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Controlling Crippled Aircraft–With Throttles

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CONTROLLING CRIPPLED AIRCRAFT—WITH THROTTLES

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ABSTRACT

A multiengine crippled aircraft, with most or all of the flight control system inoperative, may use engine thrust for control. The National Aeronautics and Space Administration's Dryden Flight Research Facility conducted a preliminary study of the capability and techniques for emergency flight control. Included in the study were light twin-engine piston-powered airplanes, an executive jet transport, commercial jet transports, and a high-performance fighter. Piloted simulations of the B-720, B-747, B-727, MD-11, C-402, and F-15 airplanes were studied, and the Lear 24, PA-30, and F-15 airplanes were flight tested. All aircraft showed some control capability with throttles and could be kept under control in up-and-away flight for an extended period of time. Using piloted simulators, landings with manual throttles-only control were extremely difficult. However, there are techniques that improve the chances of making a survivable landing. In addition, augmented control systems provide major improvements in control capability and make repeatable landings possible. Control capabilities and techniques are discussed.

INTRODUCTION

A crippled multiengine aircraft, with most or all of the flight control system inoperative, may use throttles for emergency control. Flight control systems of aircraft are extremely reliable, with multiple control surfaces, hydraulics, sensors, control computers, and control cables used to achieve high levels of control system redundancy and reliability. However, there are extremely rare occasions when potentially disastrous flight control system failures do occur. This is particularly true for military airplanes operating in a hostile environment. At such times, other forms of flight control, including propulsion, would be welcome.

Aircraft with multiple engines may be controlled to a rudimentary degree with the throttles. The use of differential thrust induces yaw and the normal dihedral effect results in roll. Many transport airplanes exhibit nose-up pitching moments from thrust that may be useful for pitch control. Also, most airplanes have positive speed stability. If speed is increased, the airplane will climb, and if speed is decreased, the airplane will descend. Airplanes with total hydraulic system failures have been flown for substantial periods with only engines for control.

In reference 1, the B-747 aircraft (Boeing Company, Seattle, Washington) was flown for approximately 1 hr using throttle control. The crew learned by trial and error, and the airplane eventually hit a mountain. In reference 2, the crew used throttles for control of a DC-10 aircraft (McDonnell Douglas Corporation, Long Beach, California) under extremely difficult circumstances and were able to execute an emergency crash landing at an airport. Many lives were saved. In

reference 3, an L-1011 aircraft (Lockheed Corporation, Burbank, California), which had a hardover stabilizer failure, was controlled using differential and collective engine thrust to supplement remaining flight controls, and it completed a safe landing. In reference 4, a DC-10 baggage compartment door opened, collapsing the cabin floor and breaking or stretching control cables. This airplane possibly could have been saved by timely application of propulsive controls. In all cases, some knowledge of potential control capability, techniques, and advice for throttles-only control would have been helpful.

To study the use of the propulsion system for emergency control, the National Aeronautics and Space Administration's Dryden Flight Research Facility (NASA Dryden) at Edwards, California, has been conducting preliminary flight, ground simulator, and analytical studies. One objective is to determine the degree of control power available for various classes of airplanes. This objective has shown a surprising amount of control capability for many airplanes (ref. 5).

A second objective is to investigate possible control modes that could be developed for future airplanes. An augmented control system that uses flight control system controllers (wheel or stick) and feedback control to provide throttle commands for emergency landings has been developed (refs. 5 and 6). This augmented system may be practical for future aircraft with digital flight and engine control systems. However, it may not be practical for aircraft with conventional mechanical and hydraulic controls. In addition, the occurrence of major flight control failure is so remote that it may not be prudent to conduct training for such an eventuality. However, it may be of value to make airline safety departments and pilots aware of the control capabilities and to develop generally applicable techniques and recommendations for manual throttles-only control for emergency flight control and landing.

Airplanes studied in simulators, based primarily on availability, have included the B-720 (Boeing Company, Seattle, Washington), MD-11 (McDonnell Douglas Corporation, Long Beach, California), F-15 (McDonnell Douglas Corporation, St. Louis, Missouri), B-727 (Boeing Company, Seattle, Washington), C-402 (Cessna, Witchita, Kansas), and B-747 aircraft. Some brief flight evaluations have also been conducted in the Lear 24 (Gates Learjet, Wichita, Kansas), PA-30 (Piper Aircraft Corporation, Vero Beach, Florida), and F-15 aircraft.

This paper presents the principles of propulsion-only control, provides awareness of the potential for using engine thrust to replace or supplement the flight control system, and shows the capabilities of augmented control systems. In all data shown, the flight control surfaces were not moved. Also, some generally applicable thoughts and information on techniques for manual flying with the throttles are presented.

NOMENCLATURE

c.g.	center of gravity
ILS	instrument landing system
K	gain constant
K_p	roll rate feedback gain
K_q	pitch rate feedback gain
K_β	sideslip feedback gain

K_γ	flightpath angle feedback gain
K_ϕ	bank angle feedback gain
LDP	landing difficulty parameter
NASA	National Aeronautics and Space Administration
PLA	power lever angle
PLF	power for level flight

PRINCIPLES OF ENGINES-ONLY CONTROL

Engine thrust can be used to control the heading and flightpath of a multiengine airplane. This section presents the principles of engines-only flight control for roll and for pitch.

Roll

Differential thrust generates sideslip, which, through the normal dihedral effect present on most airplanes, results in roll. The dihedral effect tends to be larger with greater wing-sweep angle. Roll is controlled to establish a bank angle that results in a turn and change in aircraft heading. Figure 1 shows a typical roll response to differential throttle with no stick inputs or control surface movement. Once the differential throttle is applied, the differential thrust begins to build up, inducing sideslip. The sideslip causes roll resulting from the dihedral effect. As sideslip increases, the directional stability of the airplane generates a moment equal to the moment from differential thrust. Equilibrium is reached in this case, with approximately 12 deg/sec of roll rate.

