplane also incorporates a slow-rate electric stabilizer trim system. Flaps are electrically controlled.

A high-fidelity B-720 engineering simulation was available at NASA DFRC from the Controlled Impact Demonstration flight program conducted jointly by NASA and the Federal Aviation Administration (FAA). The B-720 simulation included nonlinear aerodynamic derivatives with ground effect. The simulation was modified to permit locking of all the flight control surfaces at desired positions. This would approximate the situation that results in more modern airplanes with a total hydraulic system failure, or in the B-720 if control cables were jammed (surfaces fixed) or cut (surfaces floating). The throttles were then used for flight control.

Pilot A flew the B-720 airplane manually using TOC. Good roll capability was evident, with roll rates of approximately 20 deg/sec, but dutch-roll damping was light, particularly at the lower airspeeds. Adequate pitch capability was also found, with some pitching moment because of the thrust line below the *CG*, as well as speed stability. Maximum pitch rate at 160 kn was 1.8°/sec, and at 200 kn it was 1.1°/sec.

With this control power it was possible for a pilot to maintain gross control, hold heading and altitude, and make a controlled descent. However, it was extremely difficult for a pilot to make a landing on a runway. There was a 1-sec lag in pitch and roll before the airplane began to respond to the throttles. Judging the phugoid damping was difficult, and the lightly-damped dutch roll was a major problem in roll and heading control. Although a few pilots did develop techniques for successful landings using manual throttles, most were unable to make repeatable successful landings. Some results are shown in reference 3.

B-727 Commercial Jet Transport

The Boeing B-727 airplane (ref. 2) is a three-engine transport carrying up to 150 passengers. The airplane has a swept wing and a T-tail. The three Pratt & Whitney (East Hartford, Connecticut) low-bypass JT8D turbofan engines are mounted on the aft fuselage. The two outboard engines are mounted on short pylons; the center engine is located in the aft fuselage and has an inlet above the fuselage. The B-727 airplane has a conventional flight control system, with control cables moving hydraulically-boosted control surfaces. High-rate electric trim is available for the horizontal stabilizer. The engine response was slow (3 sec) from idle to a low power setting (*EPR* of 1.2), then fast (3 sec to reach full thrust).

The B-727 TOC capability was evaluated at a speed of approximately 200 kn in a high-fidelity motion-based simulation at the NASA Ames Research Center (ARC), Moffett Field, California. Hydraulics were turned off and the control wheel was not touched, simulating a total loss of flight control cables. In an evaluation of engines-only roll rate with the outboard engines at full differential thrust, roll rates of 3–4 deg/sec were obtained. There was a 1-sec lag before the roll rate was appreciable. From an initial wings-level condition, it took 11 sec to reach a 30° bank angle. In 4 sec, the bank angle was approximately 12°. This roll capability, while much less than the F-15 or B-720 airplanes, was surprisingly large considering the fuselage mounting of the engines.

Pitch control power was also evaluated. There is very little pitching moment due to thrust offset, but there is significant pitching authority due to speed stability. With the airplane trimmed and throttles set for level flight, noseup pitch rates at full thrust were approximately 0.75°/sec; nosedown pitch rates at idle were 0.4°/sec.

These pitch and roll control power values are smaller than those for the B-720 simulation and were slow in initial response. Precise control of *FPA* using throttles was difficult. Use of electric stabilizer trim was more successful.

The airplane was flown by pilot B using differential engine thrust for bank angle and electric trim in pitch, and gross control was possible. After 10 min of familiarization, heading could be held within approximately 2° and altitude to within 100 ft.

Landings were attempted using differential throttle and electric trim. Neither of the evaluation pilots could successfully land the airplane on the runway by themselves. The low roll rate and roll control lag made it extremely difficult to remain lined up with the runway. It was possible to maintain gross control, but not with sufficient precision to land on a runway. A well-controlled touchdown could be made, assuming an “infinite” (unlimited length and width) runway.

Improved roll control was achieved by reducing the center engine throttle to idle. The higher thrust and the faster thrust response of the outboard engines improved directional control. Splitting the control task between two pilots also helped. One pilot would fly pitch with electric trim, while the other pilot used differential throttles for roll and heading control. Even with this technique, it was not possible to make consistent landings on the runway.

B-757 Simulations

Advanced Concepts Flight Simulator (ACFS), B-757. The ACFS is an advanced technology transport research simulator situated at NASA ARC that approximately represents a B-757-class airplane. Takeoff gross weight (*GW*) is 225,000 lb. It is powered by two 42,000 lb thrust high-bypass turbofan engines. Extensive TOC and PCA tests were conducted in this simulator over a period of several years. Results of manual TOC tests are presented in reference 6. There was plenty of pitch and roll authority with thrust, damping was relatively good, and TOC control was relatively good. After some practice, pilots could make survivable landings on or near a runway.

Research Flight Development Simulator, *B-757*. Another B-757 simulation, at the NASA Langley Research Center (LaRC), was briefly tested for TOC. Results were somewhat similar to the ACFS B-757 except the lateral axis was not as easy to control. Pitch control and yaw damping were good. There was also a ground effect problem (due to landing with less-than-normal landing flap deflection) in the simulation.

The Research Flight Development Simulator is a high-fidelity simulator, similar to the ACFS at NASA ARC. It has sidestick controllers, six flat panel displays which have been programmed in-house to provide typical cockpit information, and an excellent visual system. Pilot B flew the simulator in the TOC mode with the yaw dampers off. The airplane felt much like the B-757 at NASA ARC—relatively powerful roll and pitch control with reasonably good damping. A list of 15 items was evaluated during a cruise-out to a suitable simulated airport. Spiral stability was near-neutral. Maximum roll rate was 15 deg/sec, and roll rate with a 0.1 *EPR* differential thrust was about 3 deg/sec. A 2-deg sideslip took 0.2 *EPR* to trim out. The engine model appeared very good. Once stabilized at idle, it took about 5 sec to get the engine back up to an *EPR* of 1.0—after that, it responded more rapidly.

Trim speed variations were tested. Starting clean at 255 kn, the gear was extended; speed dropped to 230 kn. The airplane has electric alternate flaps. Lowering the flaps to 1° (FLAPS 1), which lowers the leading edge slats only, reduced trim speed to 212 kn. FLAPS 5 added a 5° trailing edge flap deflection, and reduced trim airspeed to 201 kn; at FLAPS 15 airspeed was 187 kn. These data were largely consistent with results reported from another B-757 simulator.

A 180° turn was made to acquire the runway 18 ILS and start an approach. Flaps were extended to 15° for an approach speed of about 185 kn. TOC was comfortable on initial approach and a 500 ft/min sink rate was established. The ILS localizer raw signal appeared to be off slightly to the right. The approach went well until about 500 ft, as usual. Pilot B then drifted right, made a late correction back, hit rather hard and bounced back into the air, then landed again about 100 ft off to the right of the runway. Repeat approaches were attempted but most did not result in good touchdowns. Control near the ground was not as good as with the ACFS 757.

During attempted flaps-up landings the airplane would begin to float at 200 ft above ground level (AGL). Several 700 ft/min glide slopes were flown with no throttle or flight control inputs to study the ground effect model. At 200 kn with no flaps, the airplane leveled off and climbed as it reached 200 ft. With FLAPS 1 at 187 kn, the float began at 50 ft, and at FLAPS 5 at 170 kn, the sink rate went from 700 to 300 ft/min going through 100 ft and stayed there, making a smooth touchdown. It appeared that the no-flaps ground effect model may be in error. Ground effect was a big issue in both the F-15 and MD-11 flight tests. The lift change is important, but the pitching moment change is probably more important, and is often not properly modeled in simulations.

Approaches were also made with a 2° rudder bias dialed in, and these did not seem any worse than those without the rudder—the rudder offset being easily trimmed out with a throttle offset.

MD-90 Commercial Jet Transport

The MD-90-30 is a medium-sized twin-jet transport airplane built by the Boeing Company. It is 153 ft long, with a span of 108 ft, and a maximum *GW* of 157,000 lb. The MD-90 had International Aero Engines (East Hartford, Connecticut) VC2525-D5 engines with 25,000 lb of thrust mounted on the aft fuselage. The cockpit featured a full autopilot with glareshield-mounted controls and a flight management system. The autothrottle system could be set to control speed in one-knot increments.

The MD-90 simulation was a FlightSafety International (Broken Arrow, Oklahoma) Class D pilot training simulation, with much flight hardware in the loop. The MD-90 simulation was flown at a weight of 120,000 lb and a mid-*CG* with the yaw damper off. Pilot B began the test with collective and differential throttle tests at 250 kn and 200 kn in a clean configuration. Then throttle step response tests at 160 kn with 15° flaps and gear down were performed. In all cases, there was slow but positive and easily predictable roll response. A bank angle of 20° could be achieved and held within a few degrees. Bank angles in excess of 50° could be recovered with full differential thrust. Pitch control was more difficult. There was essentially no pitching moment due to thrust. Speed stability was positive but using this type of pitch response for control continually excites the phugoid. Altitude could be maintained within a few hundred feet of target, but it was very difficult to fly a constant flightpath other than approximately level.

Pilot B flew approaches in the 160 kn-15° flaps-gear down configuration. The airplane drag was very low, and it was difficult to hold a 3° glide slope even at idle power. A 2° glide slope was more manageable. No successful landings were made in this configuration. It was possible to hit the runway, but not under adequate control. Roll control was so sluggish that lineup was difficult, and the thrust needed to change bank angle upset the flightpath control and usually produced overshoots. Flightpath control was a continuous phugoid damping task which was only partially successful.

A split-task technique was also tried. Pilot B flew pitch control using the autothrottle speed control. Once trim speed was found, decreasing a few kn produced a pitchover, and increasing a few kn above trim speed produced a pitchup. Phugoid damping was much improved using this approach. Approaches were flown in this mode; Pilot B flew the speed knob for pitch and another pilot made small differential throttle inputs to control bank and heading. The autothrottles did not disconnect for the small differential inputs (about 2 in. max) that were needed. Using this technique, sink rate could be controlled reasonably well, and usually touchdown occurred near the intended location. Lineup was still difficult; with landings usually near the runway, but not always on it. Still, this was a vast improvement over the full manual TOC attempted earlier. Figure 12 shows a comparison of two approaches, one flown using the single pilot manual TOC approach. The second used the split-task technique described above, and shows much better control of the approach and touchdown. In particular, the phugoid is much better damped using the autothrottle speed-hold feature. The ability of the autothrottle system to provide pitch control was due to the location of the engines at or above the *CGZ*.

This use of the autothrottle speed-hold technique for pitch-flightpath control should work for airplanes with mid- or high-mounted engines. It does not work for airplanes with low-mounted engines because for a commanded speed increase the pitching moment due to the thrust increase results in a long-term speed decrease; thrust thus diverges to maximum trying to get the speed to increase. This speed-hold technique worked fairly well on the F-15 and F/A-18 simulations; both of these airplanes have thrust lines slightly above the *CGZ* except at high AOAs.

MD-11 Heavy Commercial Jet Transport

The Boeing MD-11 airplane is a large, long-range commercial transport. It has a 35-deg sweep low-mounted wing and is powered by three high-bypass turbofan engines. Two of the engines are mounted in underwing pods; the third engine is mounted on the base of the vertical tail. The airplane uses an irreversible hydraulic flight control system and has hydraulically-powered stabilizer trim.

The capability for engines-only control of the MD-11 airplane was investigated in the manufacturer’s flight deck simulator. At a speed of approximately 200 kn in roll, the use of differential thrust produces sluggish but reasonably well-damped roll control, with a maximum roll rate of 6–7 deg/sec. At lower speeds with flaps extended, the roll rates were similar, but dutch-roll damping was significantly reduced. In the longitudinal axis, there is substantial but confusing pitch control available, with the center engine producing strong nosedown pitching moment and the wing engines producing a moderate noseup pitching moment. A better approach was to retard the center throttle to idle and use the wing engines, which have the beneficial noseup pitching moment to augment the speed stability.

Up-and-away flying was possible, altitude could be maintained, and heading could be held within reasonable limits. Landings were attempted in the simulator. After much practice, some safe landings could be made. Workload was very high. Adding winds and turbulence made the task even harder. Reference 1 has more information on MD-11 TOC. Flight TOC tests were conducted on the MD-11 as discussed later, and tended to match the simulator results.

B-747 Heavy Commercial Jet Transport

The B-747 (ref. 7) is a very large swept-wing wide-body transport with four engines mounted on underwing pylons, and is built by the Boeing Company in Seattle, Washington. Maximum *GW* is 870,000 lb; maximum landing weight is 574,000 lb. The inboard engines are 39 ft from the centerline; the outboard engines are 70 ft from the centerline.

Tests have been performed on various simulators. Training simulators showed various responses to turning off hydraulic systems. Some immediately went out of control, while others had a mild transient as is the case in the actual airplane.

Pilot A spent much time in various B-747 simulators evaluating the controllability with throttles. Because of the large inertia of the B-747, roll response is sluggish. With practice, however, it is possible to turn to and hold a heading and to fly an approach to a runway. Pitch control power is significant, but again, large lags are present. Phugoid damping could be accomplished after much practice, using the techniques discussed below. In a flight training simulator, the B-747 trim speed was reduced from a cruise speed of 275 kn to 220 kn by lowering the gear and the inboard but not the outboard trailing-edge flaps to 25°. Two simulated landings were made. One of the landings was 2000 ft right of the runway and had an unacceptably high sink rate. The second landing was on the edge of the runway at a sink rate of 800 ft/min. Even with extensive experience, manual TOC landings on the B-747 are very difficult.

The best B-747 simulator was the NASA ARC B-747-400 simulator, a very-high-fidelity motion-based simulator which is certified by the FAA to level D. The simulated 747-400 is powered by Pratt & Whitney PW4056 engines with 56,000 lb of thrust and full-authority digital electronic control (FADEC) systems.

Several pilots were asked to attempt manual TOC approaches without extensive time to practice or become familiar with the TOC characteristics of the B-747. Pilot C, with much B-747 experience, but who had not tried TOC, made the approach shown in figure 13 in the NASA ARC simulator. The pilot was unable to damp the phugoid or achieve runway lineup, and impacted a mile short of the runway at a 3500 ft/min sink rate. Pilot D also tried TOC in the B-747 simulator. In spite of his previous flight experience eight years earlier in the DC-10 at Sioux City, Iowa, he too had difficulty controlling the flightpath, as figure 14 shows. The lineup was good, but the no-flaps high-speed case required a shallower glide slope than 3°, and the approach was discontinued when over the runway threshold still at 600 ft.

Neither pilot was able to effectively damp the phugoid. In roughly level flight prior to glide slope intercept, Pilot C had 235 kn ±13 kn, which resulted in a ±1200 fpm rate-of-climb oscillation. Pilot D had 235 kn ±15 kn, for ±1400 fpm rate-of-climb oscillation. These problems were typical of those seen by pilots without extensive TOC experience in the B-747.

After more practice, it was possible to make landings in the vicinity of the runway. Problems were encountered due to the high approach speed. The throttles were near idle, reducing the control power available and slowing engine response time. Bounces were typical. Many of these landings were not survivable.

If a runway landing was made with no hydraulic pressure, there was no braking, so the airplane could only be slowed with thrust reversing. Some B-747 engines have pneumatically-powered reversers

(General Electric engines [General Electric, Evendale, Ohio]), but Pratt & Whitney-powered airplanes use aircraft hydraulics for reversing and if hydraulics were lost they could not be stopped on any runway. In the simulator, the ground rollout from a 230 kn touchdown was 6.5 mi. Gear-up landings were made in the simulator with a ground slideout of less than 2000 ft. Landings were also made with the main gear down but the nose gear retracted, but no additional slideout drag was modeled by the simulator in this configuration. This might, however, be a viable way for an actual B-747 with no hydraulics and no thrust reversing to stop on a runway.

Pilot A had had extensive but sporadic TOC experience over a period of several years, including TOC and PCA flight tests first on the F-15 airplane in 1993 and later on the MD-11 airplane in 1995. In 1998, he was able to make survivable TOC landings in the B-747 simulator at NASA ARC after at least a year without any TOC practice. His knowledge of the proper phugoid damping techniques and close attention to making small lateral corrections to stay on course were important; as was the knowledge of the lead required to compensate for slow engine response. His experience indicates that, once learned, TOC capability does not rapidly diminish with time for an experienced test pilot.

In the simulator, the *CG* of the B-747-400 could easily be moved. The normal *CG* was 22–24 percent. With the *CG* moved aft to 40 percent, the simulator still flew well with only engine thrust for control. There was little speed stability left, but the pitching moment due to thrust was significant, and effective considering the low static stability. Even at the maximum aft *CG* position as limited by the stabilizer setting, there was still positive pitch and lateral control available with thrust. With neutral static stability, there is no longer any phugoid oscillation, and the trim speed wanders.

C-17 Military Jet Transport

The Boeing C-17 (ref. 10) is a large wide-body military transport built by the Boeing Company in Long Beach, California. It features a T-tail, a high-mounted supercritical wing, four engines mounted on underwing pylons, externally blown flaps, and a rough-field high-sink-rate landing gear. The airplane has a four-channel digital fly-by-wire flight control system powered by four independent hydraulic systems, and an advanced glass cockpit with a head-up-display (HUD). A stability and control augmentation system (CAS) is provided in all axes. The four Pratt & Whitney F117 engines each produce approximately 40,000 lb thrust and have digital controls. A typical mid-fuel weight with a medium payload was 450,000 lb.

A first TOC evaluation was flown in 1991 by Pilots A and B at the C-17 simulator at McDonnell Douglas in Long Beach, California. For this evaluation, all augmentation was turned off, leaving the airplane with only a backup mechanical yaw damper on. In this configuration, the airplane could be rather easily flown with the throttles.

For the more challenging case, all hydraulics were turned off, disabling the yaw dampers. All of the surfaces float in this configuration. With the airplane trimmed at 190 kn clean, the aileron upfloat provided a 30-kn reduction in trim speed.

Throttles-only flight was evaluated, first by pilot A, then by pilot B. The airplane could be controlled in up-and-away flight; phugoid damping was not too difficult, but precise heading control was difficult. There was significant positive pitching moment with thrust. There was adequate speed stability; when coupled with the pitching moment, the pitch control is good. In roll, there was substantial control power with full differential throttle, with maximum roll rates in excess of 20 deg/sec. However, heading control with small differential throttle inputs was quite difficult, due to the low ratio of roll rate to sideslip, and slow engine response. The initial response to differential throttle was mostly yaw, more so than in most other airplanes investigated. Differential throttle inputs had to be left in for a few sec before roll becomes appreciable. If left in too long, the dutch-roll mode was excited, and dutch-roll damping was light at the lower speeds.

Approaches were made, and it was very difficult for a single pilot to get the C-17 on the runway. The heading control task was very demanding. It was very difficult to make precise small heading corrections, and, as a result, final lineup was a major problem, and most landings were not on the runway. It was also difficult to get an adequate grip on the four throttles which are long and flexible; sometimes, they would interfere with each other.

Pilots A and B then split the task; one would fly pitch with the two inboard engines, while the other flew roll-yaw with the outboard engines. This reduced the complexity of the task and difficulty in handling the throttles. With practice, this method resulted in three consecutive safe landings. These results verify that there is adequate control power for TOC.

Later simulator tests were conducted in June of 1996 in the motion-based simulator, in conjunction with PCA system tests. In the no-flaps configuration, starting at 300 kn and upon failing the hydraulics, the outboard ailerons floated, causing a big pitchup and reducing the trim airspeed to 225 kn. Lowering the gear reduced airspeed to 215 kn.

The lateral control was marginally adequate with no flaps, probably similar to the B-747 simulator at NASA ARC. There is little roll due to yaw, and yaw damping is pretty good at the 200+ kn speeds that were flown. The thrust was low and it was hard to fly a 3° glide slope.

If the blown flaps were extended, the simulation showed that they did not move with loss of hydraulics, which may be incorrect. In any case, the lateral control with no yaw damping was poor, and got worse as speed was decreased.

With 20° or more of flaps and some powered lift, lateral control was extremely tough—much worse than the B-747 or B-757 simulators at NASA ARC. The speeds were reduced to 120 kn or lower and the dutch-roll damping was very light. The airplane was also very loose in yaw; any significant differential thrust input had to be removed almost immediately or a very large sideslip resulted with almost uncontrollable dutch roll. The big bank angles also coupled into the pitch control. Once excited, the only solution to this was just to get off the throttles and give it about 5 cycles to damp. The resulting approaches were mostly unsuccessful.

After much practice, a more effective technique was developed for flap deflections of 20 deg or greater—to use only the inboard throttles. This seemed to produce more roll and less yaw for a given amount of differential throttle. Several survivable landings were made using this technique. The better technique, however, was to increase speed and improve dutch-roll damping.

Ground effect was an issue on the C-17. At about 50 ft AGL, the nose started to pitch over and the sink rate increased to about 15 ft/sec at touchdown. Whether this would occur on the actual airplane is not known, but extensive modeling of ground effect had been done for the C-17 short-field landings. Ground effect was also an issue on the F-15 and MD-11 flight tests, as discussed below.

Reference 10 discusses some of the C-17 simulator tests using engine thrust for control. In 2003, the C-17 pilot-in-the-loop simulation at NASA DFRC was evaluated for TOC. The cockpit incorporated actual C-17 throttles but other equipment was a functional representation only. The HUD information was displayed on a projected out-the-window display.

This simulation employed the same aerodynamic and propulsion database that had been previously evaluated in C-17 simulators at Long Beach. The TOC configuration typically flown featured a surface float simulation, although a surfaces-fixed mode was also available. The C-17 simulation flew in the TOC mode much like previous simulations. After much practice, safe landings could usually be made on the 300-ft-wide, 15,000-ft-long Edwards runway. The lateral axis control seemed worse than that of the previous simulations in Long Beach.

A “cold pilot” test was conducted in which a low-time commercial pilot with no previous exposure to or knowledge of TOC and only a 15-min familiarization with the C-17 simulation, was suddenly faced with floating control surfaces from a simulated total hydraulic failure. No information or advice was provided. This pilot was able to effectively damp the resulting large phugoid oscillation, and made a 180° turn back to Edwards. Weather was clear with no wind. After a long descent, the pilot initiated a descending turn for a landing on the dry lakebed. The final approach to the lakebed looked good, but the landing gear was not deployed until on short final. The resulting transient excited a phugoid oscillation which resulted in a wings-level but very hard landing with a sink rate of nearly 2000 ft/minute. The test did indicate that under ideal conditions, a “cold pilot” might be able to make a survivable TOC landing on a large dry lakebed.

Subsequent attempts to land the C-17 simulator on the Edwards runway, even with coaching from an experienced TOC pilot, were mostly unsuccessful. Better success was achieved with two pilots (one “cold” and the other experienced) splitting the control task, with landings on or near the runway at low sink rates. The “cold pilot” commented that performing only the pitch task was an order of magnitude easier than trying to do both tasks.

Megatransport Simulation

A conceptual 800-passenger megatransport was designed and a simulation study was conducted to determine the capability of a thrust-only backup flight control system (ref. 4). Location of the four underwing-mounted engines was varied to optimize the propulsive control capability, and the time constant of the engine response was studied. The goal was to provide level 1 flying qualities with a closed-loop PCA system. It was found that the engine location and engine time constant (within reasonable limits) did not have a large effect on the control capability. The PCA design did meet level 1 flying qualities based on frequencies, damping ratios, and time constants in the longitudinal and lateral-directional modes. Pilots consistently rated the flying qualities as either level 1 or level 2 based on Cooper-Harper ratings. However, due to the limited thrust control forces and moments, the airplane design fell short of meeting the time required to achieve a 30° bank angle and the time required to respond to a control input. The TOC capability was quite similar to the B-747.

Cessna 402 Light Commuter Airplane

The C-402 airplane, a light twin-piston-engine commuter airplane, was evaluated in a motion-based simulation at NASA LaRC. As a propeller-driven airplane with both propellers turning in the same direction, the airplane rolled to the left twice as fast as it rolled to the right. However, the roll control was more linear with throttle than was the case for the PA-30 airplane discussed below. There was essentially no pitching moment as the result of power, but speed stability could be effectively used to control pitch. There was significant interaction between pitch and roll. Approaches were flown at a trim speed of 135 kn, with gear down and flaps up. With no turbulence, all landings were on the runway at low touchdown bank angles and sink rates. With light to moderate turbulence, landings were much more difficult. The phugoid was continuously excited, and the pitch-roll coupling was much more of a problem. Not all landings were on the runway at acceptable sink rates and bank angles. Additional landings were flown at 100 kn with partial flaps and with no turbulence. All of these latter landings were successful.

F-15 Fighter Airplane

The Boeing F-15 is a high-performance air superiority fighter with a maximum Mach number of 2.5 (ref. 8). The airplane features a shoulder-mounted swept wing and twin tails. Power is provided by two Pratt & Whitney F100 afterburning turbofan engines mounted in the aft fuselage. At intermediate (maximum nonafterburning) power, thrust is approximately 12,500 lb per engine. Air is supplied to the engines with variable geometry external compression horizontal ramp inlets. Flight control is provided by a conventional hydromechanical control system augmented with a redundant electronic CAS. Takeoff weight was about 40,000 lb.

A piloted simulation of the F-15 was available at NASA DFRC. This simulator was used for an initial investigation of TOC in 1989. TOC was attempted with the CAS off and flight control surfaces locked. At high speed, control power was minimal, but as speed was reduced, control power increased. At 200 kn, roll control was adequate and pitch control was acceptable for up-and-away flight. Simulated landings were attempted, and the first few landings were crashes. After some practice, however, successful landings could be made.

A high-fidelity simulation of the F-15 was also flown at the Boeing (formerly McDonnell Douglas) facility in St. Louis, Missouri. The fixed-base simulator cockpit with much flight hardware was installed in a 40-ft dome with an excellent visual system. As was the case at NASA DFRC, after some practice, TOC landings could be successfully made. Speeds of 170 and 190 kn were flown. Except for a more pronounced pitchover in ground effect, the simulation results were similar to those from the NASA DFRC simulation.

These simulation results were both grossly overoptimistic. When attempted in flight, TOC was much worse than the early simulation results showed. The evolution of the F-15 simulation and comparisons with flight data are discussed in reference 8. Simulations typically do not model subtle propulsive effects properly. A continuing interactive effort was required to get the simulator to match the airplane.

The F-15 airplane and eventually, the F-15 simulation exhibited an undesirable nosedown pitch with increasing thrust that made TOC flightpath control very difficult. It was found that by paying very close attention to airspeed and little attention to pitch attitude, improved flightpath control could be achieved.

A speed-hold autothrottle was added to the simulation, and this made good flightpath control possible. The same technique was used for TOC approaches, and greatly improved the flightpath control precision.

F/A-18 Fighter Airplane

The Boeing F/A-18 is a United States Navy high-performance ground attack-fighter with a maximum Mach number of 2.0. The airplane features a shoulder-mounted wing with actively controlled leading and trailing edge flaps and twin tails. Power is provided by two General Electric F404 afterburning turbofan engines mounted in the aft fuselage, supplied by fixed geometry inlets located under large wing leading edge extensions. Control is provided by a quad-redundant digital fly-by-wire flight control system with a limited hydromechanical backup control.

NASA DFRC F/A-18 simulation. A piloted simulation of the F/A-18 was available at NASA DFRC. This simulator was used for an initial investigation of F/A-18 TOC in 1992. The simulator could be operated in the Direct Electrical Link (DEL) mode with the flaps in override mode. In this mode, electronic feedbacks to the flight control system (FCS) were eliminated, and in the DEL-override mode, the control surfaces would not move unless the stick and rudder were moved, and leading and trailing edge flaps did not move, thus simulating a total flight control failure.

With the simulator flight control surfaces locked, TOC was attempted. Initial results were very encouraging. Pitch and roll control power was good, damping was good, and with the experience from the F-15 TOC tests, engineers and pilots could make safe landing with a little practice.

Boeing F/A-18 simulator. Initial TOC tests in the high-fidelity hardware-in-the-loop F/A-18 simulator in St. Louis were quite successful. The same DEL-override capability was available. Lateral control was good, and pitch control was sluggish but positive. Up-and-away control was quite good, and safe landings could be made after some practice.

As in the case of the F-15, the F/A-18 simulators were both overly optimistic and did not match flight results well; the evolution of the F/A-18 simulation and comparisons with flight data proceeded in a manner similar to that of the F-15. Some of these results will be discussed in the F/A-18 TOC flight results below.

Once the proper propulsive effects derived from the flight data had been added to the simulation, pitch control was very difficult. Thrust increases caused an undesirable initial nosedown pitch. However, it was found that with great attention to airspeed, it was possible to fly a reasonably stable approach. Once the trim speed was found, holding trim speed within a knot would provide a stable flightpath. To increase flightpath, add 1 or 2 kn for a few seconds, then return to the trim speed. Do the converse to reduce flightpath. Using this technique, simulator landings were again possible in smooth air. In turbulence, holding airspeed was much more difficult and flightpath deviations were larger.

Another evaluation was conducted in the F/A-18 simulator in St. Louis to evaluate the use of engine thrust as a yaw damper (EYD). If rudder control is lost, at low speed the natural yaw damping is low and a troublesome dutch-roll oscillation occurs; if engine thrust could be used for yaw damping, control would be significantly improved. The EYD required computer control, and worked very well. Aggressive tracking maneuvering with the rudders locked was evaluated and with the EYD was found to be almost as good as with normal rudder control. Manual EYD was much more difficult, and the workload was so high as to be impractical. Without much practice and attention, throttle control would aggravate rather than improve lateral control.

SR-71 Simulator TOC Evaluation

The Lockheed SR-71 is a delta-wing supersonic cruise airplane with a maximum Mach number of 3.25. It is powered by two Pratt & Whitney J58 afterburning turboramjet engines, each with 34,000 lb thrust. The engines are mounted in large nacelles midway out on the wing. There was a high-fidelity motion-based training simulator of the SR-71 at NASA DFRC. It was flown in the TOC mode by turning off the stability augmentation system and not using the flight controls. With one engine at idle and the other engine at military power (Mil), there was a very powerful roll capability, in excess of 45 deg/sec roll rate. In fact, the roll rate was so high that it was difficult to hold wings-level. The roll due to yaw was very high. Pitch control was very poor. The thrust line is approximately through the *CGZ*, so there is no pitching moment due to thrust. The unaugmented airplane has low static stability. At a speed of 250 kn at 10,000 ft, there was only slight speed stability. It was possible to head in a general direction and maintain altitude to within a few thousand feet, but even getting to an airport is very unlikely. The SR-71 is an example of an airplane that is unsuitable for TOC—it has too much roll response and too little pitch response due to the placement of the engines.

Summary of Simulator TOC Results

The many simulation tests have all shown that TOC is usually suitable for maintaining flight and flying to a landing site. Results have also shown that manual TOC is not usually suitable for repeatable safe landings. Some airplane configurations are clearly easier to control than others, the vertical location of the engines being a major factor. Some simulations were initially overoptimistic, particularly those of fighter airplanes. It must be remembered that although simulator tests are very valuable, many simulators do not adequately model engine thrust effects and results must be considered suspect until proven with flight data. Transport airplanes with podded engines are much easier to model than fighter airplanes with integrated propulsion systems.

Airplanes Tested In Flight

Several airplanes were tested in flight to determine the TOC capability. These are discussed below.

Lear 24 Executive Jet Transport

The Lear 24 airplane (ref. 2) is a twin-engine business jet. The low-mounted wing has 13 deg of sweep. The turbojet engines, each with 2900 lb thrust, are mounted high on the aft fuselage. The airplane has a T-tail arrangement and a maximum weight of 11,800 lb.

The Lear 24 airplane has a thrust-to-weight ratio of approximately 0.5, and the turbojet engines respond rapidly to throttle changes. The Lear 24 tested was a variable stability airplane. The airplane is equipped with the basic Lear 24 mechanical control system, including an electric stabilizer pitch trim capability. In addition, there are hydraulic actuators that add electrical inputs from the variable stability system to the mechanical system. The engines were very responsive, with 2.5 sec from idle to full thrust.

The basic Lear 24 TOC roll control power is large. Roll rates in excess of 25 deg/sec can be obtained with full differential thrust, even with the yaw damper engaged. Time to bank from level flight to 30° was 4 sec.

The basic Lear 24 pitch control capability was also investigated. In contrast to the roll axis, pitch control TOC was very difficult. Because of the high engine placement, a thrust increase caused a nosedown pitch. Eventually, the speed stability would bring the nose back up. The time to achieve a 5° pitch increase was 21 sec. Reducing thrust caused a slight pitchup, followed by a pitchdown as speed decreased. It took 23 sec to achieve a 5° pitch decrease. It was extremely difficult to control pitch. The phugoid was almost impossible to damp with throttle inputs, although the method of very carefully controlling airspeed was not tried.

Because pitch control with throttles was very poor, propulsion-enhanced control was investigated using throttles for roll control and the available electric stabilizer trim for pitch control. This procedure would be a viable control mode for a total failure of the mechanical control system. Starting 40 mi out at 20,000 ft, a descent and approach to the Edwards runway was flown. Despite moderate turbulence, this approach was successfully flown to an altitude of 200 ft above the runway. It is believed that a landing could have been completed.

T-38 Jet Trainer

The Northrop T-38 is a small low-wing two-seat trainer airplane, with a maximum weight of 12,000 lb. It is powered by two General Electric J85 afterburning turbojet engines located close together in the aft fuselage, each with 3850 lb of thrust. Pilots A and B flew the NASA T-38 twin-jet trainer airplane to evaluate the TOC capability in flight.

The TOC capability was evaluated at 12,000 ft and a speed of about 175 kn, with gear down and 60 percent flaps. Roll capability for a small throttle split (approximately 1 in.) was small—only about 1 deg/sec. For a full differential throttle (Mil/idle) the roll rate was 7–8 deg/sec. Using opposite differential throttles, recovery from banks of up to 60° was easily accomplished. Pitch control was also evaluated. The initial response to a throttle increase for power for level flight (PLF) to Mil was minimal; 10 sec was required for a 5° pitch angle increase. Going from PLF to idle, the nose pitched down more rapidly, 7.5 sec for a 5° pitchdown. The thrust line seemed to be through the *CGZ*; there was no apparent pitching moment due to thrust. Throttle friction was low, and was not a problem.

Phugoid damping was evaluated, and seemed to be quite easy at altitude. Roll control was also relatively easy, although it took some effort to trim for wings-level with no throttle split, and this trim seemed to change appreciably when the gear was lowered. It took a significant amount of differential throttle (2–3 in. out of a total throttle throw of about 6 in.) to raise a wing at a reasonable rate.

Approaches were flown to Edwards lakebed runway 18. The approaches were started at 4500 ft, making a 10-mi straight-in approach. There was no turbulence, but there was a slight crosswind from the west, decreasing with altitude. Surface winds were calm. Phugoid damping was more difficult on the approaches. Rate of descent, with a target of 500 ft/min, varied from 0 to –1000 ft/min. Runway lineup was good, but the workload to maintain alignment was high. There were continual small, but significant roll-offs. Returning the wings to level using differential thrust usually upset the pitch control. Roll corrections made by decreasing the appropriate (high-wing) throttle rather than using both throttles seemed more successful. None of the three approaches was fully stabilized, although all probably would have resulted in survivable landings on the dry lakebed.

In summary, the T-38 has adequate control capability with throttles for up-and-away flying. Landing on a runway is very difficult, but a survivable lakebed landing could probably be achieved after some practice.

PA-30 Piston-Powered Light Twin-Engine Airplane

The Piper PA-30 Twin Comanche airplane (ref. 2) is a light twin-piston-engine four-place airplane. It has a low-mounted unswept wing, and Textron Lycoming (Williamsport, Pennsylvania) IO-320 engines with constant speed propellers are mounted ahead of the wing in nacelles. Maximum weight is 3600 lb. The engines are each rated at 160 hp.

The PA-30 airplane was flown with throttles only and had significant pitch and roll control power. However, the airplane was very difficult to control. The roll control on the PA-30 airplane is highly nonlinear. The major rolling moment is caused by reducing the throttle on one side until the blowing over the wing is sharply reduced. The linear response to differential thrust seen on jet-powered airplanes was not present. Maximum roll rates were approximately 10 deg/sec and came only with one engine near idle power. Pitch control was difficult. There was adequate control power available from speed stability, but the longitudinal phugoid was hard to damp. Overall, it was possible to maintain gross control of heading and altitude. Landing on a runway would be extremely difficult.

T-39 Trainer Airplane

The Rockwell T-39 is a military trainer airplane similar to the Sabreliner business jet, with a maximum weight of 18,650 lb. It has two Pratt & Whitney J60 turbojet engines mounted above the *CGZ* on the aft fuselage. All primary flight controls are manual, with an electrically-powered stabilizer trim. There are no dampers. The throttles command quick and repeatable response from the 3000-lb-thrust engines.

Tests were flown in a T-39B at Edwards AFB by pilot A, in clean-configuration tests initiated at 250 and 200 kn, and with gear down at 160 kn, and with gear and flaps down at 140 kn. The lateral-directional control was very good in the clean configurations, with a smooth moderate roll response to a small throttle split. The roll response was well-damped at the higher speeds, “looser” at the lower speeds, but still adequate for landing without excessive workload.

Longitudinal control was much more difficult. The high-mounted engines produce a short-period response in opposition to the long-term speed stability. At high speed, the short-period response was mild, and pitch control was sufficient that altitude could be held to within ±200 ft. As speed was reduced, the short-period response became proportionally larger. In the landing configuration, pilot A found it impossible to compensate adequately to allow fine pitch control for landing.

An approach was flown with flaps up at 160 kn. Lineup was good and with much concentration, pilot A was able to control a shallow glide slope down to 300 ft AGL. At that point, a slight turbulence-induced pitchdown required correction, and it was clear that there was not time to wait for the long-term response to a small correction. A large thrust input was made to initiate a go-around.

The T-39 test showed that the location of the thrust line is perhaps the most important factor in TOC pitch control. The T-39, with strong speed stability, good short-period damping, good lateral-directional control, and excellent thrust response is still marginal at best for landing because of engine location. The very careful attention to trim speed that proved to be beneficial for airplanes with high-mounted engines was not tried on the T-39.

MD-11 Transport Airplane

Pilot A flew the MD-11 to investigate the TOC characteristics. The test airplane was powered by Pratt & Whitney 4460 engines. Initial conditions were a *GW* of 423,600 lb, with a *CGX* of 24.5 percent. The crew turned off the longitudinal stability augmentation system, the automatic flight control system, and yaw dampers at 250 kn, and switched the fuel system to manual to hold a constant *CGX*. Hydraulics remained on so the control surfaces did not float but remained fixed in the trim position. Pilot A released the controls and evaluated TOC. It was adequate at 250 kn, with positive pitch and roll control. He then lowered all landing gear at 250 kn with the normal gear extension system; the airplane pitched up mildly and retrimmed to 235 kn. The center engine was retarded to idle, and *VTRIM* decreased to 205 kn. A series of small throttle step tests were made, and pitch and roll response was quantified. Pilot A commented that the airplane flew much like the simulator: good roll control, no dutch roll, and slight overshoot on rollout. The speed was reduced with stabilizer trim and flaps and gear extended. At 150 kn, the dutch-roll damping was low, and a persistent dutch roll could not be damped by Pilot A or the company test pilots. Speed was increased to 165 kn, where dutch-roll damping was much improved. A series of TOC approaches were flown to Yuma runway 21 in light-to-moderate turbulence. The first approach at 200 kn with flaps up was discontinued at 500 ft AGL over the threshold, idle thrust being too high for the 3° glide slope. The second approach was flown at 165 kn with flaps at 30°. This approach was successful, and a TOC go-around was initiated at 200 ft with a minimum altitude of 50 ft AGL over the threshold. The entire pattern was flown using TOC. The third approach was flown at 165 kn and looked good at 500 ft, at which point another test required a normal landing to be made. A fourth approach was flown later in smoother air at 200 kn on a shallower glide slope. This approach was going well until a thermal upset occurred at 300 ft AGL. Overall, the airplane TOC test validated the flight deck simulator results. Of the four TOC approaches, one appeared suitable for a survivable landing.

Later, after the PCA system had been installed and tested on the MD-11, each of 20 demonstration pilots flew a few minutes of manual TOC. All commented on the difficulty of avoiding a phugoid oscillation, even when the airplane was initially in trim and in level flight. Figure 41 of reference 1 shows a typical example time history of a pilot with only a few minutes of simulator experience trying to fly TOC, and shows a divergent phugoid oscillation despite the stabilized initial condition.

B-747 Shuttle Carrier Aircraft (SCA)

During routine ferry flights of the B-747 Shuttle carrier aircraft (SCA) without the Space Shuttle aboard, some very limited and benign TOC tests were conducted. The SCA is a B-747-100 modified to carry the Space Shuttle. The addition of small vertical fins on the ends of the horizontal stabilizer and the Shuttle attach struts are the external differences. For these tests, no changes from normal SCA operation were made; the crew simply released the normal controls and Pilot A made small throttle changes. Pitch control was generally sluggish but positive, much like the simulator. Lateral control was sluggish, also similar to the simulator. A TOC descent was made, including flap extension and gear extension, and the variation in trim speed was found to be similar to that in the simulator. Lowering the landing gear reduced trim speed by 40 kn. Since hydraulics remained on for all of the tests, the effects of floating surfaces were not determined.

C-17 Military Transport Airplane

Since powered lift was a key feature in the C-17, much attention had been paid to proper modeling of thrust effects. Wind tunnel data and analytical data were supplemented by flight data taken early in the C-17 flight program.

A brief flight test was conducted on a C-17 airplane in May of 1996. The purpose was to validate simulator models of thrust effects at conditions of interest for TOC flight. For these tests, the C-17 stability augmentation system remained active; thus, the flight control surfaces moved in response to the throttle inputs.

The throttle step inputs were performed at altitudes from 20,000 ft to 5,000 ft with flap settings of zero, one-half, three-quarters, and full. The inputs were a combination of inboard, outboard or both sets of throttles for either longitudinal or lateral-directional axes. The flight control surface movements and resulting airplane motions were compared to the simulator, and good comparisons were found.

F-15 Fighter Airplane

The TOC capability of the F-15 was studied in flight. The NASA F-15 Highly Integrated Digital Electronic Control (HIDEC) airplane was used. The FCS could be operated in a mode with the CAS off and the pitch and roll ratio changers set in an “emergency” mode in which the ratios remained fixed. The automatic inlet controllers could also be set in an “emerg” position in which they did not move and would go to the full-up position. In this mode, the airplane simulated a total hydraulic failure. The pilot released the controls and used manual TOC for control. The airplane control was much worse than that seen in the simulator. Lateral control power was adequate and yaw damping was good, but roll damping was poor, and continuous throttle motion was required to hold wings-level. Pitch control was also much poorer than the simulator. Pitch control exhibited a distinct adverse effect; thrust increases resulted in an initial nosedown pitch followed later by a pitchup as speed increased. Contributing factors were high throttle friction and mismatched engines. Flight tests and simulation upgrades were made interactively over a two-year period as discussed in reference 8, and eventually the simulation was made to closely match the flight results. The simulation changes are shown in Table 3. TOC approaches are shown in figures 22 and 43 of reference 8 and exhibit the same characteristics.

Table 3. Changes to the NASA DFRC TOC/PCA F-15 simulation.