Pitch

Pitch control resulting from throttle changes is more complex. The desired result is to stabilize and control the vertical flightpath. There are several effects that may be present, depending on the aircraft characteristics (fig. 2).

Flightpath Angle Change Resulting from Speed Stability

Most airplanes exhibit positive speed stability. A thrust increase will cause a speed increase. The speed increase will then cause a lift increase, which causes a pitch rate and leads to an increased flightpath angle. This effect will increase for approximately 10 sec. If allowed to continue for a longer period of time, this effect will be oscillatory, as shown in the following subsection. The rate of change to the flightpath angle is proportional to the difference between the initial trim airspeed and the current airspeed. Thus, the effect tends to increase as speed increases. The degree of speed stability is affected by aircraft configuration and the center of gravity (c.g.) location.

Phugoid

The longitudinal long-period oscillation of an airplane is called the phugoid. It is an approximately constant angle-of-attack motion in which kinetic and potential energy (speed and altitude) are traded. The degree of oscillation in speed and altitude is related to the speed stability. Once excited by a pitch or thrust change, the phugoid, with a period of 30 to 90 sec, will be initiated and may or

may not damp naturally. The phugoid for a typical airplane is shown in figure 3. The flightpath angle increase results in a steepening climb and speed peaks. The speed begins to decrease after approximately 10 sec and oscillates about the 170-knot initial trim speed. In the oscillatory phugoid motion, flightpath angle and rate of climb lag airspeed by 90°. Altitude lags by 180°. Properly sized and timed throttle inputs can be used to damp unwanted phugoid oscillations, as discussed later.

Pitching Moment Resulting From Thrust Line Offset

If the engine thrust line does not pass through the c.g., there will be a pitching moment introduced by thrust change. For many transport aircraft, the thrust line is below the c.g. Increasing thrust results in a nose-up pitching moment, the magnitude being a linear function of the thrust change (fig. 2). This effect is the desirable geometry for throttles-only control, because a thrust change immediately starts the nose in the same direction as will be needed for the long-term flightpath angle change. High-mounted engines result in the effect fighting the results of speed stability.

Flightpath Angle Change Resulting From Vertical Component of Thrust

If the thrust line is inclined to the flightpath, as is commonly the case, an increase in thrust will cause a direct increase in vertical velocity or rate of climb. The result is an increase in flightpath angle (fig. 2). For a given aircraft configuration, this effect will increase as speed decreases because angle of attack increases.

The previously mentioned effects will be slow and weak compared to a normal flight control system response. This is because of the slow response of turbine engines and the low control power available once the engines have responded. Therefore, normal control techniques in which the pilot flies tightly in the loop will not work. Instead, slower open-loop techniques in which the pilot makes a small input and waits to observe the resulting effect will be needed to accommodate the slow engine response and low control power.

Speed Control

Once the flight control surfaces of an airplane are locked at a given position, the trim airspeed is usually only slightly affected by engine thrust. Retrimming to a different speed may be achieved by other techniques like variable stabilizer control, c.g. control, lowering of flaps, landing gear, and so forth. In general, the speed will need to be reduced to an acceptable landing speed, implying developing nose-up pitching moments. Methods include moving the c.g. aft, selective lowering of flaps, and, in aircraft with more than two engines, varying the thrust split between engines.

Thrust Response

Most turbine engines respond faster at higher thrust levels than at lower thrust levels. In particular, high-bypass turbofans may be very slow in response at flight idle. For example, a typical

high-bypass-ratio engine takes as much as 3 sec to go from flight idle to 30-percent thrust, then 3 more sec to go from 30- to 100-percent thrust. Turbojet and low-bypass-ratio turbofan engines typical of fighter airplanes and older transports are faster in response, in some cases as fast as 2.5 sec from idle to full thrust. Piston engines respond rapidly, but piston-powered airplanes often have lower thrust-to-weight capability.

Effects of Speed on Propulsive Control Power

For turbine-powered airplanes, engine thrust is not a strong function of airspeed. However, the stabilizing effects of vertical and horizontal stabilizers are a function of dynamic pressure, which is proportional to the square of airspeed. As a result, the propulsion system control power increases as airspeed decreases. For example, at high airspeed, differential thrust develops a yawing moment that is small compared to the restoring moment produced by the vertical tail. Therefore, the sideslip is small and the roll rate resulting from differential thrust is low. At low speed, the differential thrust moment may be the same as at high speed. The aerodynamic restoring moment will be much smaller and larger sideslip will develop, producing higher roll rates. A similar effect occurs in the pitch axis, where speed stability increases as speed decreases.

F-15 FLIGHT AND SIMULATION EVALUATIONS, WITH RESULTS

NASA Dryden has conducted simulator and flight studies on the F-15 airplane. These results are discussed, followed by results for other airplanes in which either flight or simulation studies have been conducted. In all results discussed, the flight controls were not moved, and the control surfaces stayed fixed or moved only slightly.

Airplane Description

The F-15 airplane (fig. 4 and table 1) is a high-performance fighter airplane with a maximum Mach capability of 2.5. The airplane has a high wing with 45° sweep and twin vertical tails. It is powered by two afterburning turbofan engines mounted close together in the aft fuselage. The thrust-to-weight ratio is very high, approaching 1 at low altitudes. The engine response is fast, 3 sec from idle to intermediate power. The F-15 airplane has a mechanical flight control system augmented with a high-authority electronic control augmentation system (CAS). Hydraulic power is required for all flight control surfaces. Total hydraulic system failure was simulated by locking the flight control surfaces.

Table 1. Physical characteristics of the airplanes.

	Airplane							
	F-15	Lear 24	PA-30	B-720	B-727	MD-11	B-747	C-402
Typical midfuel weight, lb	35,000	11,000	3,000	140,000	160,000	359,000	550,000	6,000
Wing quarter chord sweep, deg	45	13	0	35	32	35	45	0
Wing span, ft	43	36	35.98	130	108	169.6	195.7	40
Wing area, ft^2	608	231	178	2,433	1,700	3,958	5,500	196
Length, ft	64	43	25.16	137	153	192	225	36.4
Number of engines	2	2	2	4	3	3	4	2
Maximum thrust/ engine, sea level static, lb	13,000*	2,900	(160 hp)	12,500	15,000	60,000	47,000	(330 hp)

*F-15 engine at intermediate power

Simulation

The simulation of the NASA F-15 airplane is a high-fidelity nonlinear piloted simulation valid over the full flight envelope. The airplane was flown in a fixed-base simulator cockpit with actual F-15 stick and throttles. A visual scene, including the Edwards runways, was provided on a video monitor.

Manual Throttles-Only Control

Although the engines are very close to the centerline, the F-15 airplane shows significant rolling resulting from differential thrust, with rates of approximately 10 deg/sec at 300 knots, increasing to 20 deg/sec as speed decreases to 170 knots. In pitch, at speeds above 250 knots, there is no pitching moment resulting from thrust, and speed stability is weak. When trimmed for 200 knots, there is some pitch control available. Figure 5 shows the pitch axis response, at 170 knots, going from power for level flight (PLF) to intermediate (maximum nonafterburning) power. The pitch rate increases as speed increases, reaching a value of 2 deg/sec 10 sec after the throttle advance. The lack of initial response is typical of fighter aircraft in which the thrust passes through the c.g. The pitch rate is primarily the result of a speed increase that increases lift. The speed increased to over 200 knots. If the maneuver had been allowed to continue, the speed and altitude would have become oscillatory as shown because of the phugoid oscillation.

The piloted F-15 simulation was later used in a landing study. With the control augmentation system turned off and the surfaces locked, the pilots used throttles-only control to fly approaches and landings using the video display of the 15,000-ft-long Edwards runway. Starting at a trimmed condition at 170 knots and 5 mi out, eight consecutive landing approaches were made. Figure 6 shows results of the first several landings for two pilots, plotted with a landing difficulty parameter (LDP). The LDP is a newly developed parameter that is the sum of, at touchdown, sink rate in ft/sec, absolute value of bank angle in deg, and a touchdown dispersion penalty. The dispersion penalty was 0 on the runway, 5 within 300 ft of the runway, and up to 30 for landings more than 2000 ft from the runway, as shown. Based on F-15 characteristics, LDP values up to 10 would result

in a landing with no damage. The LDP values of 15 to 25 would be survivable, but damage might occur. With LDP values of 30 and above, there would definitely be damage and possible injury.

During the initial landing attempts, control was extremely difficult. The longitudinal phugoid was excited at the initializing point and was a constant problem through touchdown. Throttle inputs to damp the phugoid were hard to judge. Roll control, while adequate in rate, had the troublesome 1-sec lag. The combined task was so difficult that the initial landings had high sink rates and large touchdown dispersions. This resulted in LDP values in the "certain damage" category.

After a few manual throttles-only landings, the proper lag compensation technique for bank angle control was learned. This compensation technique made it possible to concentrate on pitch control, which is primarily phugoid damping. Techniques for finding the proper degree of throttle input were learned after approximately five landings. For each pilot, the last landings shown in figure 6 had acceptable sink rates and bank angles, and were made on the runway. These landings demonstrated the sharp learning curve associated with throttles-only control. In addition, the landings showed that adequate control power was available to land the F-15 airplane.

Augmented Control System

An augmented control system developed by Gilyard and Conley (ref. 6) was implemented on the F-15 simulation. The augmented control provided two important improvements over manual throttles-only control. First, the augmented control system used conventional flight control effectors such as a stick or autopilot pitch and bank angle control knobs, rather than the throttles. Second, feedback of key pitch and roll parameters was provided to stabilize the flightpath. Figure 7 shows a block diagram of the augmented control system. In the pitch axis, flightpath angle and pitch rate feedback are provided. The pitch rate feedback provides phugoid damping. In the roll axis, feedbacks were available. However, adequate performance was attained with all feedbacks set to zero. Thus, straight differential thrust was used, but implemented through the stick or bank angle knob, for roll control.

By using the augmented system, precise control capability was greatly enhanced. Inexperienced pilots were able to make good landings on their first tries (fig. 8). Thus, it appears, based on simulation results, that the augmented control system makes runway landings practical using throttles-only control.

Flight Tests

The F-15 throttles-only flight characteristics were evaluated in a series of flight tests. Some tests were conducted to validate the simulation results previously mentioned. Figure 9 compares the flight and simulation pitch rates as a function of speed. Good agreement is shown. Note the rapid increase in pitch rate capability as speed decreases.

Figure 10 shows the flight and simulation maximum roll rates as a function of speed. The simulation roll rates are higher by approximately 2 deg/sec than the flight-determined roll rates. Again, there is a significant increase in roll rate capability as speed decreases.

Preliminary flight studies of the manual throttles-only control during landing approaches have been conducted. In general, the airplane is more difficult to control than the simulator. It is more

difficult to trim the airplane, to maintain wings-level, and to establish and hold a rate of descent. The reasons for the better performance of the simulator are being investigated. Unmodelled effects that are, in normal flight, so small as to be negligible may become important for throttles-only control. These effects include gyroscopic moments of the engines, fuel slosh, and very slight flight control surface movement from stick and control system inertia. Therefore, it may be important to extend simulation studies to flight whenever possible.

AIRPLANES TESTED IN FLIGHT

Lear 24 Executive Jet Transport

The Lear 24 airplane (table 1) is a twin-engine business jet. The low-mounted wing has 13° of sweep. The turbojet engines, each with 2900-lb thrust, are mounted high on the aft fuselage. The airplane has a T-tail arrangement. Maximum weight is 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 Calspan variable stability airplane was used in this first evaluation. 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 throttles-only 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 deg was 4 sec.