SIMULATION CHANGE
1. Lock F-15 control surfaces at any given position
2. Incorporate augmented PCA control laws from B-720
3. Incorporate inlet effects at 8° AOA
4. Separate *Fg* and *Fr* terms
5. Add thumbwheels for control inputs
6. Incorporate *CGZ* and *CGX* as a function of fuel quantity
7. Model no-feedbacks flight control system
8. Add airplane manufacturer’s ground effect model
9. Add landing gear dynamics model
10. Incorporate improved engine thrust and dynamics model
11. Add engine gyroscopic moments
12. Accept flight inputs into batch simulation mode
13. Add nonlinear inlet effect at 8° AOA
14. Add flightpath command box to HUD
15. Add airplane manufacturer’s PCA control laws
16. Incorporate updated *CG*, inertia, weight for test airplane
17. Incorporate velocity feedback into PCA mode
18. Revise ground effect model per flight test data
19. Incorporate heading command mode into PCA logic
20. Incorporate added bank angle control logic features
21. Incorporate updated differences between auto and emergency inlets for full AOA range and the inlet effect as a function of AOA and throttle

F/A-18 Fighter Airplane

A Boeing F/A-18 airplane at NASA DFRC was modified to conduct manual TOC tests. The program support flight control computers were installed, which allowed the DEL mode to be selected from the cockpit. In this mode, electronic feedbacks to the FCS were eliminated, and in the DEL override mode, the leading and trailing edge flaps did not move. In August of 1995, flights were conducted. It was found that the TOC capability of the airplane was much worse in flight than that found in the F/A-18 simulator operating in the same DEL-override mode. Pitch control exhibited a distinct adverse effect; thrust increases resulted in an initial nosedown pitch followed by a pitchup as speed increased. Lateral-directional characteristics were also worse than the simulator. Roll control power was similar, but dutch-roll damping was much less than in the simulator. The F/A-18 TOC results have not been reported previously, so some detail is presented here.

The NASA F/A-18 flown was a two-seat F/A-18B, tail number 845. With test equipment and instrumentation and ballast, it had an empty weight of approximately 26,000 lb and 36,000 lb at full fuel.

The airplane was flown in the clean configuration with a nominal *CGX* at takeoff of 21.7 percent. Figure 10 shows the F/A-18 *Fg* and *Fr* vectors for AOAs of 0° and 10°. The engine *Fg* vector is located at waterline (WL) 100, while the *Fr* vector is at WL 86. The unfavorable inlet thrust moment at 0 deg is significantly reduced at 10 deg.

Because the *CGZ* had been found to be important for TOC in the F-15, the *CGZ* for the F/A-18 was calculated and is shown in figure 15. It is seen that fuel quantity has a substantial effect on *CGZ* as well as on *CGX*, and that the heavy high-sink-rate landing gear position also has a big effect—when lowered, it hangs far below the airplane.

Figure 16 shows a time history of a throttle reduction at 210 kn, with gear down and flaps in the auto (3°/3°) position with gain override on, allowing no control surface or flap movement. With 7000 lbs fuel, *CGX* was 21.5 percent and *CGZ* was 101 in. and AOA was 7°. Both throttles were reduced by 10 deg. Speed decreased immediately, but the nose did not drop for the first 5 sec. Although both throttles were reduced by the same amount, there was a small yawing moment induced, probably because of unequal thrust decrease or differing engine response. The yaw rate and sideslip initially appear divergent, the dutch roll caused airplane roll rates that reached 5 deg/sec, and the bank angle exceeded 20°. The presence of a roll response when only a pitch input was attempted contributed to the difficulty in manual TOC on the F/A-18, as it had in the F-15.

Throttle increases resulted in a definite nosedown pitch at all but the lowest tested airspeeds. Figure 17 shows a summary of four throttle step increases for a variety of speeds and configurations. In all cases, the AOA is reduced and the initial pitch rate is negative. The overall response, however, varies from a favorable *FPA* increase at the lowest airspeed to unfavorable *FPA* decreases for the higher speeds. The worst response was for the gear-down high-speed case.

Differential throttle doublets were also tested. Figure 18 shows tests at two airspeeds in which the right throttle was first decreased by 0.5 in., then increased by 1 in., and then returned to the trim position. A roll rate of 10 deg/sec resulted at both airspeeds; the damping was higher at the higher speed.

The effects of airspeed and configuration were studied. The adverse pitch response was improved by operating at high fuel quantity, with gear up, and lower speed. Lowering the gear, flying faster, and flying at light weights exacerbated the pitch control problem. The disagreement between flight and simulation was very similar to that seen on the F-15, and the lessons learned were applied in updating the simulator. The CGZ effects of fuel and landing gear position were first properly modeled, which accounted for part of the discrepancy. The inlet *Fr* vector had to be moved to lower than its actual position to match flight data. This was probably due to the inlet being under the wing leading edge extension and mass flow variations affecting the pressure on the lower leading edge extension surface. Once these data were added to the simulator, the pitch response matched flight well. The lateral response in the simulator was still too optimistic.

Summary of TOC Tests

Several airplanes have been tested in simulation, in flight, or in both, to determine the propulsive flight control power available. Some aircraft have also had a PCA system developed and evaluated. Thrust-only control has been evaluated on these aircraft and can be generalized as follows:

- Starting from an initially trimmed condition, every airplane studied has adequate gross control capability using only engine thrust for continued flight.

- After some practice, heading or flightpath could usually be controlled to within 3° to 5°; after more practice, heading and flightpath could usually be controlled to within 2° to 3°.

- Using manual TOC, making a safe runway landing is very difficult. The low propulsive control forces and moments, the slow engine response, and the difficulty in damping the phugoid and dutch-roll oscillations create an extremely high pilot workload. Unless there is much time for practice, a safe runway landing is very unlikely.

- Simulators of transport airplanes tend to be good, but simulations of fighter airplanes with highly-integrated propulsion systems require much more effort to achieve a good match with flight.

OBSERVATIONS FROM AUGMENTED TOC (PCA) RESULTS

Augmented TOC systems called PCA systems have been developed and tested in flight on the F-15 and MD-11; and on simulations of the C-17, B-747, ACFS B-757, B-720, and a conceptual megatransport. These results have been reported previously. For this report, it is of interest to observe the computer-controlled closed loop system thrust response, since the flight control precision and damping is greatly improved. There may be some observable characteristics that can be used by pilots to improve TOC.

The thrust response to a step input in commanded *FPA* was somewhat similar for the MD-11, B-747, B-720, and F-15 PCA systems. The response for the F-15 PCA system in flight is shown in figure 19. Note that there is an initial large throttle input followed very quickly by a reduction in throttle back to or even below the trim thrust value. The response for the transport airplanes, B-720, MD-11, and B-747 is shown in figure 20. This time, *EPR*, a parameter proportional to thrust, is the parameter shown. The *EPR* is the actual engine thrust response whereas throttle position is the thrust command. In any case, similar characteristics are shown. The PCA logic basically employs attitude and attitude rate feedback in both axes to provide stable well-damped control. The initial throttle or thrust “pulse” gets the rate going; the logic then reduces thrust to control the rate until the target attitude is reached.

This “pulse” usage of thrust is considerably different than the typical pilot flying manual TOC who makes a small throttle input and leaves it in until the response is observed (see figure 13). A pilot is usually good at seeing the attitude changes, but not necessarily so good at seeing the rate changes. Once the attitude change is observed, the established rate often guarantees an overshoot and the need for another correction. In the longitudinal case, the phugoid natural damping is usually very low, and once excited, specific actions need to be taken for damping it out. The use of short thrust pulses may be a way of improving the success of TOC flight control, but this has not been studied in detail in flight.

This thrust pulse technique was used to some degree in the F-15 simulation after the F-15 PCA flight tests were completed, and showed some promise; Figure 55 of reference 8 shows the use of thrust pulses and the resulting improved flightpath control. Further evaluation of this technique is needed.

Thus, a better technique for manual TOC may be to make a relatively large throttle step input and then remove it almost immediately. The resulting motion can then be observed and additional inputs made as required.

SUGGESTED TECHNIQUES FOR TOC FLIGHT CONTROL

The following techniques should be generally valid for TOC of a multiengine aircraft as might be required after total loss of hydraulic pressure, a total loss of hydraulics to the tail, or severing or jamming of some or all flight control cables. Of course the degree of success for a specific airplane will depend on its unique aerodynamic and thrust response characteristics. Depending on the subsystems design, there is the possibility of using secondary and backup systems in addition to thrust to effect a measure of control.

Immediate Actions

If a subsystem is deteriorating (such as gradual loss of hydraulic fluid) and is likely to fail before a landing can be made, consider establishing a landing configuration and trim to a safe approach speed before total system loss. Once all primary flight controls are lost, the first requirement is to level the wings and establish constant altitude and heading flight. There is a steep learning curve in the throttle-only technique. What seems impossible at first will usually show rapid improvement with practice. Often there will still be some flight control surfaces still operating. Splitting the roll and pitch tasks between pilots may improve performance and lessen workload.

Lateral-Directional Control Techniques

Lateral-directional TOC involves yaw control and dutch-roll damping. These are discussed below.

Yaw Control

Differential thrust may be used to control yaw. Depending on the engine locations, they may be very effective or rather ineffective, but all multiengine airplanes have a usable amount of yaw control, and this results in roll control. Differential throttle inputs, however, often excite the dutch-roll oscillatory mode.

Dutch-Roll Damping

Dutch-roll oscillations that may occur, being of relatively short period (approximately 6–8 sec), are often very difficult for a pilot to control with manual TOC. In fact, the dutch-roll mode is often aggravated by pilot attempts to damp with throttle inputs because the engine lag is similar to the period. It is best to let the dutch roll damp naturally, and to minimize inducing dutch roll by using only small differential throttle inputs or using short throttle pulses when changing bank angle. If the dutch-roll oscillations are persistent or very objectionable, dutch-roll damping can usually be improved by increasing airspeed, if practical.

If a yaw offset exists, such as might be caused by airframe damage, throttle stagger may be required to trim to a near-zero sideslip. The throttle stagger will not necessarily be a constant amount, particularly as throttle position approaches idle, and should be handled cautiously.

Bank Control

Bank control can be accomplished using differential thrust between left and right engines; the resulting yaw causes a roll rate which can be modulated to give the desired bank angle. Engine spoolup lag, distance of the engines from aircraft centerline, amount of dihedral effect, roll due to yaw coupling, and roll damping all affect the timing and technique needed to precisely establish the desired bank. On aircraft with more than two engines, reducing thrust on inboard engines will allow higher thrust on outboard engines which may improve roll control response. Dutch-roll oscillations are usually aggravated by throttle inputs—it is best to let them damp naturally, and to minimize inducing them by using small differential throttle inputs or using short throttle pulses when changing bank angle.

Bank angles must be kept small to avoid interactions with pitch control. Keeping bank angles to less than 10° and preferably within 5° will minimize the pitch-bank interactions.

If the airplane is not trimmed laterally because of damage, it may be necessary to hold a steady throttle offset (stagger) to maintain wings-level. Lateral mistrims equivalent to as much as 3° of rudder may typically be accommodated. Throttle stagger may complicate pitch control when either idle or full thrust is required. If a substantial throttle split is required to hold a constant heading, it may be possible to reduce the throttle split by transferring fuel and/or payload away from the engine with the higher throttle setting.

Pitch Control Techniques

As discussed above in the “longitudinal control principles” section, there are several effects of thrust that affect pitch control. Only two of these are of importance to the flight crew—the pitching moment due to the thrust, and the phugoid mode.

Pitching Moment Due to Thrust

For a transport with underslung engines, thrust will directly control AOA, and hence pitch attitude. An increase in thrust will rotate the airplane to a higher AOA, increasing lift as well as (over the short term) increasing speed. The key is to monitor pitch attitude closely, preferably with reference to a visual horizon, and to make immediate thrust corrections to stop any pitch movement, however tiny. The use of short throttle pulses may be preferable to making a throttle input and leaving it in until the effect is apparent.

Phugoid Mode

If the long-period oscillatory mode in which airspeed and altitude are traded (phugoid mode) is excited, it will usually not damp in a reasonable time. Figure 8 shows the important parameters in a phugoid. Note that airspeed leads pitch attitude by 90 deg which leads altitude by 90°. Note also that the phugoid period is on the order of 40 sec, much longer than the engine lag time, so pilot throttle inputs are effective in damping the phugoid mode.

Determining Trim Airspeed

The trim airspeed, shown in figure 8, is important in pitch and phugoid mode control. There are several ways to find the trim speed. Be sure NOT to make any big thrust changes while determining trim airspeed.

a. Averaging method: One is to note the maximum and minimum speeds during a phugoid cycle and average these values. Note and set an airspeed reference bug, if available, at this speed.

b. Speed at maximum nose-high attitude: Another perhaps easier way to find the trim speed is just to note the airspeed as the nose stops rising during the phugoid oscillation. Set an airspeed reference bug, if available, at this speed.

c. Speed at lowest nose-low attitude: The trim speed is also reached just as the nose reaches its lowest point and starts to rise. Set an airspeed reference bug, if available, at this speed.

Trim airspeed may slowly change over a period of many minutes, as weight changes as fuel is burned, or as *CGX* shifts slightly with fuel burn. Thus, it may be necessary to occasionally redetermine the trim airspeed.

The above information is valid for wings-level flight. During a turn, the trim airspeed does not change, but a higher speed will be required to maintain a given flightpath. Do not try to determine trim airspeed during a turn with anything other than a small bank angle of less than 5°.

Phugoid Damping

Good phugoid damping is critical for TOC flight. A variation around the trim speed of ±5 kn will cause approximately ±500 fpm variation in rate of sink. Once the trim speed is determined using any of the three techniques, it is then necessary to force the airplane to fly at the trim speed and keep it there within a knot or two. This may be done by trial and error, or more efficiently, by the methods discussed below.

Phugoid Damping—Low-mounted Engines. The transport airplane with underslung engines is the easiest configuration for damping the phugoid. There are at least three methods that will work.

Phugoid Damping Method 1. As shown in figure 21, as the nose is falling from the maximum pitch attitude toward the level flight attitude, airspeed will be decreasing toward the minimum value. As the nose is falling, add sufficient thrust to force the airspeed to increase as closely as possible to the “bug” speed just as the nose falls to the level flight attitude. Immediately reduce thrust to that required for level flight.

Continue this damping procedure until the pitch attitude is completely stabilized. Reset the reference bug to exactly the trim speed and monitor speed continuously. More than a knot or two of speed change will indicate the need for a thrust correction to avoid an unwanted pitch attitude change.

Phugoid Damping Method 2. A similar procedure will also work, and is shown in figure 22. It uses a thrust reduction just as the nose has reached its maximum dive and is starting up, but it may not work as well as method 1 if thrust is already low or near idle. Continue this damping procedure until the pitch attitude is completely stabilized. Reset the reference bug to exactly the trim speed and monitor speed continuously. More than a knot or two of speed change will indicate the need for a thrust correction to avoid an unwanted pitch attitude change. (If holding the trim speed is not producing the desired flightpath, adjust the bug slightly).

Simple Phugoid Damping Method. A third method works for airplanes with underslung engines. It does not require finding the trim speed, but simply calls for the following: if the nose is coming up (rate of climb is increasing), reduce thrust slightly. (The nose is coming up because you have more speed than needed). If the nose is dropping (rate of climb is decreasing), increase thrust slightly (the nose is dropping because you have less speed than needed). Keep the thrust changes small and use the pulse method and soon the phugoid should be smaller. Keep at it until it's well damped. You'll be at the trim speed without even knowing what it is. Now note it (set bug), keep the speed with a few kn of the trim speed, and the pitch is under control.

Phugoid Damping—High-Mounted Engines. The normal underslung-engine phugoid damping techniques do not work for an airplane with high-mounted engines having the thrust line above the *CGZ*. In fact, using the underslung-engines techniques aggravates the phugoid. But a technique has been developed that relies on the strong pitching moments from high-mounted engines and close attention to trim speed. As before, the trim speed can be found from any of three techniques:

a. Calculate the average of the maximum and minimum speeds during cycles of the phugoid.

b. Note the speed just as the nose stops dropping on the down cycle.

c. Note the speed just as the nose stops rising on the up cycle.

Phugoid Damping Method. Knowing the trim speed, as the rate of climb is at a maximum (being at the trim speed), sharply increase thrust as represented in figure 23. This forces the nose down and keeps the speed up near the trim speed. Then, as the nose falls through an *FPA* still slightly positive (approximately 2°), go immediately to idle. This gives a strong noseup moment and, if executed properly, results in a slight positive *FPA* with the speed still at the trim speed. Then, easing the throttle back up to the trim throttle setting pushes the nose down to level flight.

Simple Method. A simpler but less effective way to damp the phugoid of an airplane with high-mounted engines is just to find the trim speed and use throttles to force the airspeed to the trim speed, independent of pitch attitude. This method will take longer but will eventually reach the goal of zero pitch rate at the trim airspeed.

Autothrottle Speed-Hold Method. Another way to damp the phugoid if an airplane has a speed-hold autothrottle is to determine the trim airspeed, dial it into the airspeed window, and engage the autothrottle system. THIS ONLY WORKS FOR AIRPLANES WITH MID- OR HIGH-MOUNTED ENGINES!

Once the phugoid is damped, small throttle movements may be made to vary flightpath, with much attention to speed and not much to attitude. It takes about 10–20 sec after a thrust increase before the *FPA* becomes positive, but if speed is only increased a few kn and then returned to near the trim speed, the long-term effect will be the desired slight climb. Much experience is needed to properly use thrust for flightpath control for airplanes with mid- or high-mounted engines.

Long-Term Flightpath Control

Once the phugoid is damped and a stable flightpath has been reached, a pilot will want to know how to climb and descend without excessively exciting the phugoid mode. Obviously, to climb, a pilot will need to increase thrust, and the short-term effect will be a speed increase. But for an airplane with underslung engines, increasing thrust will rotate the airplane to a higher AOA and, in the long term, decrease speed slightly. So contrary to intuition, to climb, a pilot would need to set the airspeed bug to a lower value, and conversely, to descend, the speed bug should be increased to a slightly higher airspeed. A +1°-change in flightpath typically requires approximately a –2-kn change in airspeed. In figure 14, note the 5–6 kn increase in speed on the 3° glide slope.

For an airplane with high-mounted engines, the opposite is true; the speed change is in the same direction as the flightpath change. This is why a speed-hold autothrottle will stabilize the phugoid and provide flightpath control for the high-mounted engine configuration.

Airspeed Control Techniques

As discussed earlier, if the horizontal stabilizer cannot be moved, the trim airspeed will be only slightly changed by thrust. Other methods will have to be used for control of airspeed such as a *CG* shift by moving fuel and/or payload, lowering gear, extending flaps. If the speed is higher than that desired for approach, there will probably be ways to lower the trim speed. If the speed is already at or below the desired approach speed, it may be desirable to increase the trim speed, and there may be fewer ways of increasing trim speed.

WARNING

Do not reconfigure the airplane without first considering the likely effects on trim airspeed.

Methods of Airspeed Control

Some methods of trim airspeed control have been studied for the MD-11, B-747, C-17, and B-757 transport airplanes, and are discussed below.

If there is a loss of hydraulic pressure, the trim airspeed may be strongly affected by floating control surfaces. The typical situation is for the ailerons to float up. If there are outboard ailerons on a swept wing, this will create a noseup moment that lowers trim airspeed. This is a situation over which you have no control.

MD-11. The MD-11 flaps are driven by hydraulic power, so if that is lost, the flaps cannot be moved. However, the fuel system provides the crew with the ability to shift fuel. There is an alternate gravity landing gear extension system, and the three-engine layout allows thrust to be redistributed. Reference 1 discusses speed control options for the MD-11. With the stabilizer locked at climb or cruise settings, it is still practical to lower the landing speed to a desirable 200 kn, as shown in figure 24. Although the chart is based on analysis and simulation results, some of these numbers were verified in flight test, including the control surface float with ALL hydraulics shut off.

B-747. The B-747 has an electric alternate flap extension system, and with proper selection of cockpit switches and circuit breakers, inboard and outboard flaps can be controlled independently. In some simulators, lowering inboard but not outboard flaps lowered the trim speed significantly. With the cruise stab setting for 285 kn, lowering the gear and flaps showed an airspeed of 195 kn. In the NASA ARC B-747 simulator, the effects of surface float and flap extension were modeled and resulted in smaller reductions; from cruise at 290 kn, after all hydraulics were failed and gear lowered, airspeed was 240 kn. The JAL accident airplane (see appendix A) started at 300 kn and after surface float was at 250 kn, and after gear extension was at 225 kn; however, the exact tail configuration of this damaged airplane was unknown.

B-757. The B-757 airspeed control was also investigated in the NASA LaRC simulator. Beginning at 255 kn, lowering the gear reduced speed to 230 kn. Lowering the flaps (with the electric alternate extension system) to 1° (leading edge slats only) lowered trim speed to 212 kn. FLAPS 5 trim speed was 201 kn, FLAPS 15 was 187 kn, and FLAPS 20 was 162 kn. This simulator did not attempt to model control surface float and possible interaction between flap downwash and flow over the horizontal tail.

C-17. Speed control on the C-17 simulator showed a slowing due to aileron float of 35 to 75 kn. Lowering the gear reduced speed another 10 kn.

Summary of Airspeed Changes from Methods other than *CG* shift

Figure 25 shows the airspeed changes with configuration for the C-17, B-757, B-747, and MD-11. Although each airplane has its own capabilities and features, each is capable of reducing speed by as much as 100 kn without using *CG* shift. These data, except for the MD-11, are based on simulation results that may or may not be accurate, but do illustrate a range for various airplanes.

Effects of *CGX* Shift

The *CGX* may be shifted on some airplanes. Moving *CGX* aft decreases trim airspeed. (In one incident described in appendix A, a crew moved passengers forward to help counter a jammed stabilizer).