The basic Lear 24 pitch control capability was also investigated. In contrast to the roll axis, pitch control with thrust was very difficult. Because of the high engine placement, a thrust increase caused a nose-down pitch. Eventually, the speed stability would bring the nose back up. Time to achieve a 5° pitch increase was 21 sec. Reducing thrust caused a slight pitchup, followed by a pitch down 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.

Because pitch control with throttles was very poor, propulsion-enhanced control was investigated using throttles for roll control and 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.

PA-30 Piston-Powered Light Twin-Engine Airplane

The PA-30 Twin Commanche airplane (table 1) is a light twin-piston-engine four-place airplane. It has a low-mounted unswept wing, and engines are mounted ahead of the wing in nacelles. Maximum weight is 3600 lb. The engines are rated at 160 hp each.

The PA-30 airplane was flown with throttles only and had significant 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 other 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.

AIRPLANES TESTED IN PILOTED SIMULATORS ONLY

Several airplanes have been tested using piloted simulators, including the F-15 aircraft. Others tested were the B-720, the B-727, the MD-11, the C-402, and the B-747 airplanes. Manual throttles-only control was tested on all of these airplanes. On the B-720 airplane, additional tests were conducted with augmented control.

B-720 Commercial Jet Transport Throttles-Only Control

The Boeing 720 airplane (fig. 11 and table 1) is a four-engine transport designed in the late 1950's. The airplane has a 35° 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 aircraft also incorporates a slow-rate electric stabilizer trim system. Flaps are electrically controlled.

A high-fidelity B-720 engineering simulation was available at NASA Dryden from the Controlled Impact Demonstration flight program conducted jointly by NASA and the Federal Aviation Administration. 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 simulate the situation that results in more modern airplanes with a total hydraulic system failure, or in the B-720 if control cables were jammed or cut. The throttles were then used for flight control.

Manual Control

The pilot of the B-720 airplane flew manually using the throttles only. Good roll capability was evident, with roll rates of approximately 20 deg/sec. Good pitch capability was also found, with some pitching moment because of the thrust line below the c.g., as well as speed stability. Pitch rate at 160 knots was 1.8 deg/sec, and at 200 knots, it was 1.1 deg/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.

Augmented Control Capability

An augmented control system was developed for the B-720 simulation. This augmented control allowed the pilot to fly using normal flight control effectors (control wheel, stick, or autopilot trim wheels) rather than using the throttles. The control also provided feedback for phugoid damping, flightpath angle control, and bank angle control. With the augmented system, it was possible to make repeatable landings on a runway (ref. 6). Cooper-Harper pilot ratings with the augmented system were approximately four higher than for manual control, indicating the substantial control improvement.

Instrument Landing System-Coupled Landing Capability

An instrumented landing system (ILS)-coupled automatic landing capability was also investigated (ref. 6) to study the potential of a coupled throttles-only control mode. The ILS error signals for glide slope and ground track were used in place of pilot commands to the augmented control system. A crude flare algorithm was incorporated that was not optimized to give low touchdown rates of sink. With this ILS-coupled technique, the control power available from the throttles was more than adequate. Repeatable landings were made in turbulence levels up to moderate.

A summary of the B-720 landings for manual, augmented, and ILS-coupled landings in light turbulence are shown in figure 12. The vertical bars represent the combined touchdown sink rate in ft/sec and absolute value of roll angle in degrees at the location shown. Many of the manual landings were not on the runway, and sink rate plus roll angle values were high. In the augmented mode, all landings were on the runway at survivable touchdown conditions. In the ILS-coupled mode, all landings were on the runway grouped near the ILS intercept point. The great advantage of augmented and coupled control is evident.

Asymmetry Handling Capability

It is unreasonable to assume that major flight control damage will occur without any damage to the airplane structure or change to the aerodynamics. The ability of the B-720 augmented system to accommodate significant lateral asymmetry was also evaluated in the simulation. Sixty-five percent of full left aileron input was locked in as an initial condition, simulating an aileron hardover on one side, or the loss of an outer wing panel. The results are shown in figure 13. The pilot commands of 0° bank angle were met by the augmented system, with the thrust of the left engines maintained at approximately three times the thrust of the right engines. Adequate pitch and roll capability remained to complete the landing, as shown in the figure.

Damage that causes pitch disturbances will result in changes in trim speed. These effects may be handled with the techniques discussed previously for changing trim speed.

Manual Control of Airplanes in Simulations

B-727 Commercial Jet Transport

The B-727 airplane (table 1) is a three-engine transport carrying up to 150 passengers. The airplane has a swept wing and a T-tail. The three low-bypass 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 (engine pressure ratio of 1.2), then fast (3 sec to reach full thrust).

The B-727 engines-only control was evaluated in a high-fidelity motion-based simulation at the NASA Ames Research Center at a speed of approximately 200 knots. 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 4 to 5 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, nose-up pitch rates at full thrust were approximately 0.75 deg/sec; nose-down pitch rates at idle were 0.4 deg/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 flightpath angle using throttles was difficult. Use of electric stabilizer trim was more successful.

The airplane was flown 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 keep 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.

MD-11 Commercial Jet Transport

The MD-11 airplane (table 1) is a large, long-range commercial transport. It has a 35° swept low-mounted wing and is powered by three high-bypass turbofan engines. Two of the engines are mounted in underwing pods, and the third engine is mounted on the base of the vertical tail. The airplane uses an irreversible hydraulic flight control system and has electric stabilizer trim.

The capability for engines-only control of the MD-11 airplane was investigated briefly in flight simulators, all at a speed of approximately 200 knots. Research found that there is substantial but confusing pitch control available, with the center engine producing strong nose-down pitching moment and the wing engines producing weak nose-up pitching moment. In roll, the use of differential thrust produces very sluggish roll control, with maximum roll rate of 3 deg/sec. Control capability at lower speeds was not investigated. However, based on trends of the F-15 airplane, the roll rate capability of the MD-11 airplane may be larger.

Up-and-away flying was possible, altitude could be maintained, and heading could be held within reasonable limits. The low roll rate makes runway lineup very difficult, even without any turbulence or crosswind. Landings were attempted in the simulator. While it was possible to come close to the runway, it was not possible to make repeatable controlled landings on it.

B-747 Heavy Jet Transport

The B-747 airplane (table 1) is a large commercial transport. It has a 45° swept wing and is powered by four high-bypass turbofan engines mounted in nacelles ahead of and below the wing. The complex flight control system is powered by four independent hydraulic systems. No quantitative data are available for the B-747 airplane. However, time has been spent in the simulator evaluating the controllability with throttles. Because of the large inertias, 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 available, but again, large lags are present. Phugoid damping could be accomplished using the techniques discussed later in the paper. The airplane was retrimmed from a cruise speed of 275 knots to 220 knots by lowering the inboard but not the outboard trailing-edge flaps to 25°. Fuel transfer could also have been used, but was not tried because of lack of time. 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.

Cessna 402 Light Commuter Airplane

The C-402 airplane (table 1), a light twin-piston-engine commuter airplane, was evalued in a motion-base simulation at the NASA Langley Research Center. As a propeller-driven airplane with both propellors 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. 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 knots, with gear down and flaps up. With no turbulence, all landings were on the runway at low touchdown bank angles and rates of sink. 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 knots with partial flaps and with no turbulence. All of the landings were successful.

SUGGESTED TECHNIQUES FOR ENGINES-ONLY FLIGHT CONTROL

The following techniques should be generally valid for control of a multiengine aircraft with throttles-only as might be required after total loss of hydraulic pressure. 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 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. Splitting the roll and pitch tasks between pilots may improve performance and lessen workload.

Bank Control

Bank control can be accomplished using differential thrust between left and right engines. 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 as small as possible differential throttle inputs when changing bank angle.

Pitch Control

Getting the pitch attitude under control is usually the most challenging immediate (and continuing) task. The secret, once stabilized, is to watch pitch attitude very closely, preferably with reference to a visual horizon, and to make immediate thrust corrections to stop any pitch movement, however tiny.

If the long-period (phugoid) mode is excited, it will not usually damp in a reasonable time. It may even go divergent, so positive pilot action is required. A suggested method for phugoid damping (fig. 14) is as follows:

1. Determine the trim airspeed. This may be found by noting the maximum and minimum speeds during a phugoid cycle and averaging. Set an airspeed reference bug, if available, at this speed.

2. As the nose is falling from the maximum pitch attitude toward the level flight attitude, airspeed will be decreasing toward the minimum value. At this time 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. The same technique may be employed in reverse during the nose-low part of the cycle.

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

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 widest suitable surface of sufficient length within range at the existing speed and fuel state. The combined task of controlling sink rate, touchdown position, and runway alignment is extremely difficult. The condition of the surface to the side of the runway is important. A hard, smooth, dry lakebed would be the ideal site. Other considerations are weather, preferably visual flight rules with low winds and turbulence, and availability of fire, rescue, and hospital services. Fuel should not be dumped, but saved for technique practice and multiple approaches, if needed.

Landing Configuration and Speed

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 lowering inboard flaps only on a swept wing, shifting c.g. aft by fuel management or cargo shift, and backup system repositioning of the horizontal stabilizer. All configuration changes should be made slowly and carefully, keeping the phugoid well damped as the trim speed changes.

Approach

Adding power slowly and climbing away from the ground is relatively easy, so unless there are deteriorating conditions, plan for multiple approach attempts. Bank angle should not exceed 5° to prevent unwanted pitch perturbations. Pitch attitude must be rigidly controlled to maintain a constant 1° to 2° glide slope, with an approximately 400- to 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.

Touchdown

Hold the constant approach path to touchdown, reducing thrust only after ground contact. Then reduce thrust to idle and use reversers and wheel brakes, if available, for directional control and deceleration. Depending on the landing surface, a gear-up landing may be appropriate.

CONCLUDING REMARKS

A study has been conducted by the NASA Dryden Flight Research Facility to determine the emergency flight control capability of multiengine airplanes using throttles-only control. Simulation and flight studies have determined the control power available for several airplanes, ranging from

piston-powered light twin-engine airplanes to high-performance fighters to commercial transports. Preliminary techniques for manual throttles-only control have been developed, and an augmented control system has been developed and evaluated on simulations of the F-15 and B-720 airplanes.

All the airplanes evaluated have significant control power from engine thrust. Up-and-away flight using manual throttles-only control is difficult, but with practice, heading may be controlled to within a few degrees. Once any phugoid oscillation is damped, altitude may be controlled to within a few hundred feet.

Based on simulation studies, landing with manual throttles-only control is extremely difficult. It is practical, with practice, to land on an "infinite" (unlimited length and width) field, but landing on a runway is extremely hazardous.

With an augmented throttles-only control system where conventional flight controllers are used and appropriate feedback parameters are used for stabilization, it is practical in simulations to make runway landings.

A technique for phugoid damping, a persistent problem for all airplanes tested and required for manual throttles-only control, has been developed and was shown to be effective.