MD-11. On the MD-11, there is about 5 kn of slowing per percent of *CGX* shift, and the fuel system has the capability for the crew to shift *CGX*. However, *CGX* is normally kept near the aft limit during climb and cruise flight, so there may not be any further shift available. Longitudinal stability with the aft *CGX* is lowered, but the thrust of the underslung engines is then even more effective at producing pitching moment. Simulation and flight results showed that TOC was as good at aft *CG* as at forward *CG*.

B-747. On the B-747, the crew has less control over the *CG* than on the MD-11. But tests in the simulator showed that moving the *CG* aft did not affect the TOC capability. In figure 26, the PCA system step responses of an extreme aft *CG* limited by the travel of the stabilizer are compared to those of a normal aft *CG*. Although the responses were produced by PCA system tests, TOC would be subject to the same effects. Note the smaller change in thrust at the aft *CG* required to produce the same pitch response. Also note the very small airspeed change at the aft *CG*.

Approach and Landing

For the approach and landing phase, important issues include the selection of the landing site and landing configuration. These are discussed below.

Selection of Landing Site

Once in reasonably straight and level flight, the best available landing site should be determined and the aircraft headed in that direction. The prime consideration is to find the longest and widest suitable surface within range at the existing speed and fuel state. The combined TOC task of controlling sink rate, touchdown position, and runway alignment is extremely difficult. The condition of the surface around the runway is important due to the strong possibility of an undershoot, overshoot, or off-the-side touchdown. A hard, smooth, dry lakebed would be the ideal site. A very large smooth agricultural field might be better than a confined runway. Other considerations are weather, daylight, and availability of fire, rescue, and hospital services. Visual flight rules with low winds and turbulence are preferable. Fuel should not be dumped unless necessary, but saved for TOC technique practice and for making multiple approaches.

Selection of Landing Configuration

Methods to establish landing configuration and retrim to an appropriate approach speed may be considered enroute. These actions should be accomplished during a slow descent well in advance of an attempted approach. Possible ways to retrim to a slower speed are: shifting the *CG* aft by fuel management or payload shift, lowering inboard flaps (only on a swept-wing airplane), backup system repositioning of the horizontal stabilizer, and lowering landing gear (as discussed above in the “airspeed control” section). All configuration changes should be made slowly and carefully, keeping the phugoid well-damped as the trim speed changes. Keep in mind that lowering the gear will probably lower trim speed 15–40 kn. Burning off fuel will also result in a gradual change in trim airspeed, usually a reduction.

Most airplanes have brake accumulators that will provide limited braking after landing. If wheel braking is not available, a gear-up or soft field landing may be needed. A B-747 with no hydraulics will have no wheel braking, and from a 220 kn runway touchdown, will roll for nearly 6 mi.

Gear Up or Down?

There are arguments in favor of either technique. Depending on the landing surface, a gear-up landing may be appropriate. A gear-up landing will certainly damage the airplane and possibly increase the danger of fire, but it will derotate the airplane, prevent a bounce, and provide a short slideout. Lowering the gear will increase drag, probably reducing trim speed and increasing the required thrust, which may be important. In addition, the gear will absorb some energy in a very hard touchdown. The decision will depend on the selected landing site, the availability of braking, the trim airspeed, and the need for the extra drag of the extended gear and open gear wells.

If the decision is made to lower the gear, do so at an altitude well above the ground (several thousand feet). Remember the experience of the C-5 and B-52 crews (see appendix A) when they lowered the gear and lost 5000 and 8000 ft, respectively!

With underslung engines, adding some thrust as required will prevent a pitchover as the gear extends; the trim speed will be reduced. With high-mounted engines, added thrust will be needed, which will cause a short-term pitchover and eventually a retrim to higher airspeed.

If the airplane is equipped with an alternate gear extension system, it usually leaves the wheel wells open and the landing gear doors extended. This can be a useful way to increase the drag and further lower the trim airspeed.

Approach Glide Slope

The TOC approach glide slope is an important consideration. If the trim airspeed is high (above about 190 kn for a typical transport airplane) and flaps cannot be lowered, it may be difficult or impossible to fly a normal 3° glide slope because of low drag. It is important to have engine thrust well above idle for faster engine response and thrust modulation, but this further shallows the flyable glide slope. The B-747-400 with gear and flaps up at 220 kn requires a glide slope of approximately 2° or shallower to maintain thrust above idle. The MD-11 with no flaps and gear down at 200 kn requires a 2.3° or shallower glide slope. The C-17 with gear down but no flaps at 200 kn can fly a 2.5° or shallower glide slope.

A shallow glide slope is also desired for a TOC approach, if practical, so that the sink rate is relatively low and not much flare is required. This would also suggest a 1–2° glide slope. However, depending on the landing site, such a shallow approach has a higher possibility of landing short, and this must be considered.

Initial Approach

Once the approach configuration and airspeed have been decided and achieved, a trial glide slope should be executed, and the airplane TOC pitch and bank response **IN THIS CONFIGURATION** should be evaluated. If possible, spend 15–30 min in this evaluation, first descending on a glide slope, aggressively maintaining a heading, and then climbing out. Be sure to note the altitude loss in a simulated go-around ***particularly with high-mounted engines***. It may be less than 100 ft for an airplane with underslung engines and more than 300 ft for high-mounted engines.

Once the TOC response is well-understood, begin an initial approach to the landing site. The longest possible approach is the best—20 mi is not too long. Once on the desired glide slope, aggressively try to maintain runway alignment and glide slope as this will be the difficult task for the actual touchdown.

Final Approach

Do NOT assume that having been able to achieve enough control to get to the landing site and begin an approach guarantees that you will have the same success landing. The final approach will be the time when control limitations with TOC become critical. The gross control that was adequate for cruise and initial approach will likely NOT be adequate for achieving and maintaining runway lineup and glide slope. This is why multiple approaches and go-arounds are suggested if time and fuel permit.

Underslung Engines. For a transport with underslung engines, adding power and climbing away from the ground is relatively easy, so unless conditions are deteriorating, plan for multiple approach attempts. On final approach, bank angle should not exceed 5° to prevent unwanted pitch perturbations. Pitch attitude must be rigidly controlled to maintain a constant shallow glide slope, with an approximately 400–500 ft/min descent rate, all the way to touchdown. Below 500 ft any slight balloon, phugoid oscillation, or bank upset greater than 5° is reason to add power, go around, and make another attempt. A go-around may be possible as low as 100–200 ft AGL, depending on the sink rate.

High-Mounted Engines. For an airplane with high-mounted engines, a go-around below the altitude found above will not be possible, so practice as much as practical and then commit to the landing. Remember that any go-around must be initiated well above the ground, as the initial response to thrust will be to increase sink rate for the first *5–10 sec*, and it may be 10–20 sec or more before a positive *FPA* is achieved! If the sink rate nearing touchdown is too high, the thrust may be *reduced* a few sec before reaching the ground.

Flare and Touchdown

For a runway landing, hold the constant approach path to touchdown, reducing thrust only after ground contact or if floating just a few feet above the runway. As ground effect is entered, there may be a pitchdown or pitchup, depending on configuration, airspeed, and flap setting. It may be better to accept a moderate sink rate (500–600 ft/min) rather than to try to flare and possibly balloon or float in ground effect. Then use reversers if available and wheel brakes if available for directional control and deceleration.

With underslung engines, there are two typical but improper pilot responses on a first actual TOC landing. One is to reduce thrust to idle as the runway is approached—this will increase the sink rate to possibly dangerous levels and may cause a roll input as well if there was any throttle stagger required to hold wings-level. The other reaction is to add thrust just prior to touchdown to reduce the sink rate. A little thrust pulse may be warranted, but if too much, this causes a balloon which may force a go-around. For underslung engines, a go-around after a balloon should still be possible.

For a non-runway landing, first priority is to land wings-level. The sink rate can be quite high and still result in a survivable landing. Shutting off underslung engines immediately prior to touchdown might reduce the fire hazard, but will likely increase the sink rate significantly and decrease lateral control, and should be delayed until after touchdown.

TOC Go-Around

The go-around is easily accomplished for airplanes with underslung engines, but there is one caution. Maximum thrust can be used initially to rotate the airplane and get rapidly to a positive rate of climb. However, at high thrust on climb-out, the strong noseup pitching moment will increase AOA and **REDUCE** the trim airspeed appreciably. If trim airspeed on approach is relatively low, it may be necessary to use less-than-full thrust on climb-out to prevent the trim airspeed from getting too low and/or AOA becoming too high.

With high-mounted engines, a go-around is NOT possible, once below the critical go-around altitude.

Additional TOC Help and Aid

Additional help for a TOC landing may be available in certain circumstances. Some of these are discussed below.

ILS

If the intended landing site has an ILS and your airplane has a functioning ILS system, the ILS error signals can be helpful in making a TOC approach. The ILS errors display smaller errors than can be sensed visually, and can be used for making small throttle inputs to correct the errors. It may be desirable or necessary to fly a lower-than-normal glide slope, perhaps one to two dots low. This increases the thrust required and decreases the sink rate and flare requirements. Of course, an ILS may be needed if visibility is limited.

Flight Director

If the aircraft is equipped with a flight director, this can provide even more help than the ILS error signals. The flight director senses rates as well as position errors, thus providing additional help in staying on the intended approach path.

Splitting of Control Tasks

Depending on the airplane configuration and the controllers remaining, it may be desirable to split the lateral and longitudinal control tasks among the crewmembers. For example, on a four-engine airplane, it has been demonstrated that one pilot controlling pitch with inboard engines and another controlling lineup with outboard engines provides a better chance of a survivable landing than one pilot doing both. In any case, each task is so difficult that combining the two may be an intolerable workload for a single pilot.

If there is remaining lateral control available with aileron or rudder, that task may be performed by one pilot while the other handles the pitch control with thrust. A third example, on an airplane with high-mounted engines, was having one pilot use the autothrottle speed controller for pitch control while the other pilot made differential throttle inputs for lateral control.

In any case, such split-control strategies should be conceived and practiced as much as possible before committing to an approach or landing.

Ten Steps to a Survivable Landing Using Only Throttles

All of the above discussion has been summarized in the condensed list below:

1. If a wing is low, push that wing's throttle(s) up until wings are level. Continue to use asymmetric thrust as required to control bank angle and heading.
2. If the pitch attitude and airspeed continually oscillate, determine the approximate steady state trim airspeed by averaging the high and low speeds seen and set a reference bug or mark at that speed.
3. Damp the pitch oscillation using aggressive throttle inputs to force the airspeed to the steady state trim airspeed as the nose approaches a level attitude.
4. Continue this process until all pitch oscillations are stopped. Constant, precise control of airspeed is the key to prevent oscillations from beginning anew.
5. Gentle climbs and descents can be initiated with a thrust change and then repeating the damping process of step 4. The steady state trim airspeed may change slightly in a climb or descent.
6. Select a suitable landing site: the widest, longest and smoothest landing area with good weather within reach. Emergency services and ILS are also desirable.
7. Well before a landing attempt, configure for landing. Expect a pitch upset and a corresponding trim airspeed change when landing gear are lowered. Flaps, if available, should be lowered in very small increments.
8. Make a very long, flat, straight-in approach with no configuration changes.
9. Hold a flat approach all the way to the ground; do not reduce thrust before touchdown unless floating just above the ground.
10. Last minute lineup corrections are very difficult, go-arounds are easy. Fuel permitting, a go-around should be accomplished if in doubt about the impending touchdown.

For technique advice: Gordon Fullerton at 661-276-3214.

TOC Techniques for Single-Engine Airplanes

The above discussions assume multiple engines for TOC. However, a single-engine airplane that has some other source of lateral control capability but no pitch control, may still use TOC as an option. Appendix B discusses the transport airplane that may be able to use a *CGY* shift to allow a single remaining engine to provide limited pitch and roll capability. Appendix C (ref. 11) discusses the light single-engine airplane that might still have rudder or aileron control but needs to use the throttle for flightpath control.

CONCLUDING REMARKS

If normal flight controls are lost, emergency flight control may be attempted using only engine thrust. Flight test and simulation results on many airplanes have shown that pilot manipulation of throttles is usually adequate to maintain up-and-away flight, but is most often not capable of providing safe landings. Problems with throttles-only-control (TOC) involve weak control moments, difficulty in damping phugoid and dutch-roll oscillations, coupling between pitch and roll, and sluggish engine response. Techniques exist that will improve control and increase the chances of a survivable landing. The principles of TOC are reviewed. A history of accidents or incidents in which some or all flight controls were lost is given. Manual TOC results from numerous simulation and flight tests are reviewed, and suggested techniques for flying with throttles are presented, both for lateral and longitudinal control. The techniques differ for airplanes with underslung engines and for airplanes with high-mounted engines. Methods for changing the trim airspeed are also discussed.

Methods for damping the phugoid oscillation involve properly timed thrust pulses to stabilize the airplane at the trim airspeed. Dutch-roll oscillations are best left to damp naturally. The ability to use TOC effectively improves rapidly with practice. Small throttle pulses may be more effective than larger throttle movements. TOC for up-and-away flight and initial approach may appear adequate but the refined techniques needed for final approach and landing require extensive practice and experience and should be practiced as much as practical. A shallower-than-normal approach may be needed. If the engine configuration is appropriate, splitting the TOC task among crewmembers is probably desirable.

FIGURES

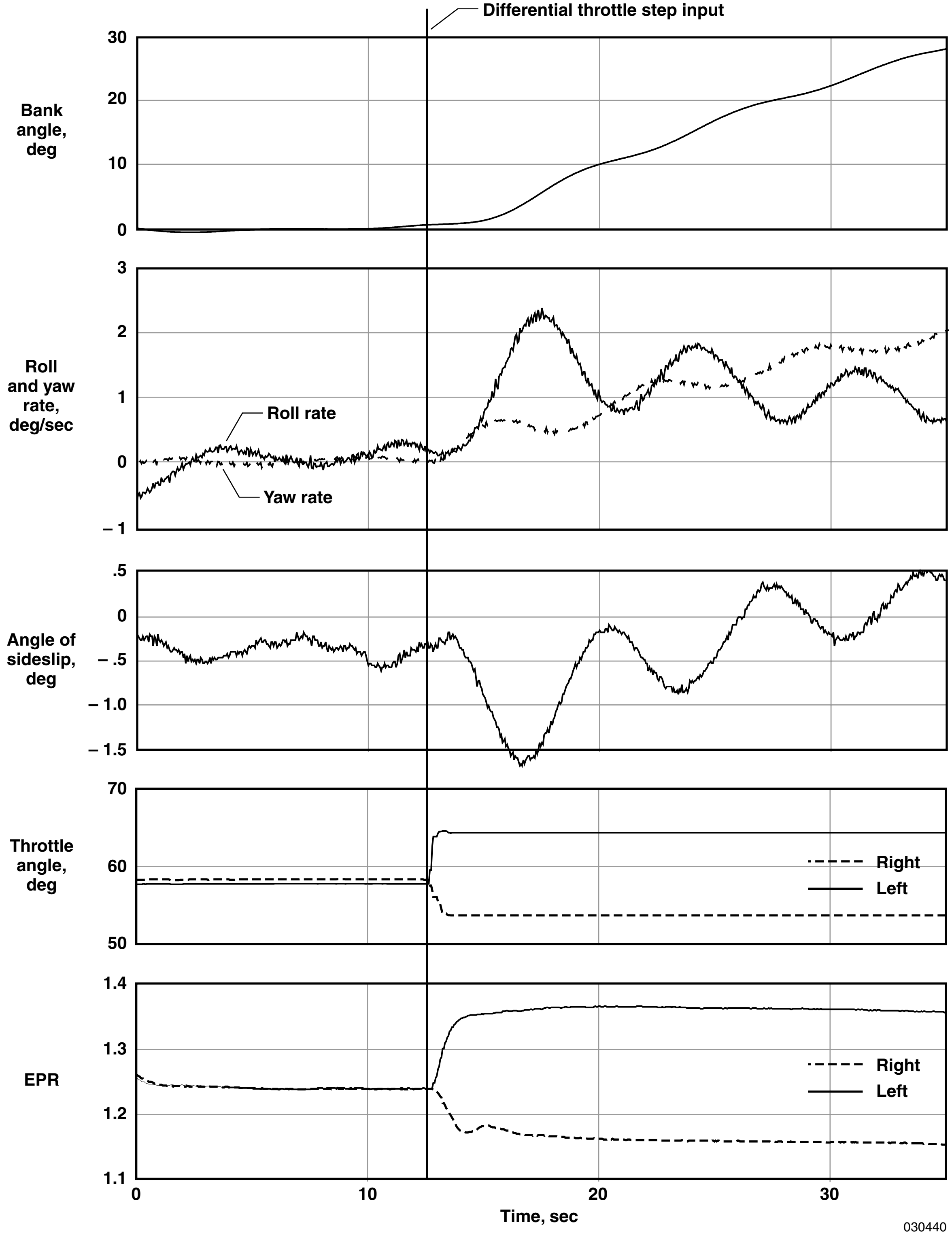


Figure 1. Differential thrust open-loop step response, MD-11 flight data, 220 kn, an altitude of 15,000 ft, flaps up, gear down, center engine idle, pitch and yaw dampers off.

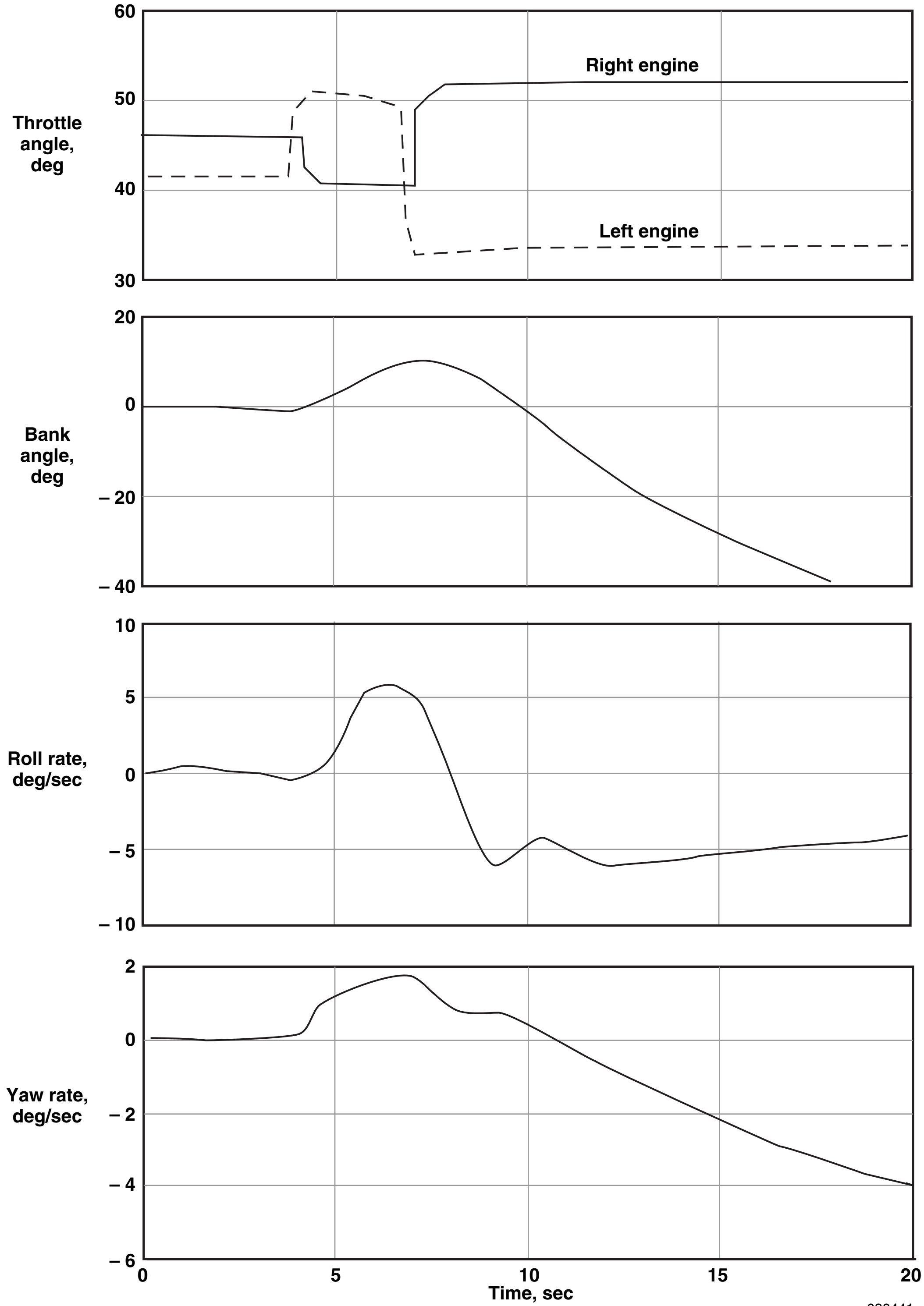


Figure 2. Differential thrust doublet, F-15, gear down, flaps up, 170 kn.