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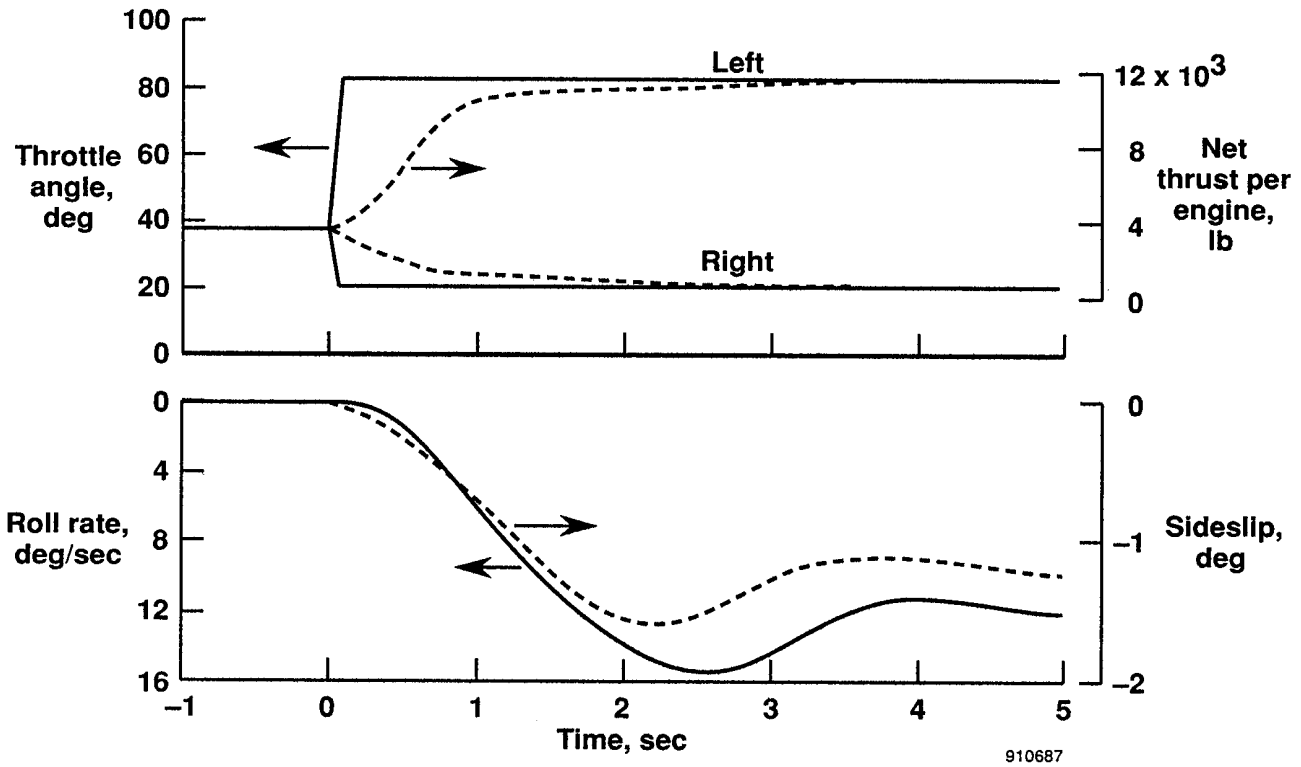

Figure 1. Roll control resulting from differential thrust.

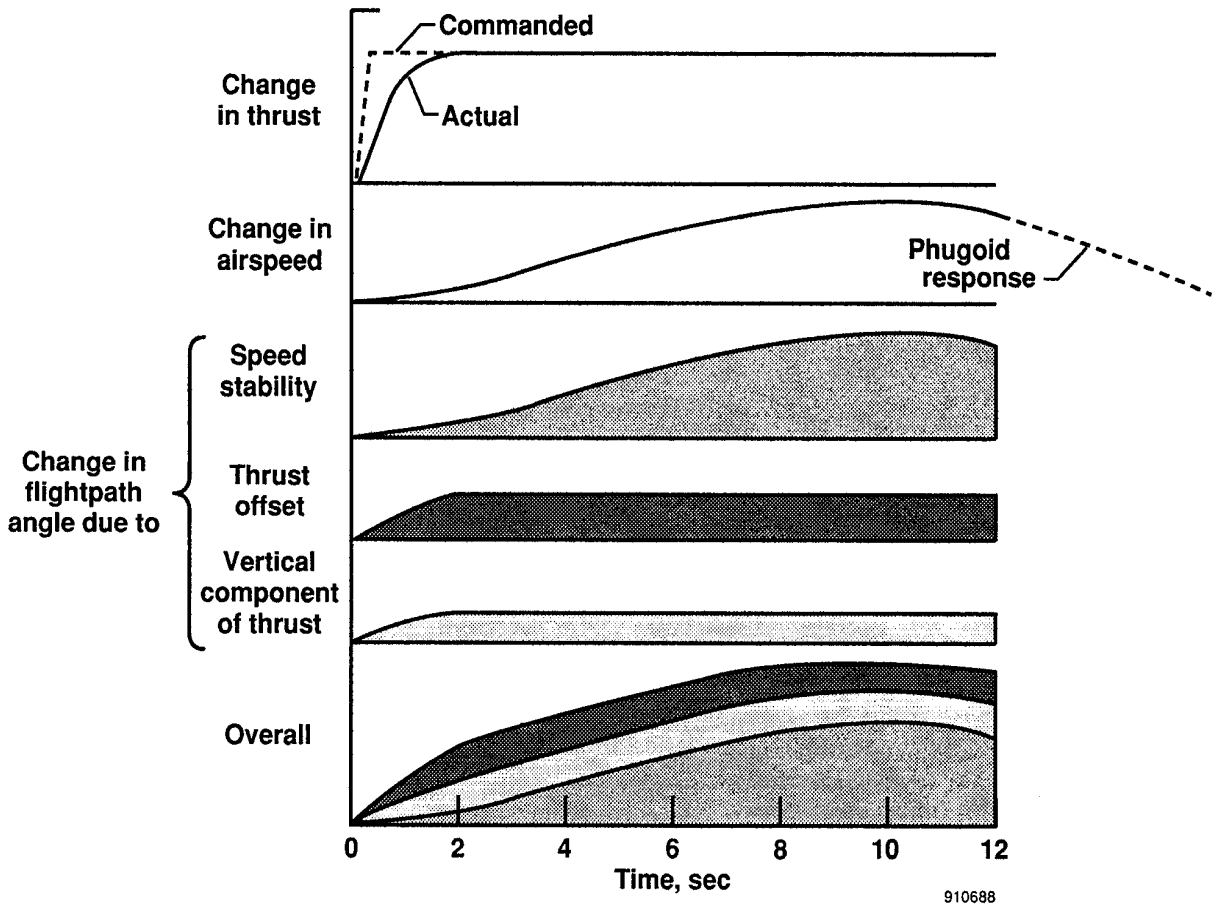

Figure 2. Pitch control from throttle increase resulting from speed stability, thrust offset, and vertical component of thrust.