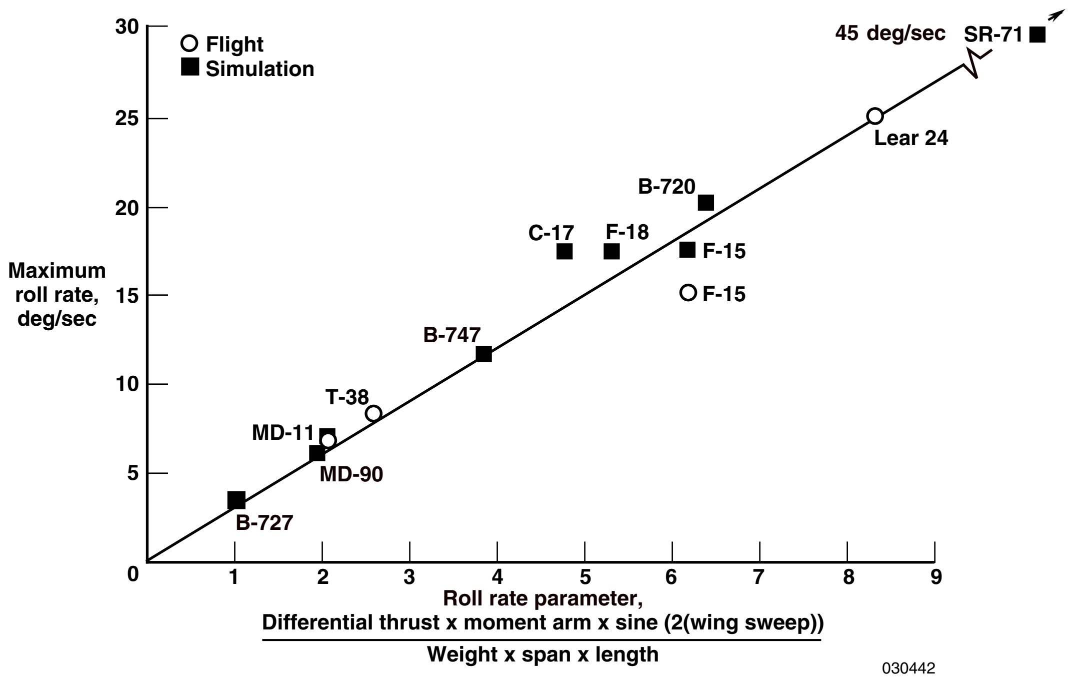


Figure 3. Maximum roll rate as a function of roll-rate parameter, approximately 200 kn, flaps up, full (nonafterburning) differential thrust.

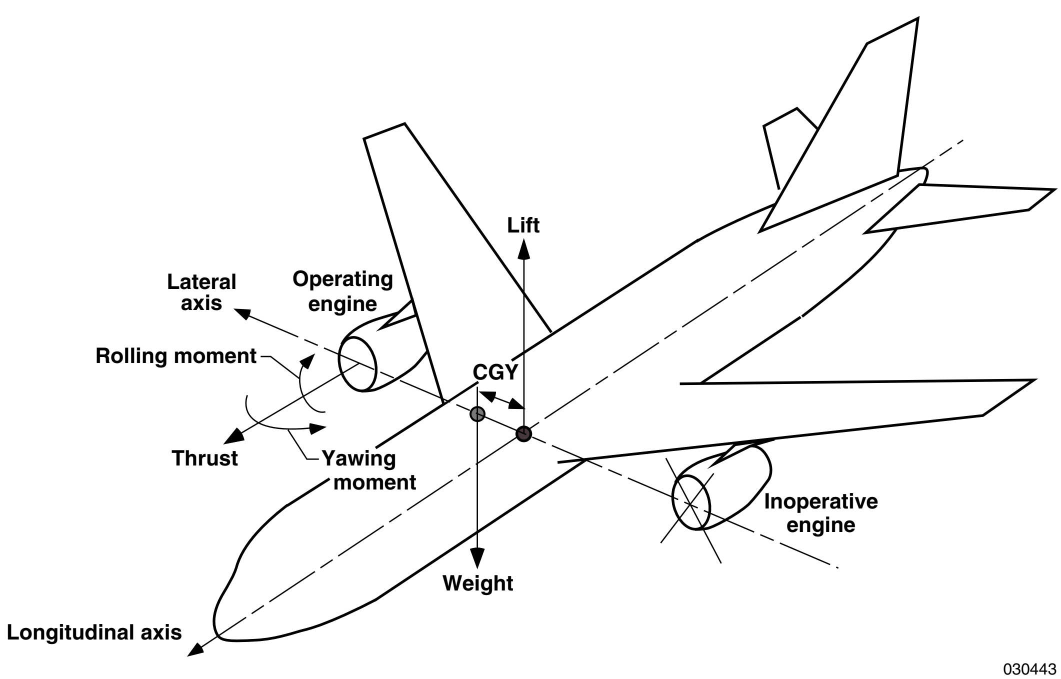


Figure 4. Forces and moments on an airplane with a wing engine inoperative and a *CGY* offset.

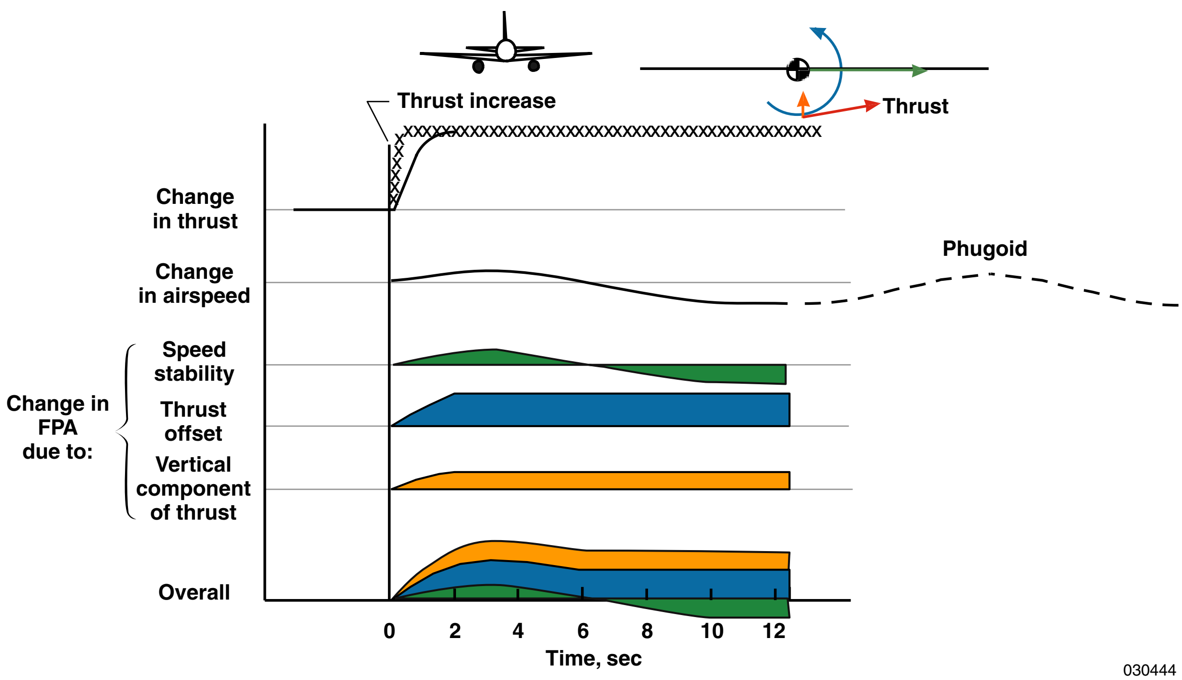


Figure 5. Pitch axis effects resulting from thrust increase, thrust line well below the *CG* (underslung engines).

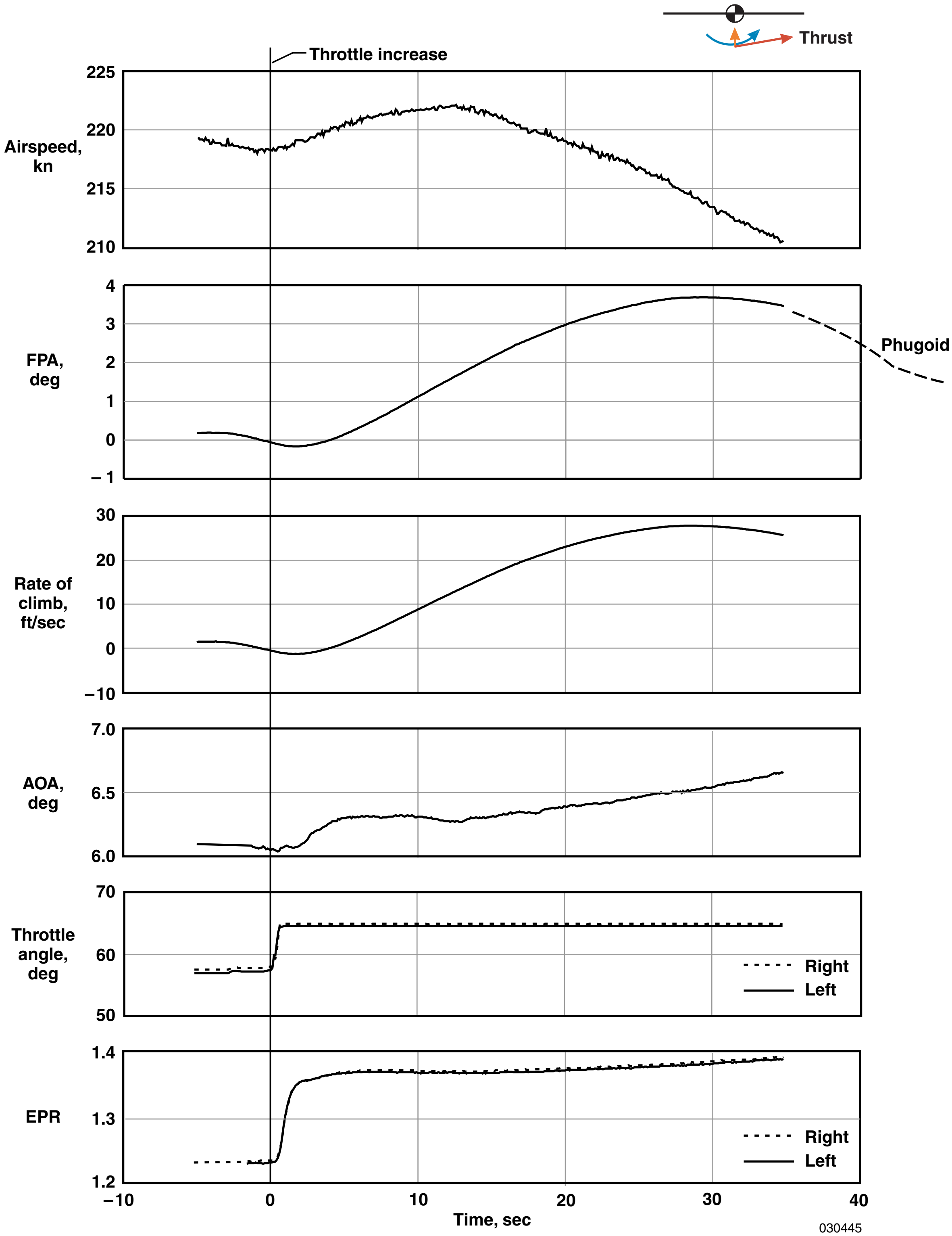


Figure 6. Longitudinal response to open-loop step throttle increase, MD-11 flight data, center engine idle, gear down, flaps up, an altitude of 15,000 ft, no control surface movement.

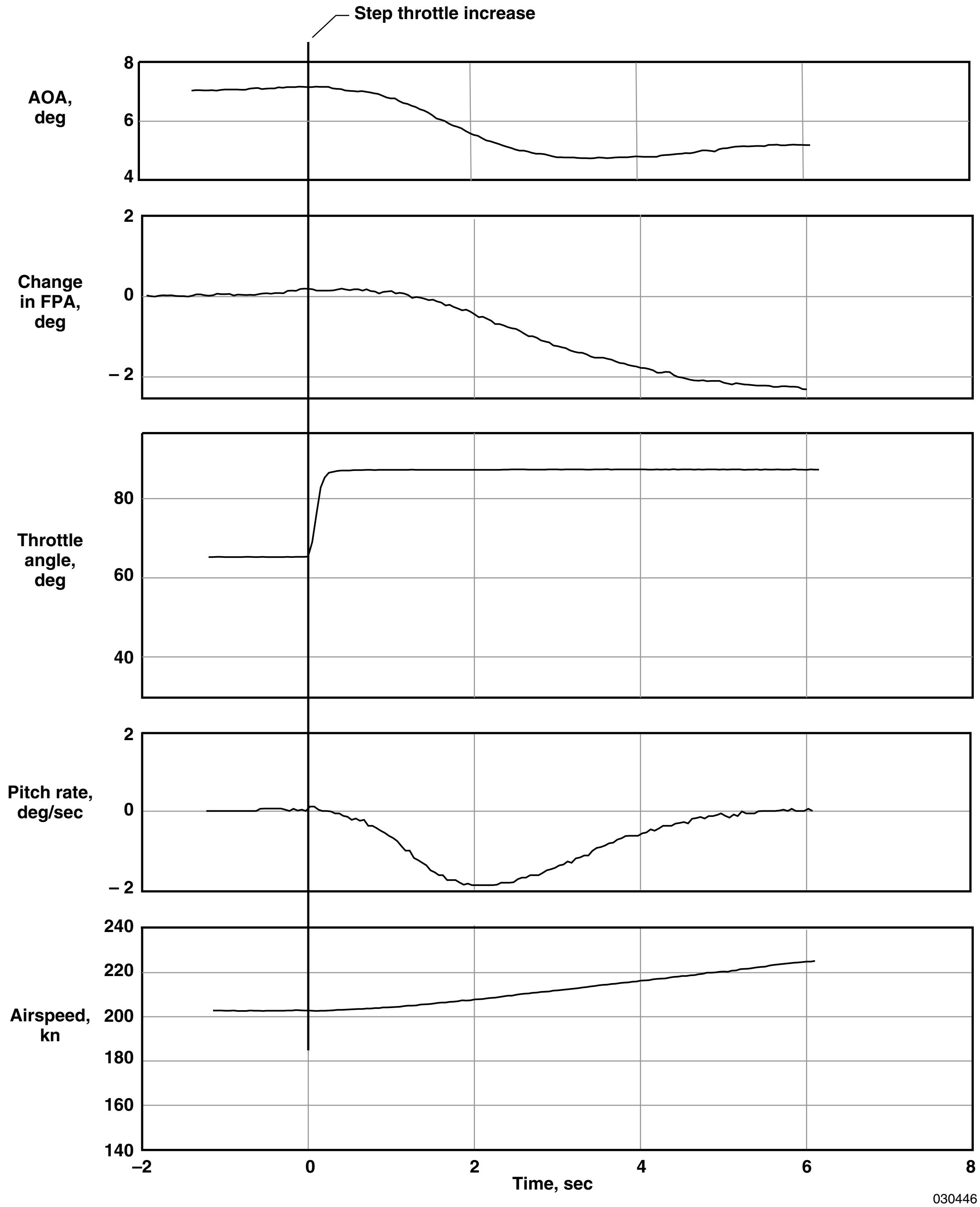


Figure 7. In-flight F/A-18 airplane TOC response to step throttle increases, no control surface motion, landing gear down, leading and trailing edge flaps down 3°, *CGZ* = 98 in., (2 in. below the thrust line).

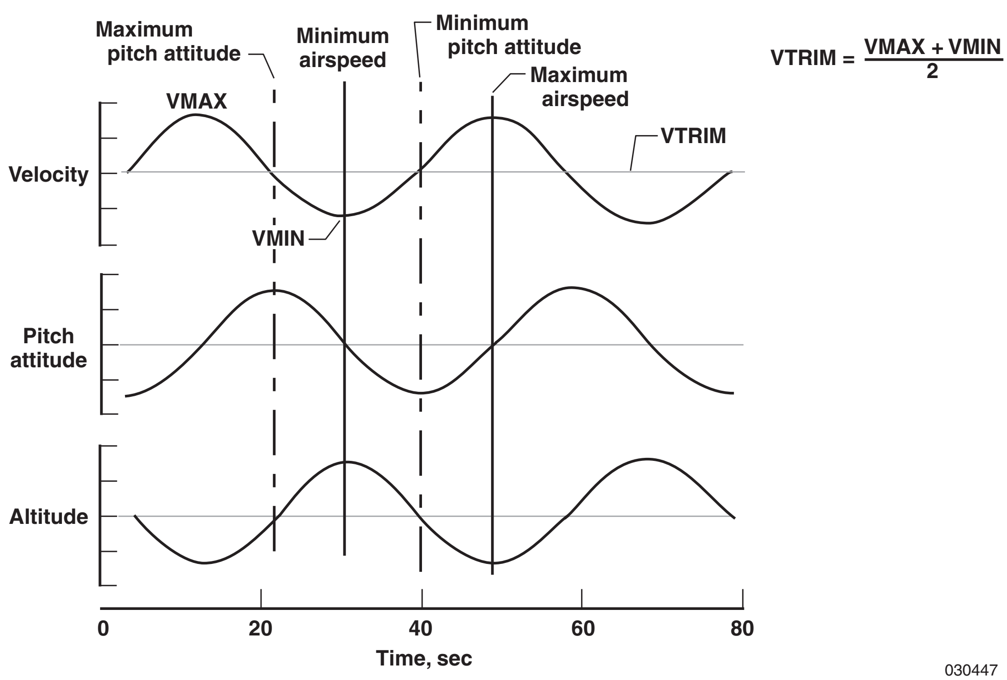
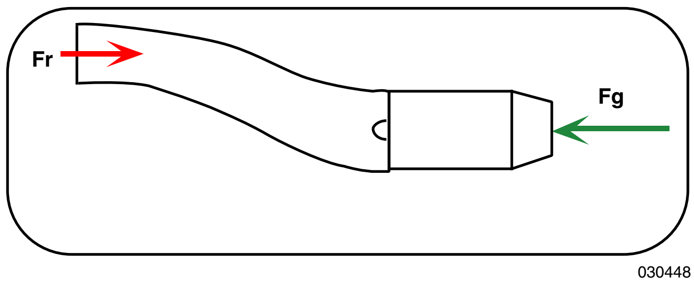
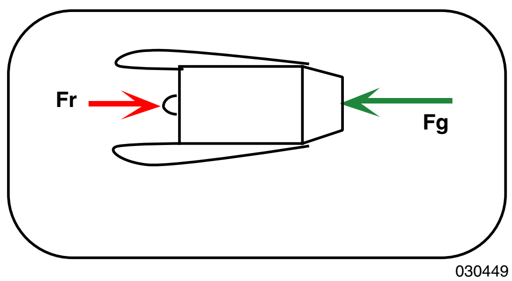


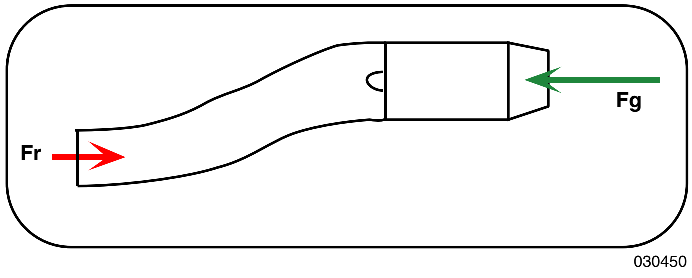
Figure 8. Typical longitudinal phugoid oscillation showing *VMAX*, *VMIN*, and *VTRIM*, which occur at maximum and minimum pitch attitude.



(a) Favorable configuration (B-2, center engines of L-1011, B-727, Falcon 50); *Fr* above *Fg*, noseup moment with thrust increase.



(b) Neutral configuration (podded engines); no pitching moment from *Fr* and *Fg*.



(c) Unfavorable configuration (F-16, F-18); *Fr* below *Fg*, nosedown moment with thrust increase.

Figure 9. Effects of relative positions of engine inlet and exhaust nozzle on thrust pitching moment.

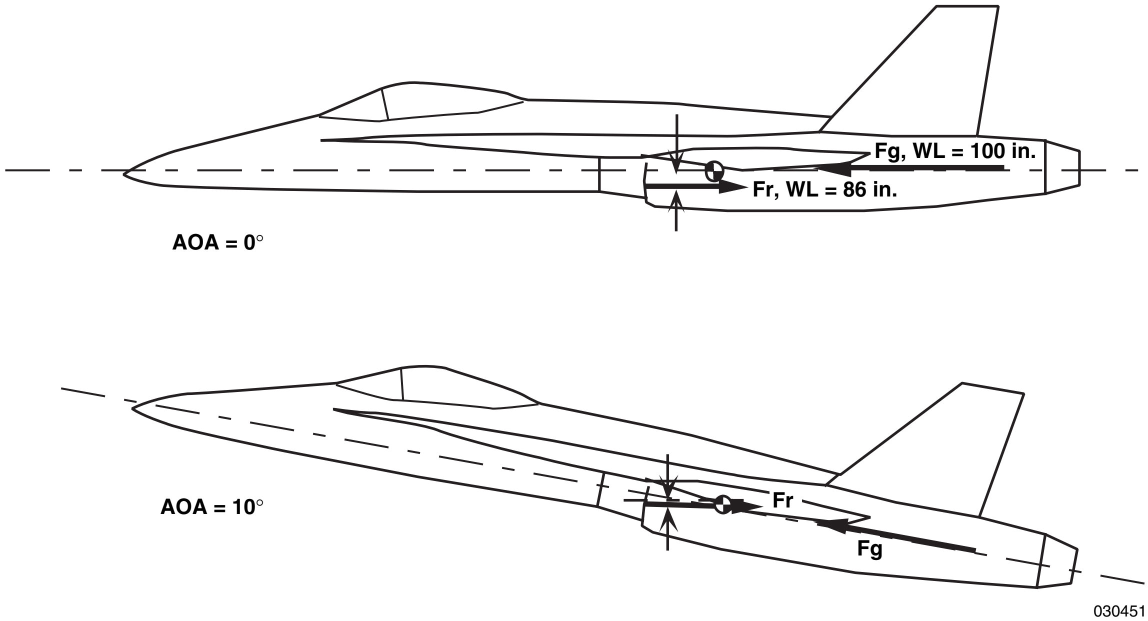


Figure 10. Effect of AOA on F/A-18 *Fg* and *Fr* vectors showing that increasing AOA reduces the unfavorable pitchdown, *CGZ* = 99 in.