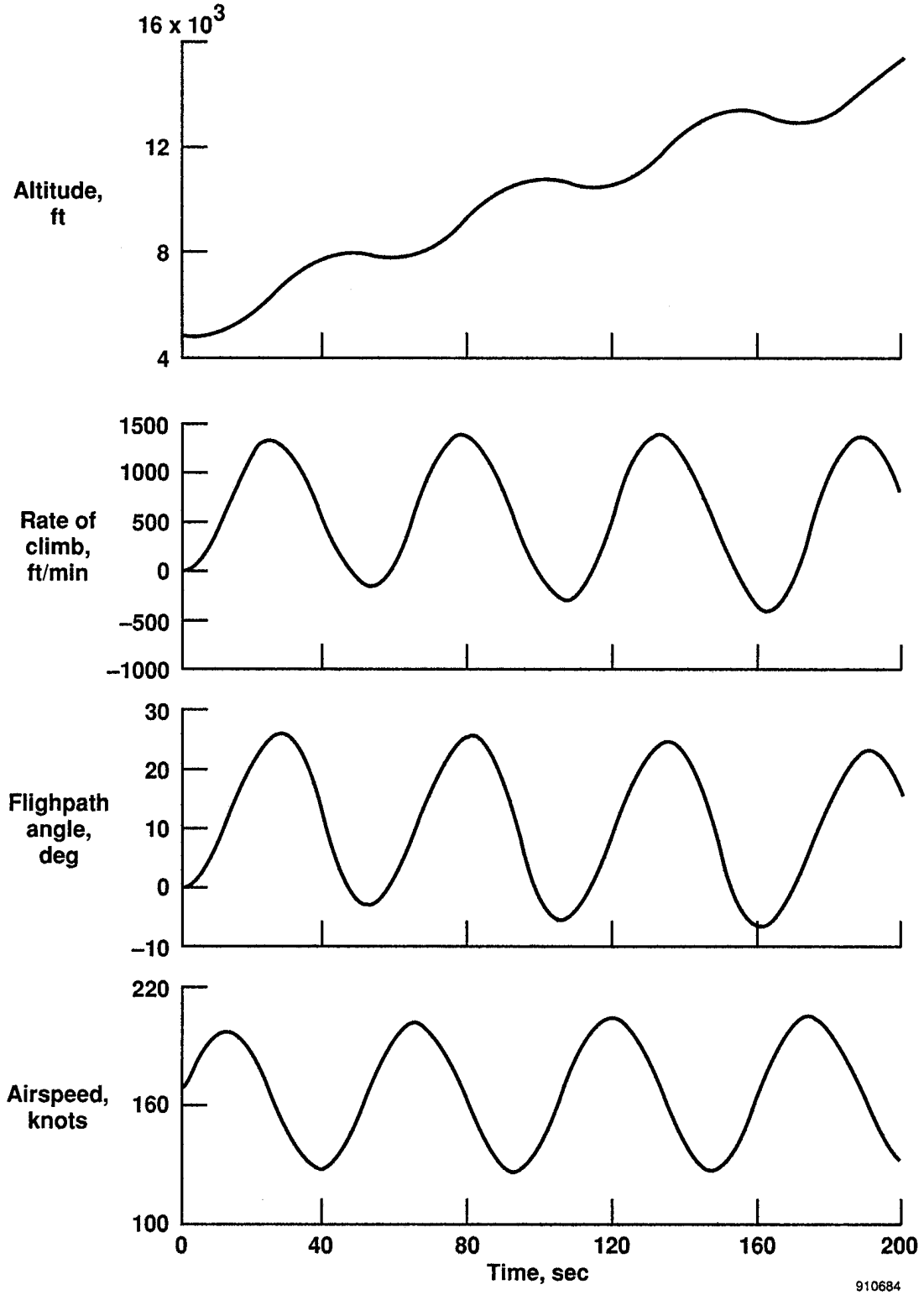

Figure 3. Typical phugoid oscillations time history; trim speed 170 knots.