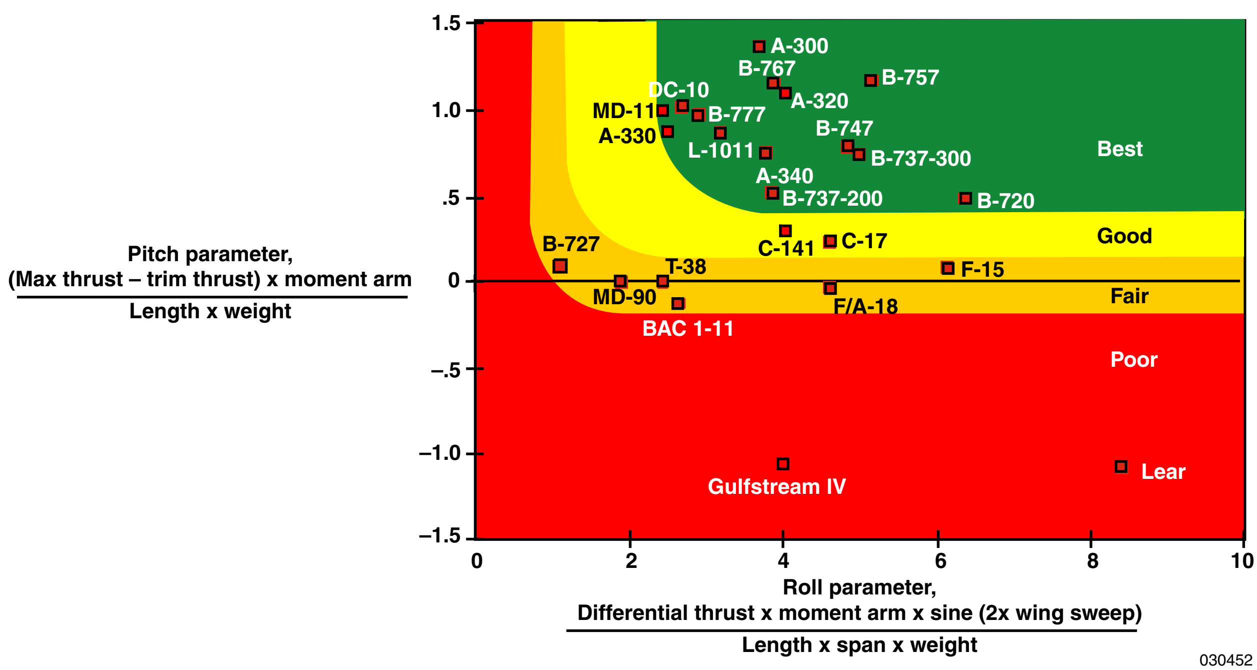


Figure 11. TOC pitch and roll correlation parameters, maximum capability (without afterburning), 200 kn, low altitude.

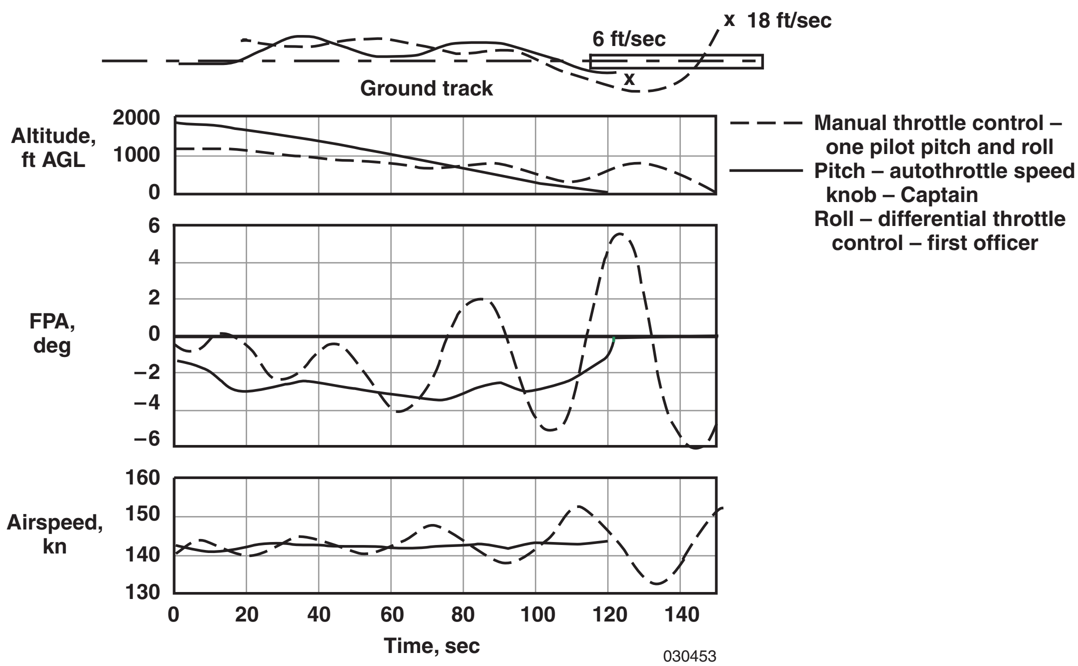


Figure 12. Comparison of manual TOC and autothrottle speed hold, MD-90 simulator approach and landing, 30° flaps, yaw damper off, no control surface movement.

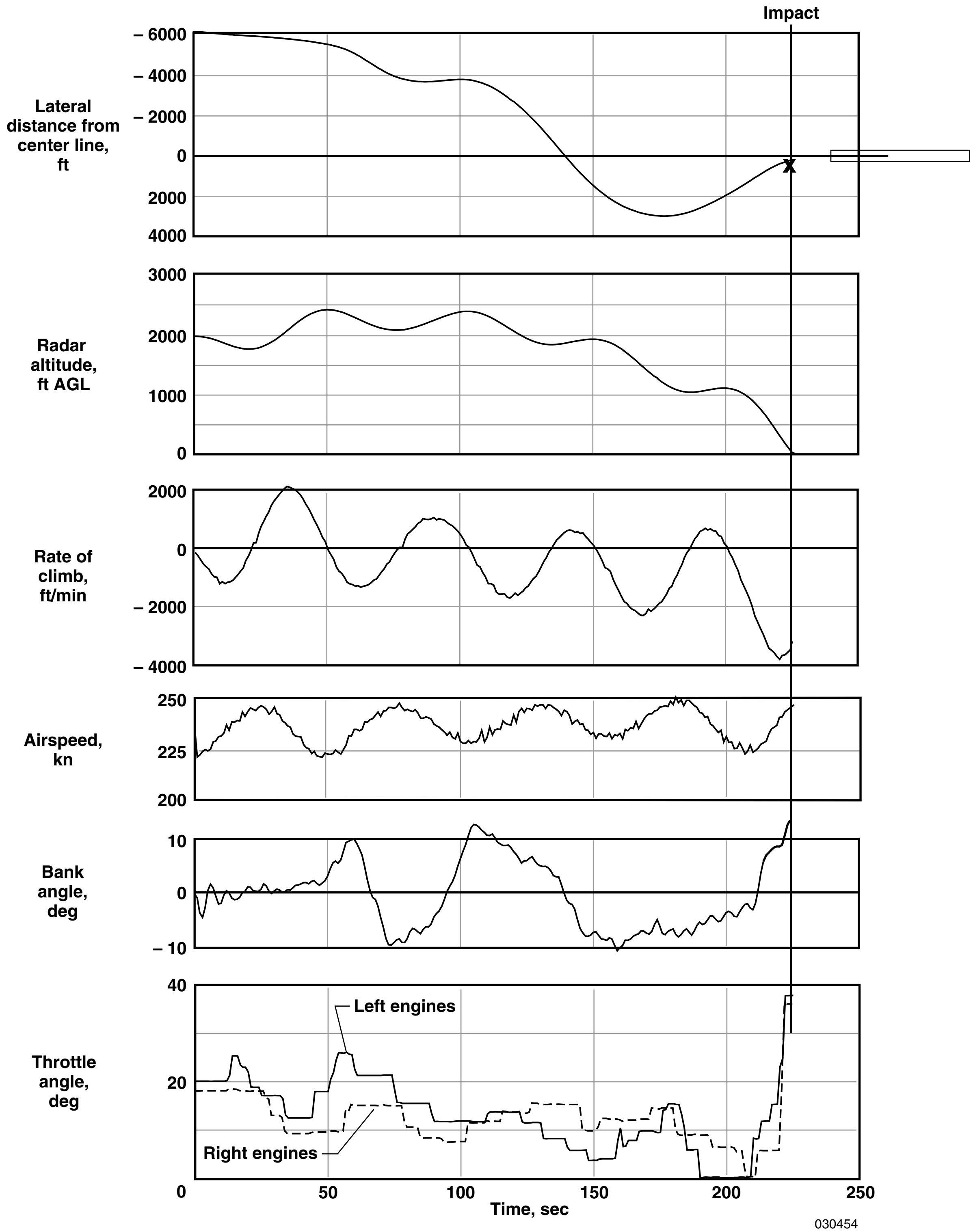


Figure 13. Manual TOC approach with all flight controls failed, Pilot C, gear down, flaps up, B-747-400 simulator.

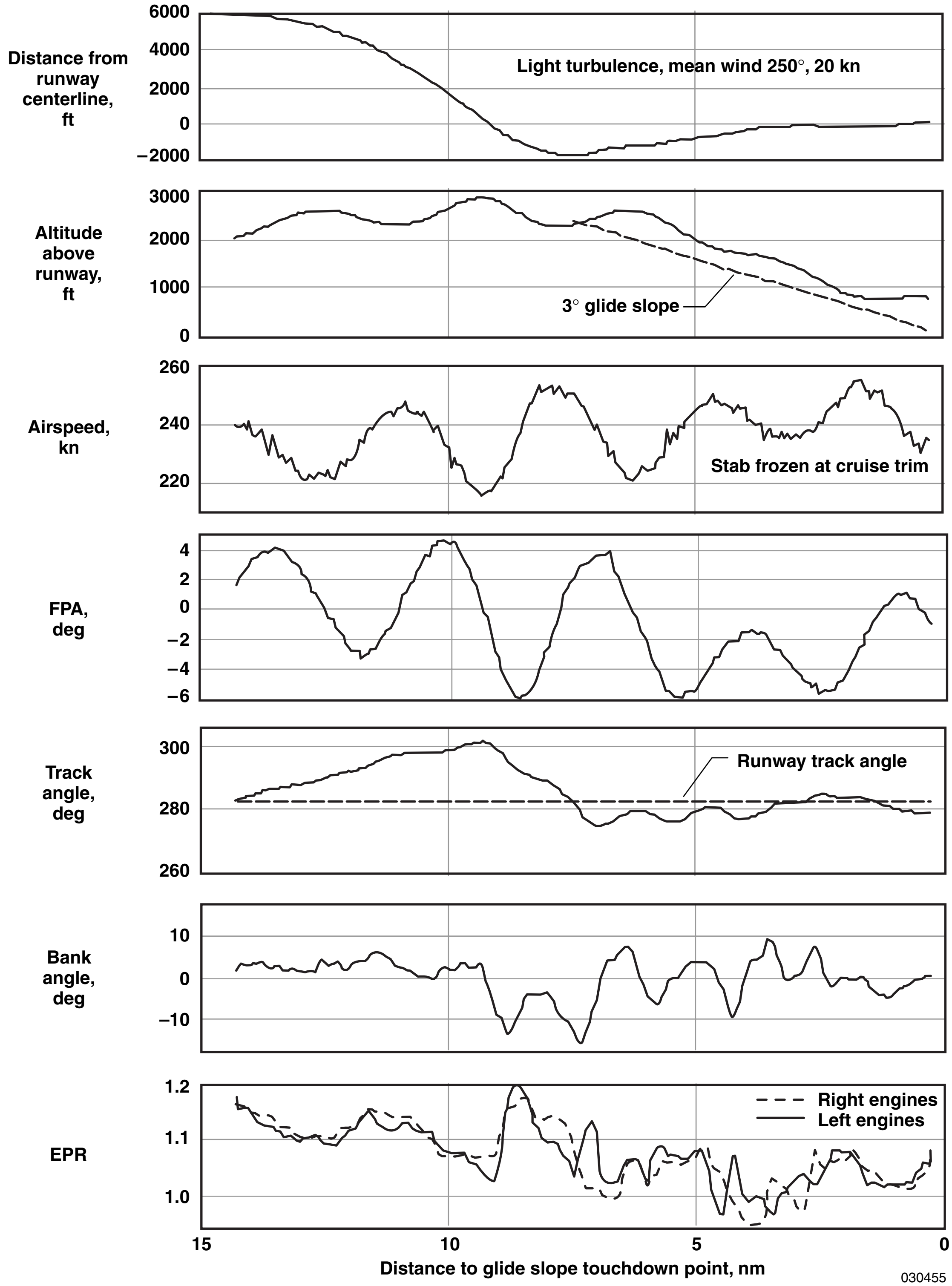


Figure 14. Manual TOC approach with all flight controls failed, Pilot D, gear down, flaps up, GW = 540,000 lb, CGX = 22 percent, B-747-400 simulator.

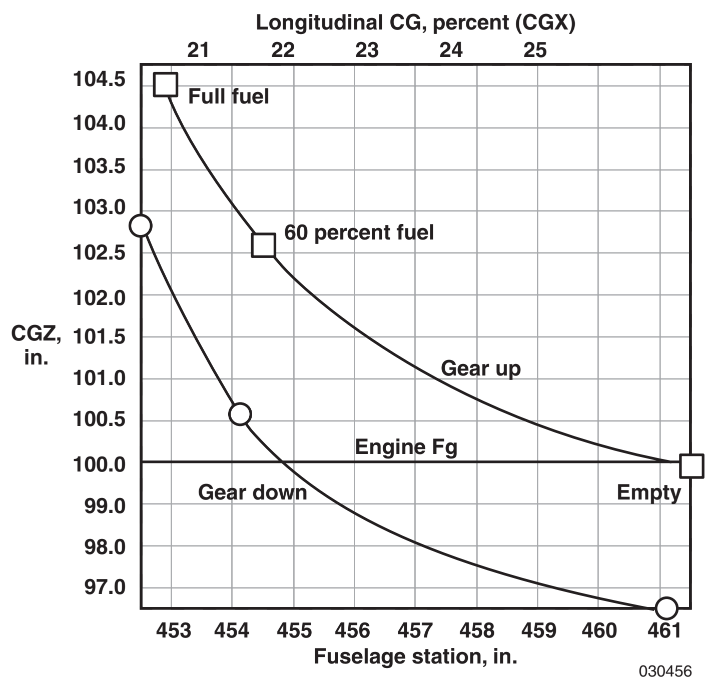


Figure 15. Estimated *CGZ* and horizontal *CGX* variation with fuel quantity and landing gear position, F/A-18 845.

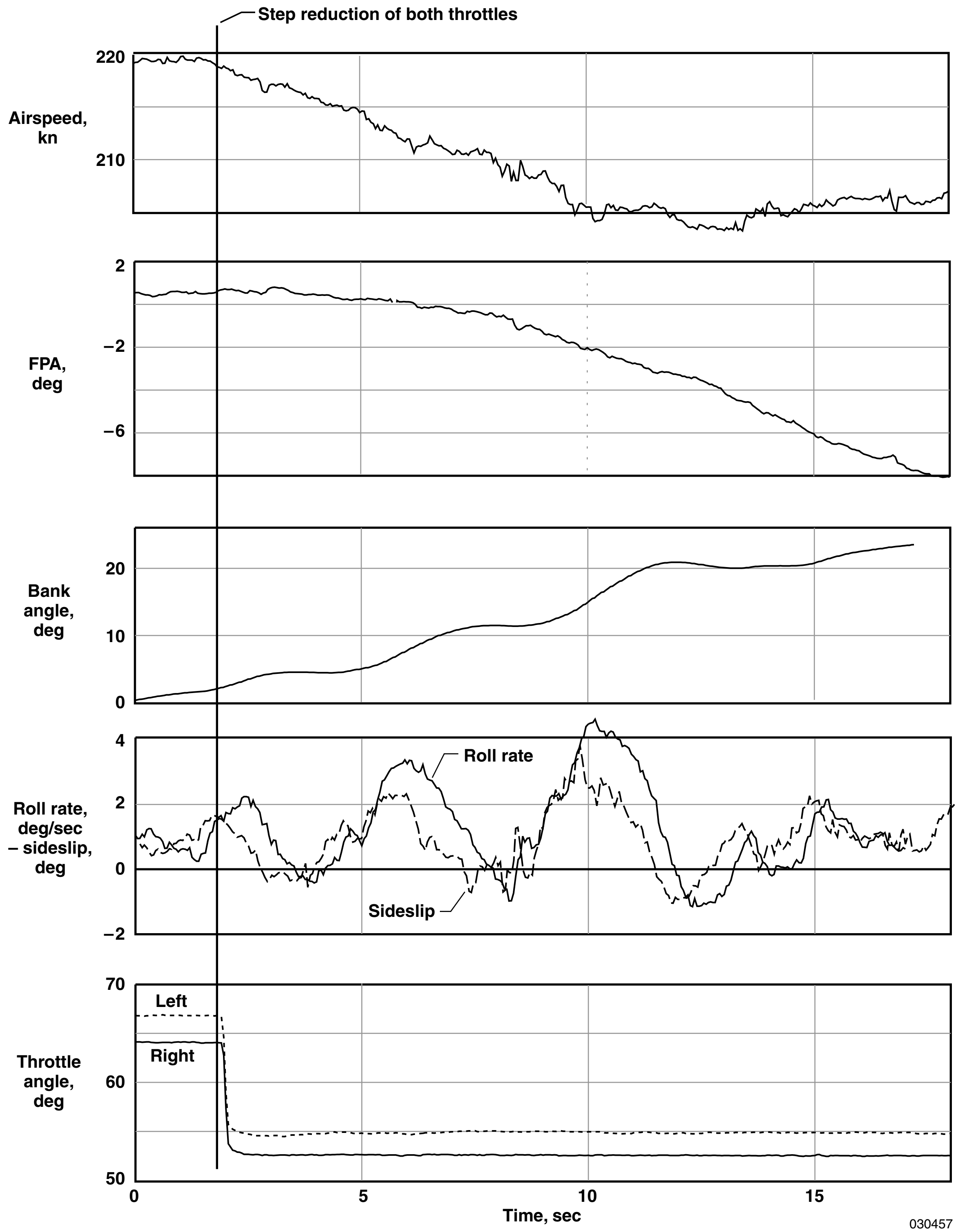


Figure 16. F/A-18 flight, –1/2 in. throttle step reduction on both engines, flaps 3/3, gear down, light turbulence, fuel = 7000 lb.

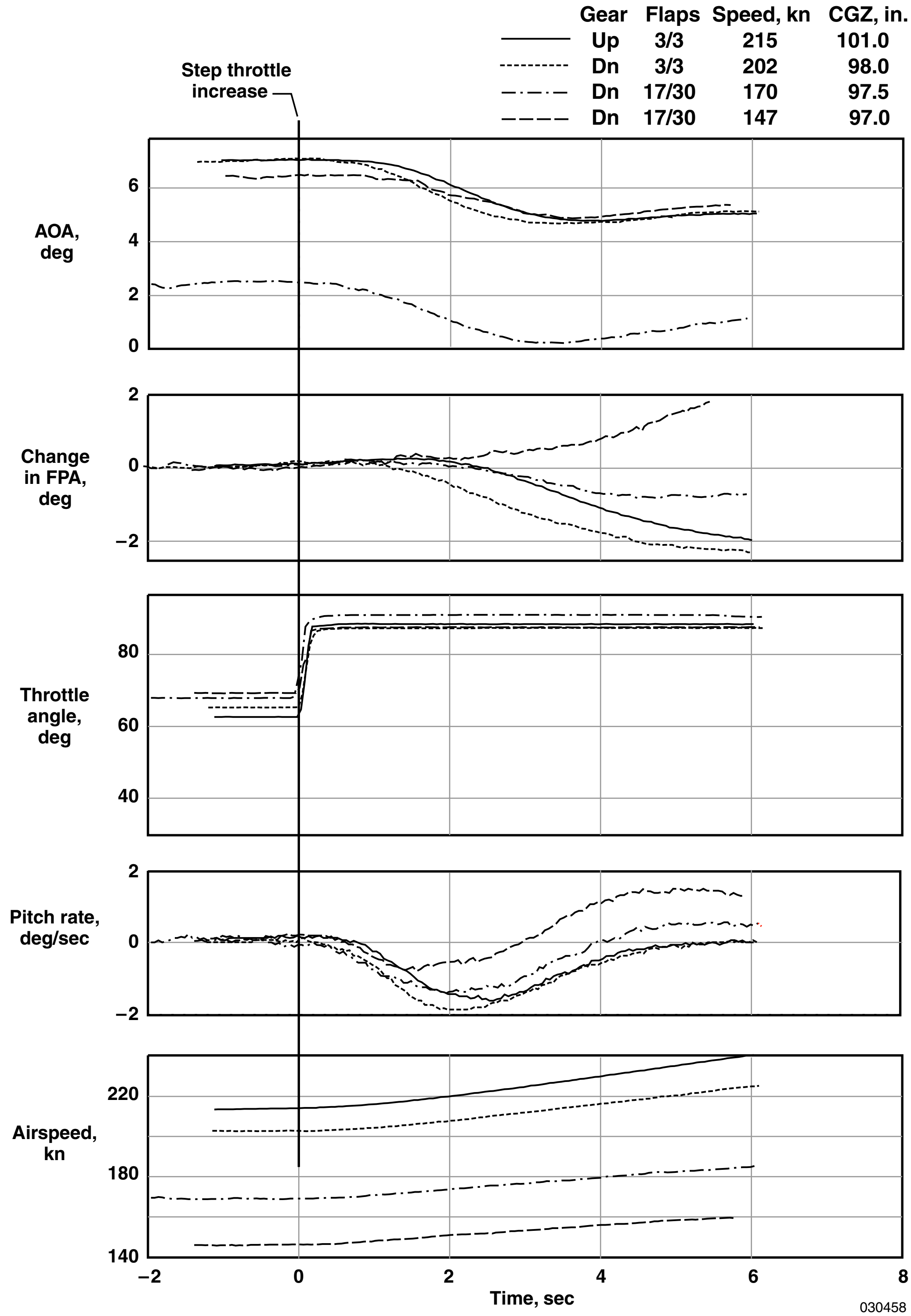


Figure 17. F/A-18 airplane TOC response to step throttle increases, no control surface motion.

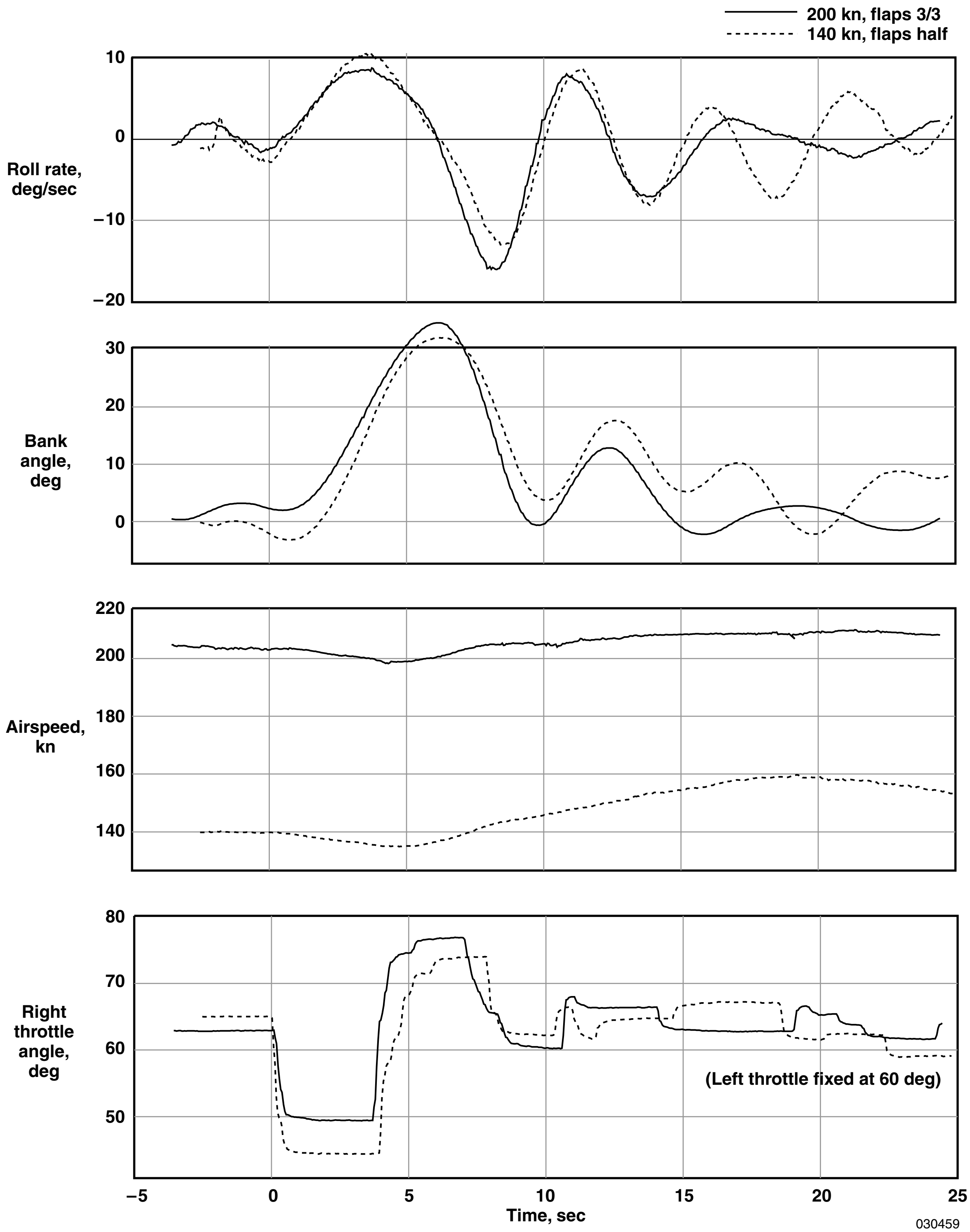


Figure 18. Lateral response to differential throttle doublet, F/A-18, gear down, no control surface movement.

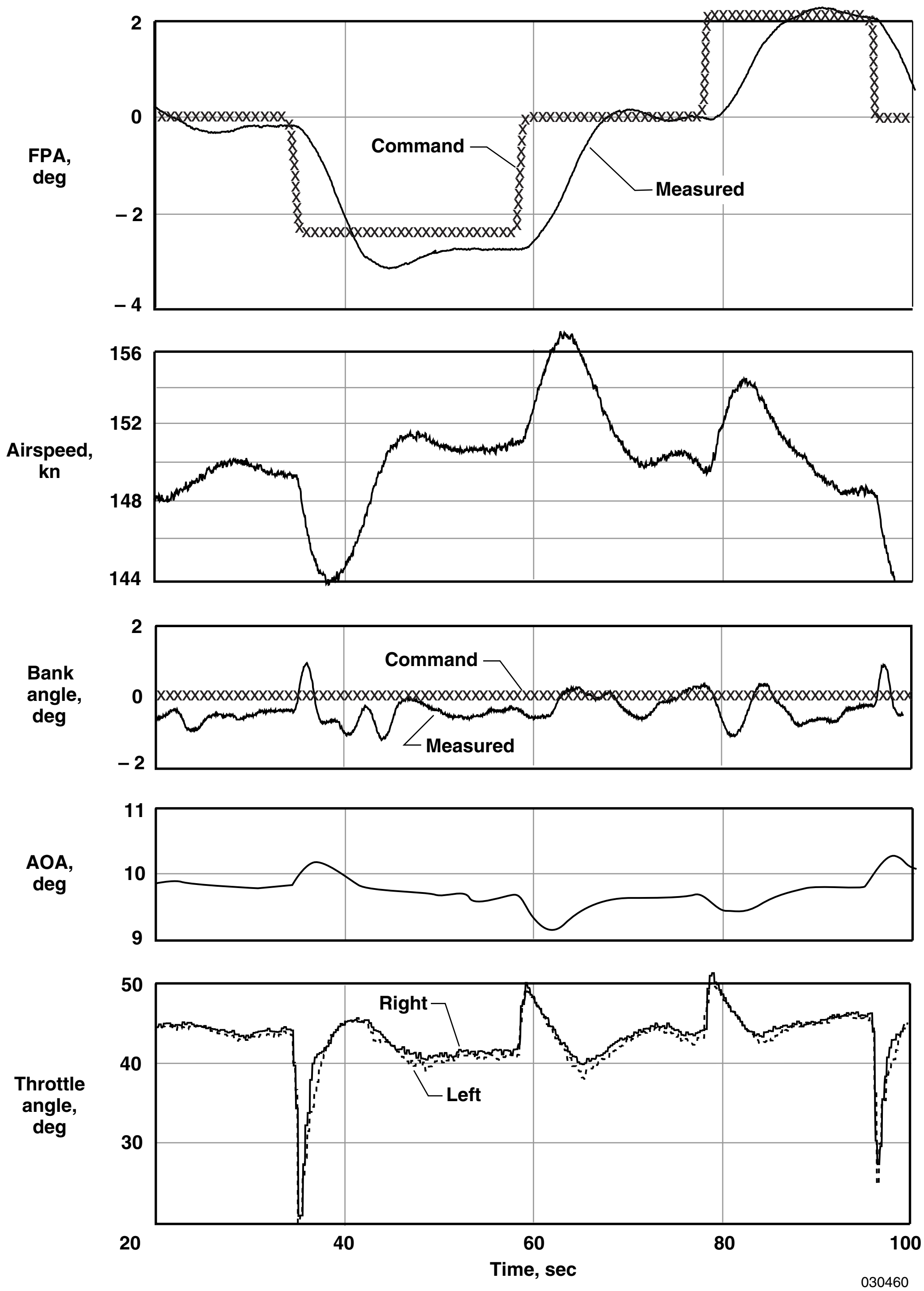


Figure 19. Response of PCA computer-controlled thrust system to flightpath step command, F-15 flight data, gear and flaps down, no control surface movement.

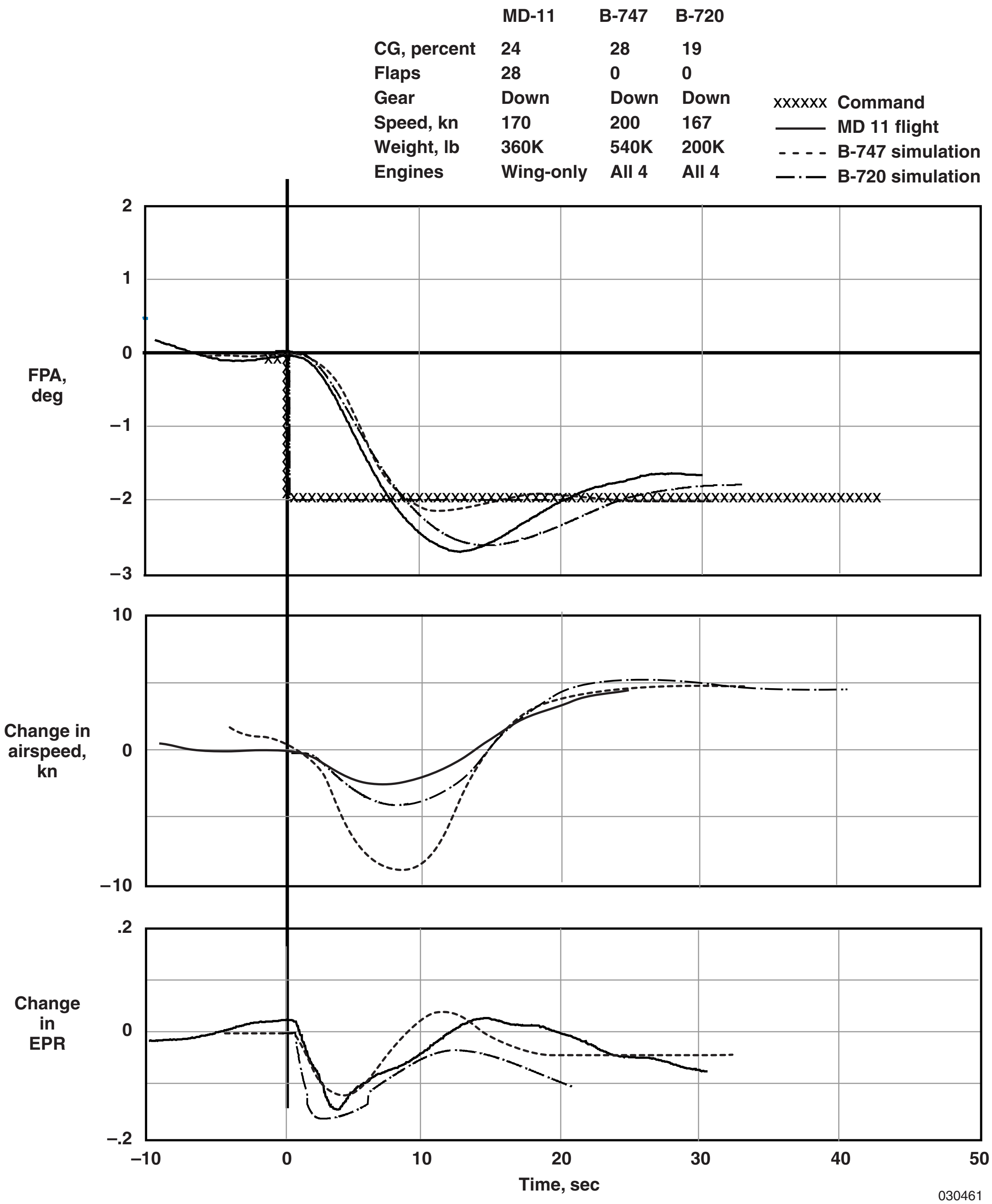


Figure 20. Computer-controlled PCA system response to –2° step reduction in *FPA* command, MD-11 flight, and simulations of B-747 and B-720 transport airplanes.

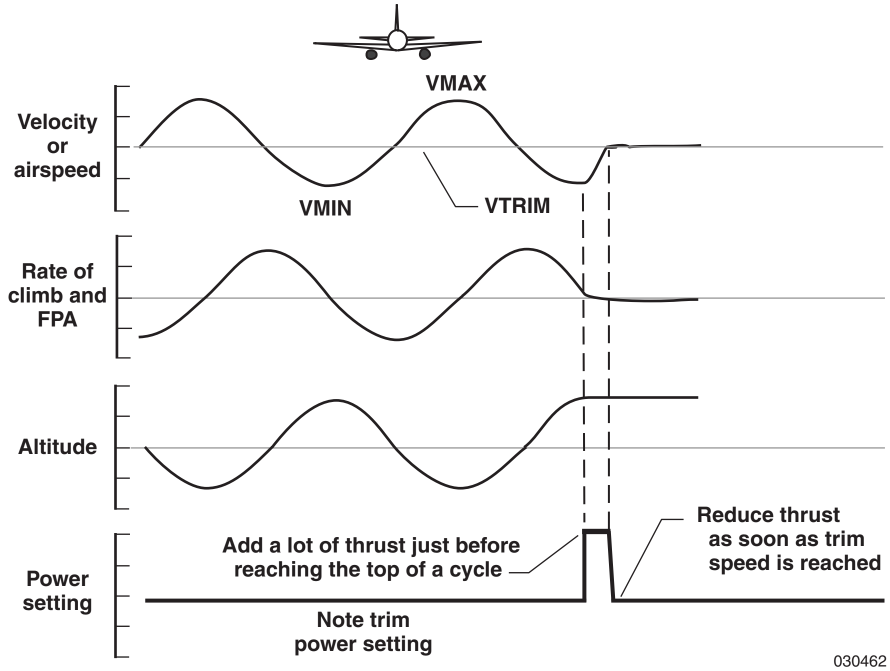


Figure 21. Suggested phugoid damping method 1, for airplanes with underslung engines.

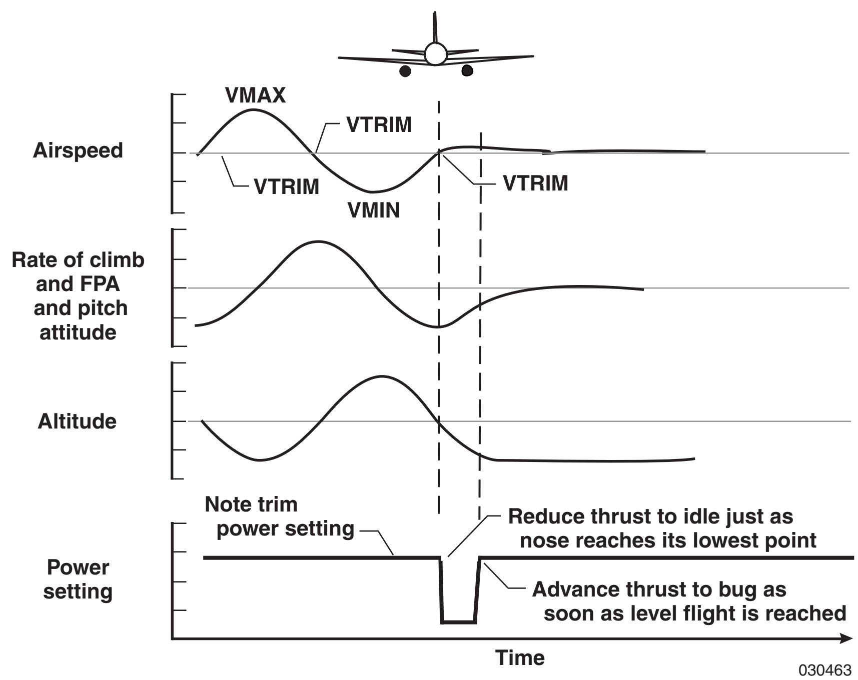


Figure 22. Suggested phugoid damping method 2, for airplanes with underslung engines.

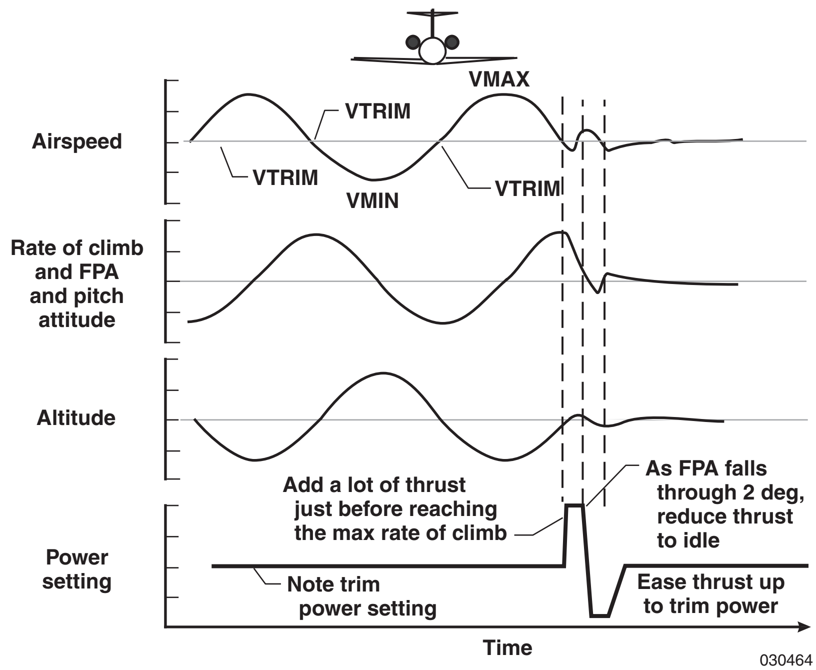


Figure 23. Suggested phugoid damping method for aircraft with high-mounted engines.

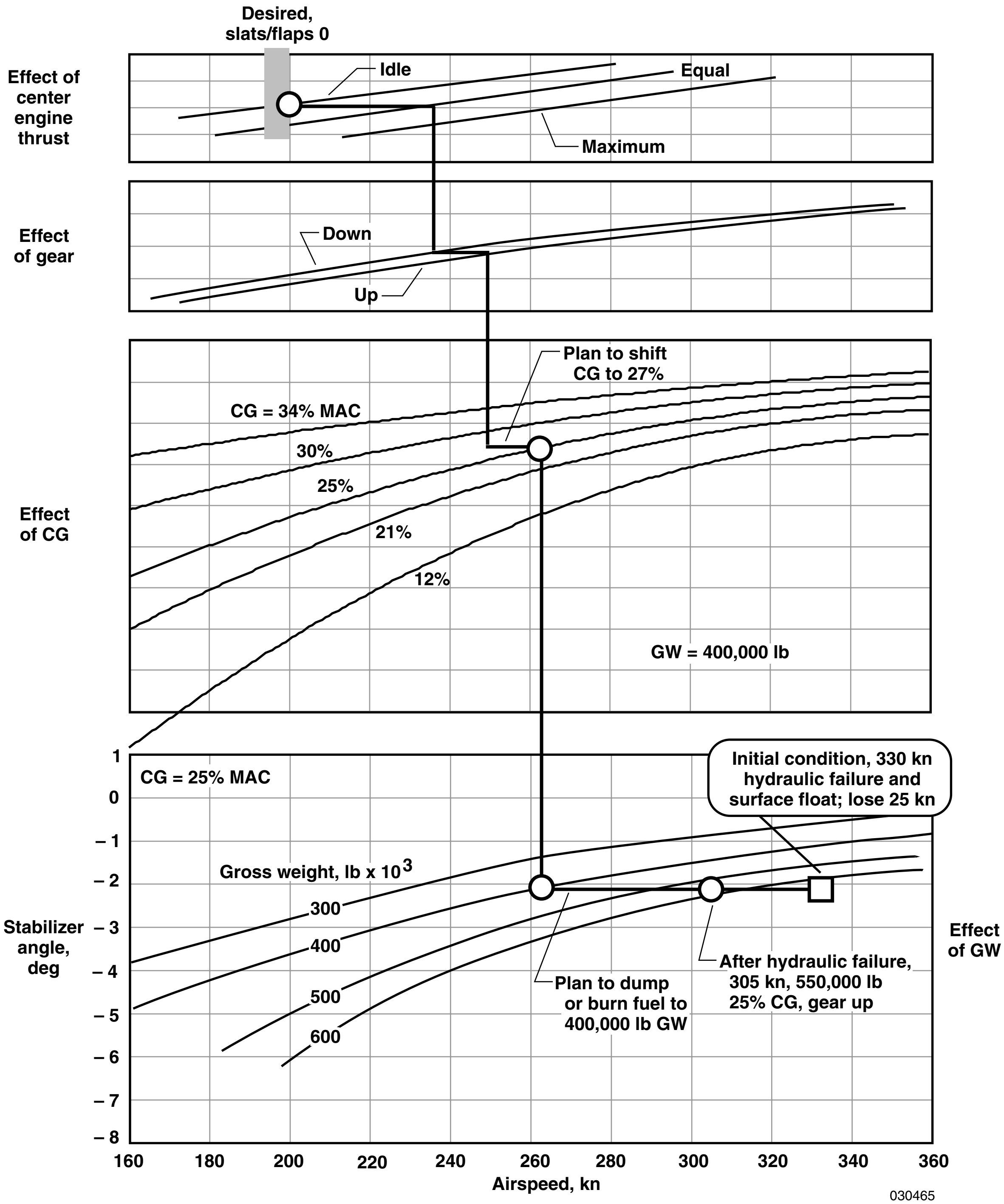
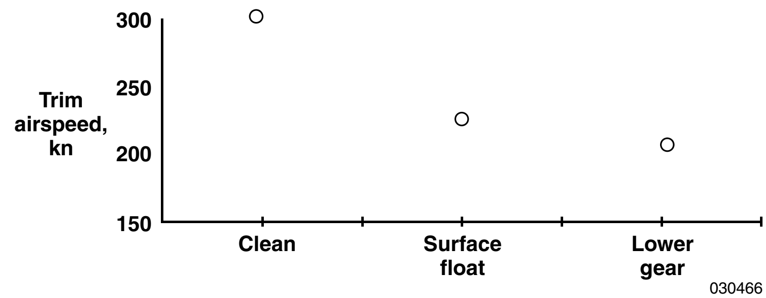
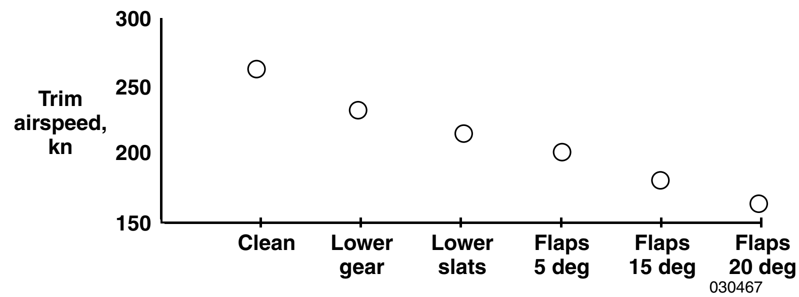


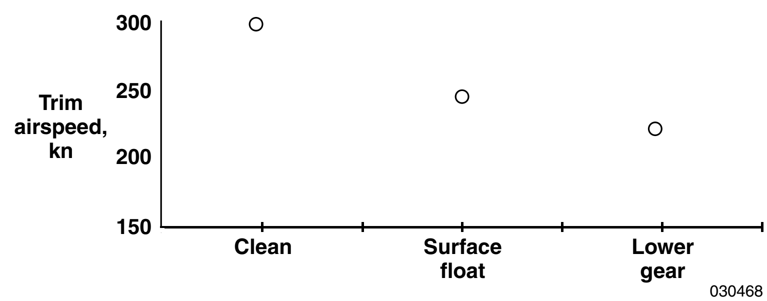
Figure 24. MD-11 variation in trim airspeed with *GW*, *CGX*, landing gear position, and center engine thrust.



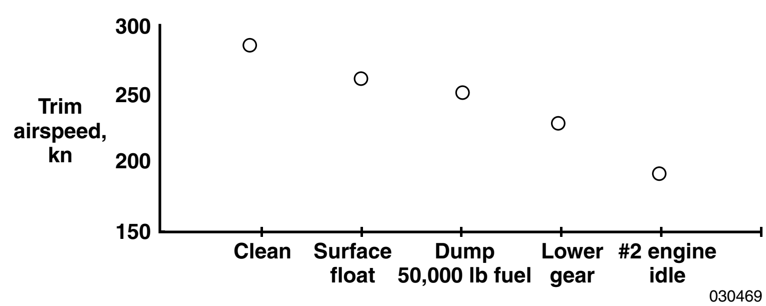
(a) C-17 motion-based simulation, no flaps.



(b) B-757, NASA Langley Research Center flight simulation, no surface float.



(c) B-747, NASA Ames simulation, no flaps.



(d) MD-11, flight simulator data, no flaps.

Figure 25. Effects of configuration changes on trim airspeed; stab fixed, no *CG* shift.

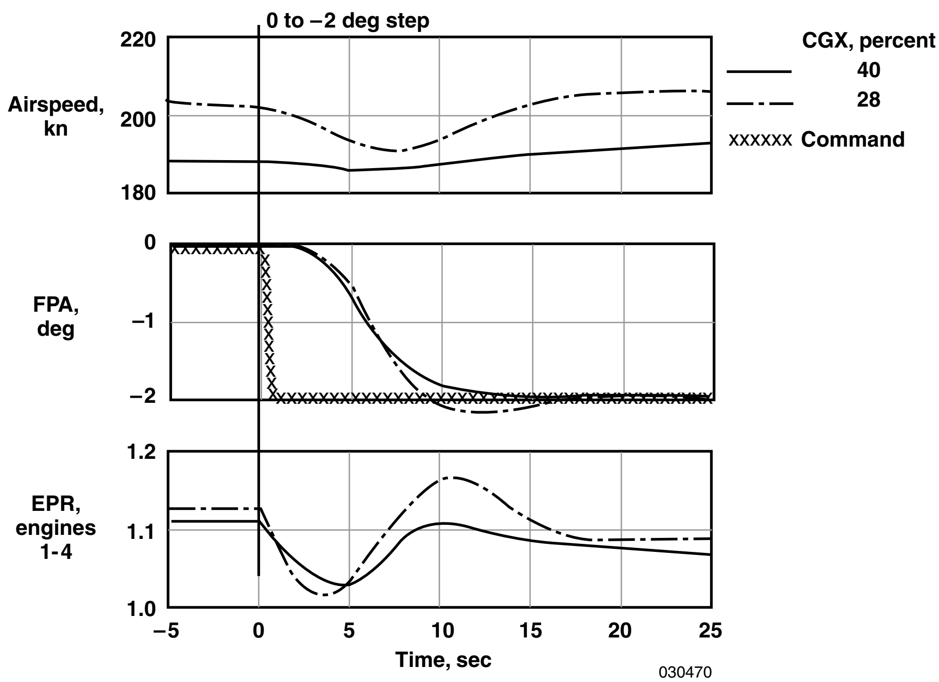


Figure 26. Effect of *CGX* on pitch step response to thrust, B-747-400 simulator, gear down, flaps 20, *GW* = 540,000 lb.

APPENDIX A
SUMMARY OF LOSS-OF-FLIGHT-CONTROL ACCIDENTS OR INCIDENTS IN WHICH THROTTLES WERE OR COULD HAVE BEEN USED

B-747, Japan

In 1985, a four-engine Boeing 747 airplane, Japan Airlines flight 123, was climbing through 24,000 ft at 300 kn when it experienced a total hydraulic system loss as a result of an aft cabin pressure bulkhead failure. Most of the vertical fin was also lost. After the failure, the aircraft trimmed at about 255 kn, with persistent dutch-roll and phugoid oscillations. The throttles and electrically driven flaps were the only usable devices for control. It was flown for over 30 minutes using only throttles for control. Landing gear was lowered, reducing trim airspeed from 250 to 225 kn. Later, flaps were extended using the electrical alternate flap system, and then shortly afterward, flap retraction was initiated. The crew was not able to effectively control the airplane and eventually hit a mountain. Five hundred and twenty lives were lost.

DC-10, Sioux City, Iowa

In July of 1989, a McDonnell Douglas DC-10 trijet, United Airlines (UA) flight 232, in cruise flight suffered an uncontained tail engine failure that caused the loss of all hydraulics. After the failure, the airplane trimmed at approximately 210 kn with a significant yaw due to damage to the center engine nacelle. The crew learned to achieve gross control under extremely difficult circumstances using wing engine throttles for control; the right engine thrust was required to be about twice the left engine thrust to fly a constant heading. In spite of these difficulties, the crew did reach the airport at Sioux City, Iowa 44 min after the uncontained engine failure. There was not enough control precision for a safe landing; the phugoid was not well damped, and a wing dropped just before impact. The controlled crash landing, however, saved 181 of the 296 persons onboard.

A300, Baghdad, Iraq

On November 22, 2003, a DHL A300B4 cargojet was hit by a ground-to-air missile at 8000 ft climbing out from the Baghdad airport (ref. 12). The missile caused extensive damage to the left wing and all hydraulics were lost. The outboard fuel tank was punctured and a fire resulted, causing further damage to the aft part of the wing. The crew had been present at a safety briefing by UA DC-10 flight 232 Captain Al Haynes, and when all flight controls failed, they knew they could use the throttles for emergency flight control. The crew commented that they were surprised at how much control was available using only the throttles. They made one circle, lowered the landing gear, then made a low approach to the runway and a go-around. Next, they made a long 20-mi straight-in approach to runway 33R, but were thrown off course on short final and made a heavy and not-well-aligned landing on runway 33L. With no rudder and no nosewheel steering, the aircraft ran off the runway to the left and stopped in soft sand. The crew was not injured; the aircraft sustained some additional damage. The outstanding performance of the crew was due in part to the briefing by Capt. Haynes, in part due to the favorable pitching effect of the engines on the A300 (see figure 11), and in part because the loss of lift on the damaged left wing was partially offset by the loss of fuel.

DC-10, Windsor, Ontario

In June of 1972, a potentially serious DC-10 trijet incident occurred after a cargo door failure occurred on American Airlines flight 96. The resulting decompression damaged controls to the tail. The center engine went to idle and had no control. The rudder was jammed with an offset, half of the elevator was lost, and the remaining half of the elevator had severe control cable binding. Electric, but not mechanical, stabilizer trim control was available, but the cockpit indicator showed no movement. Accordingly, the crew presumed it was inoperative and did not use it. With barely sufficient pitch and full roll capability remaining, the airplane landed safely. During landing rollout, with the rudder offset and no nosewheel steering control available, differential reverse thrust was required to keep the airplane on the runway, and it ran slightly off the runway just before stopping.

DC-10, Paris, France

In March of 1974, a Turkish Airlines DC-10 trijet, flight 981, climbing out of Paris, suffered a failure of the aft cargo door. The decompression buckled the cabin floor, breaking or stretching control cables to the tail. The airplane impacted the ground at high speed in nearly level flight, killing all 346 persons onboard. It is possible that adding thrust to the wing engines (and possibly shutting down the tail engine) would have pulled the airplane out of the dive, although the trim condition might have been at a very high speed.

L-1011, San Diego, California

In April of 1977, a Lockheed L-1011 trijet, Delta flight 1080, had one of the horizontal stabilizers jam in the full trailing edge-up position prior to an instrument flight rules departure out of San Diego. This resulted in a large noseup pitching and rolling moment that almost exceeded the capability of the flight controls. The airplane was just about to stall in the clouds, when the Captain, using amazing insight, retarded the wing engine throttles and firewalled the center engine. This allowed him to regain enough control to maintain flight. The crew learned rapidly, continuing to use the throttles to supplement the remaining flight controls and moving passengers forward to reduce the pitchup tendency. They completed a safe landing. A less-capable crew would likely have been unable to save this airplane.

B-52, Dayton, Ohio

In May of 1974, an eight-engine United States Air Force (USAF) Boeing B-52H lost all tail hydraulic control due to a leak in a common drain line to the separate hydraulic reservoirs. The crew still had stabilizer trim for speed control and spoilers for roll control. For pitch, they used the throttles and airbrakes. All eight engines were functioning normally. The crew split the task, with one manipulating the throttles while another handled the airbrakes. They made a practice approach at 10,000 ft using these controllers, and were satisfied that they could land. At that point the gear was lowered; the upset caused them to lose 8,000 ft prior to regaining control. In spite of these control difficulties, the crew elected to try to land at Patterson AFB. The phugoid was not adequately damped, and the aircraft hit the ground on the downswing of the phugoid. The impact broke off the nose section forward of the front landing gear. The remainder of the airplane was consumed by fire, but all eight crewmembers survived.

After this accident, several flights were flown to determine the controllability of the B-52 with this type of failure, and procedures were developed. The procedures call for a flaps-up landing at a higher speed, which improves the pitch response to airbrakes.

B-52, Warner-Robbins AFB, Georgia

In 1981, a similar failure occurred on a USAF B-52G. The procedure described above was followed, and a landing was attempted at Warner-Robbins AFB. The airplane hit hard enough to crack the fuselage just aft of the wing, but there were no injuries and the airplane was repaired.

C-5A, Saigon, Vietnam

In April of 1975, a USAF Lockheed C-5A four-engine military transport was carrying 314 orphans on an evacuation flight in Vietnam. Climbing through 23,000 ft, the rear pressure bulkhead, which is part of the cargo-loading ramp, failed, causing secondary damage to the aft fuselage and the loss of all hydraulic controls for the tail. The aircraft remained roughly in trim, and wing-mounted control surfaces and flaps were still available. Pitch was controlled with throttles. The crew practiced using this control mode for 30 min, and commented on the difficulty in achieving precise control because of the slow response of the engines. They made a practice landing at 10,000 ft and then tried an approach to the runway. When the landing gear was lowered at 5000 ft, a phugoid oscillation was excited which caused ground impact 1.5 mi short of the runway. The airplane hit very hard, broke up, and was destroyed by fire. One hundred and thirty-eight were killed and many more were injured. As a result of this accident, extensive simulation studies were conducted. To this day, C-5 crews perform some simulator TOC practice to prepare for loss of hydraulic controls.

F/A-18, Indiana

In 1989, over Indiana, a U.S. Navy McDonnell Douglas F/A-18 twin-engine fighter had a failure of the dam seal in the right horizontal tail actuator, which caused loss of hydraulic fluid in both systems. After all fluid was lost, all flight control surfaces were inoperative. The airplane initially remained in trim; then experienced a very slow rolloff to the right. When the roll reached 90°, the pilot ejected.

F/A-18, Sea of Japan

An F/A-18 fighter experienced a failure of the left horizontal tail linear variable differential transformer position feedback indicator. This failure resulted in extreme actuator inputs of random size and timing. With the airplane uncontrollable in this mode the pilot selected the backup mechanical control system, which operated normally but is not recommended for landing. After repeated tries to reselect the digital mode, each causing the wild gyrations, the pilot reselected the mechanical system, went out over the ocean, and ejected.

A-10, Desert Storm

An A-10 flying over Iraq in 1991 was hit by ground fire, which caused loss of control to all tail control surfaces. The pilot was able to use thrust for pitch control along with normal controls for roll, and landed safely.

XB-70, Edwards AFB, California

The six-engine USAF XB-70A airplane was involved in a mid-air collision in 1966 which tore off both vertical tails. The airplane slowly diverged in yaw, and entered a spin. One crewmember ejected but was injured, while the other was unable to eject and was killed. A PCA system should have been able to at least maintain control until all crewmembers could safely eject.

A300-600, New York, New York

An A300-600, American flight 587, lost the vertical tail shortly after takeoff at New York in November of 2001. The tail was lost after a wake vortex encounter and large pilot rudder inputs. Without yaw stability, the airplane rolled out of control and crashed. A PCA system could have provided yaw control and possibly saved the airplane, depending on how rapidly it was engaged after the failure.

B-747, Anchorage, Alaska

In October of 2002, Northwest B-747-400 flight 85 cruising at 35,000 ft experienced a failure in the lower rudder control module housing that allowed the lower rudder to deflect full left, rolling the airplane to 30° to 40°. Initially, there was enough control authority with the upper rudder and aileron for the crew to recover and trim the airplane, but as the crew slowed the airplane for landing, it became necessary to use differential engine thrust to augment the remaining flight controls. A safe landing was made in Anchorage, Alaska.

F-14A, Long Island, New York

The #1 U.S. Navy Grumman F-14 twin-engine fighter airplane experienced cracks in titanium hydraulic lines on its first flight. On approach, the last hydraulic fluid was lost, and control was lost. The crew ejected safely.

Southeast Asia Losses

Historical data from Southeast Asia operations in the 1970–1980 time period showed that 18 percent of the more than 10,000 aircraft lost were lost due to flight control failure. It is not known how many of these could have been saved with a PCA system.

APPENDIX B
TOC FOR A TWIN-ENGINE AIRPLANE WITH ONE ENGINE INOPERATIVE

If the near-ultimate bad day incident leaves an aircraft with inoperative flight control surfaces and all engines inoperative on one wing, **there may still be hope** for a survivable landing (ref. 9). ***In such a case, it is necessary to immediately reduce the thrust of the remaining engines to idle!*** If the *CGY* can be offset toward the side with the operating engine(s), the engine's thrust will create a yawing moment and a resulting rolling moment (from the dihedral effect) that is counter to the rolling moment resulting from weight times the offset distance *CGY*. For example, if the incident results in an engine nacelle (or nacelles) departing the aircraft, that in itself will offset the *CGY* toward the good engine(s). A mid-air collision, an engine pylon failure or an uncontained engine failure could cause such a situation.

Depending, of course, on the available thrust and the degree of the *CGY* offset, there is a thrust level that creates a rolling moment that exactly counters the rolling moment due to the *CGY* offset and results in zero roll rate. Increasing the thrust above this value results in the airplane rolling away from the operating engine(s), while decreasing the thrust below this value results in rolling toward the operating engine(s). Modulating thrust thus allows bank angle control and wings-level or constant heading flight. Because the laterally offset thrust generates rolling moment indirectly through forces applied in the yaw axis, there will be a steady-state sideslip and thus a corresponding steady-state bank angle will be required to maintain a constant heading.

The overall thrust level also determines the *FPA* of the airplane for a given aircraft configuration. Thus there is strong coupling between the longitudinal and lateral-directional axis. In particular, the thrust level needed to provide a desired *FPA* is unlikely to be the thrust level needed to maintain a desired bank angle. Larger *CGY* offsets require larger thrust levels to counteract and will result in a more positive *FPA*; therefore, control of the degree of *CGY* offset provides limited *FPA* control. A *CGY* offset may be accomplished by transferring fuel or payload, jettisoning stores, or utilizing other options that may exist. Fuel transfer for *CGY* control was investigated on four transport airplanes (the MD-11, B-747, CV-990, and C-17) and was found to provide a *CGY* shift varying from 2.5–3.5 percent of wingspan and sufficient for approximately level or descending flight.

Control in this mode will be extremely limited, and a safe runway landing would be most unlikely. however, A crash landing under limited control, however, might be survivable if a suitable landing site can be reached.

APPENDIX C
TOC FOR A SINGLE-ENGINE LIGHT AIRPLANE

On a light single-engine airplane, there is no differential thrust available for lateral control. However, there may be cases in which roll or yaw control is still available to some degree, and engine thrust may be able to provide limited pitch control.

For a typical single-engine general aviation class of airplane, there have been many failures of control cables or push-rods. Some of these can be accommodated as discussed in reference 11, and are summarized below.

For partial flight control failure:

- Rudder—use aileron, avoid cross-wind landing
- Aileron—use rudder, avoid cross-wind landing
- Partial elevator failure:

    "UP" cable failure—trim up more than needed and fly with "DOWN" cable

    "DOWN" cable—trim down more than needed and fly with the "UP" cable

- Total elevator failure:

Use throttle for pitch control . . . same methods as discussed for high-performance airplanes, and remaining rudder and or aileron for lateral control.

Practice phugoid damping and make simulated approaches and go-arounds at altitude before committing to low approaches and landing.

REFERENCES

1. Burcham, Frank W., Jr., John J. Burken, Trindel A. Maine, and C. Gordon Fullerton, *Development and Flight Test of an Emergency Flight Control System Using Only Engine Thrust on an MD-11 Transport Airplane*, NASA/TP-97-206217, 1997.

2. Burcham, Frank W., Jr. and C. Gordon Fullerton, *Controlling Crippled Aircraft—With Throttles*, NASA TM-104238, 1991.

3. Gilyard, Glenn B., Joseph L. Conley, Jeanette L. Le, and Frank W. Burcham, Jr., *A Simulation Evaluation of a Four-Engine Jet Transport Using Engine Thrust Modulation for Flightpath Control*, NASA TM-4324, 1991.

4. Gerren, Donna S., *Design, Analysis, and Control of a Large Transport Aircraft Utilizing Selective Engine Thrust as a Backup System for the Primary Flight Control*, NASA CR-186035, 1995.

5. Feather, J. B. and S. Goldthorpe, *Preliminary Design and Simulator Evaluation of a Propulsion Controlled Aircraft (PCA) System for a C-17 Transport*, MDC-96K7083, September 1996.

6. Bull, John, Robert Mah, Gloria Davis, Joe Conley, Gordon Hardy, Jim Gibson, Matthew Blake, Don Bryant, and Diane Williams, *Piloted Simulation Tests of Propulsion Control as Backup to Loss of Primary Flight Controls For a Mid-Size Jet Transport*, NASA TM-110374, 1995.

7. Bull, John, Robert Mah, Gordon Hardy, Barry Sullivan, Jerry Jones, Diane Williams, Paul Soukup, and Jose Winters, *Piloted Simulation Tests of Propulsion Control as Backup to Loss of Primary Flight Controls for a B-747-400 Jet Transport*, NASA TM-112191, 1997.

8. Burcham, Frank W., Jr., Trindel A. Maine, C. Gordon Fullerton, and Lannie Dean Webb, *Development and Flight Evaluation of an Emergency Digital Flight Control System Using Only Engine Thrust on an F-15 Airplane*, NASA TP-3627, 1996.

9. Burcham, Frank W., Jr., John Burken, Trindel Maine, and John Bull, *Emergency Flight Control Using Only Engine Thrust and Lateral Center-of-Gravity Offset: A First Look*, NASA TM-4798, 1997.

10. Burcham, Frank W., Jr., Trindel A. Maine, John Kaneshige, and John Bull, *Simulator Evaluation of Simplified Propulsion-Only Emergency Flight Control Systems on Transport Aircraft*, NASA/TM-1999-206578, 1999.

11. Schiff, Barry, "Out of Controls," *AOPA Magazine*, October 1991, p. 130.

12. Hughes, David and Michael A. Dornheim, "No Flight Controls," *Aviation Week & Space Technology*, vol. 159, no. 23, 2003, pp. 42–43.

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If normal aircraft flight controls are lost, emergency flight control may be attempted using only engines thrust. Collective thrust is used to control flightpath, and differential thrust is used to control bank angle. Flight test and simulation results on many airplanes have shown that pilot manipulation of throttles is usually adequate to maintain up-and-away flight, but is most often not capable of providing safe landings. There are techniques that will improve control and increase the chances of a survivable landing. This paper reviews the principles of throttles-only control (TOC), a history of accidents or incidents in which some or all flight controls were lost, manual TOC results for a wide range of airplanes from simulation and flight, and suggested techniques for flying with throttles only and making a survivable landing.

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