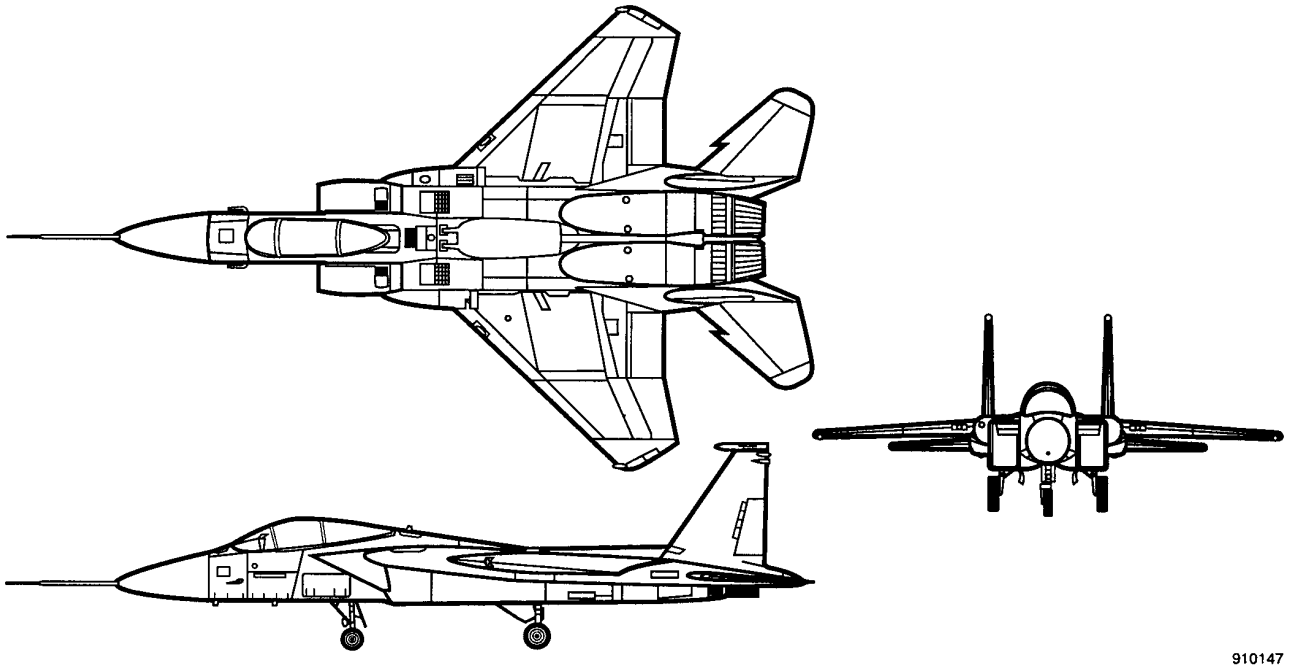

Figure 4. The F-15 airplane.

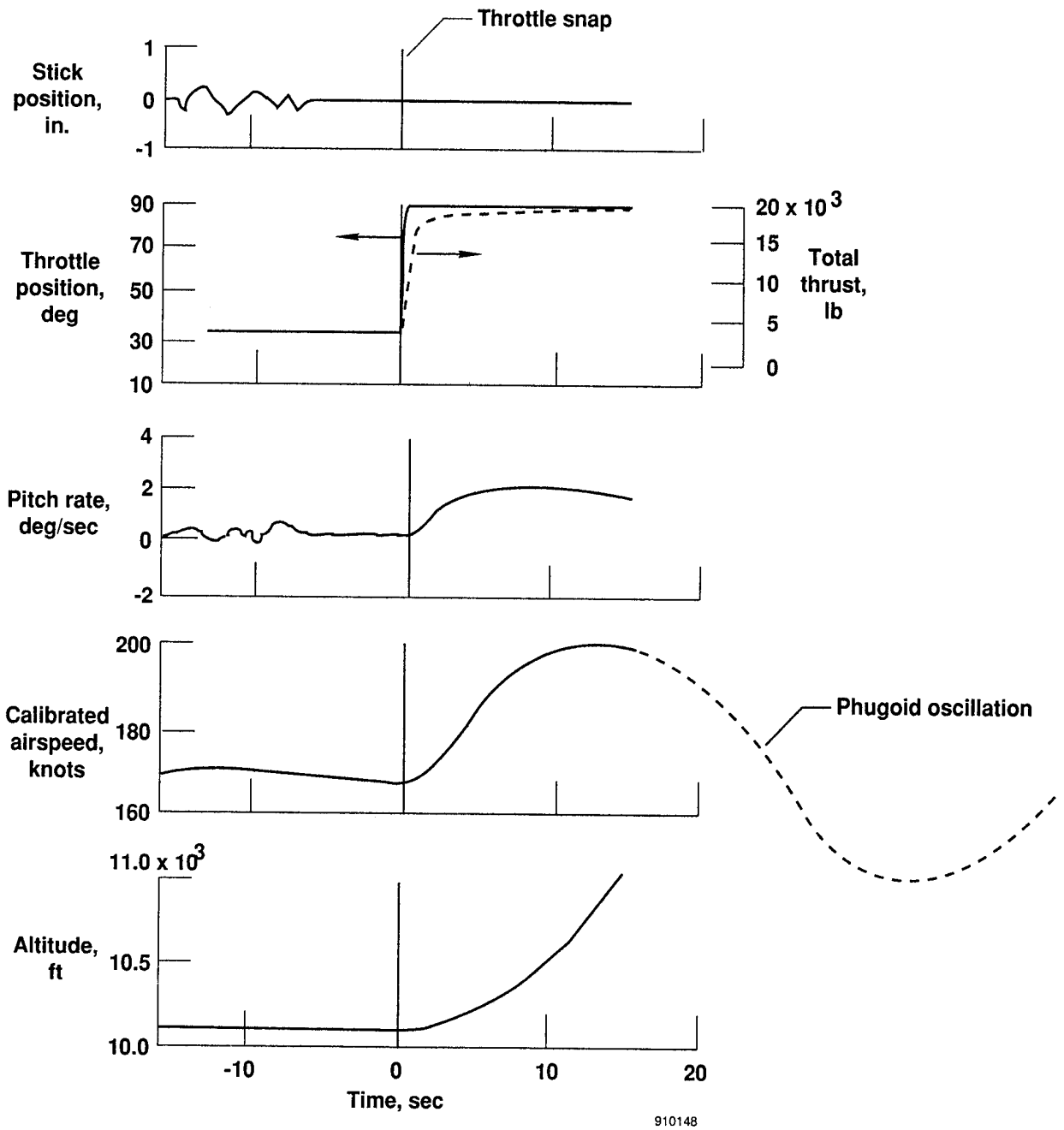

Figure 5. F-15 simulation time history for pitch-up resulting from throttle increase from power for level flight to intermediate; 170 knots.

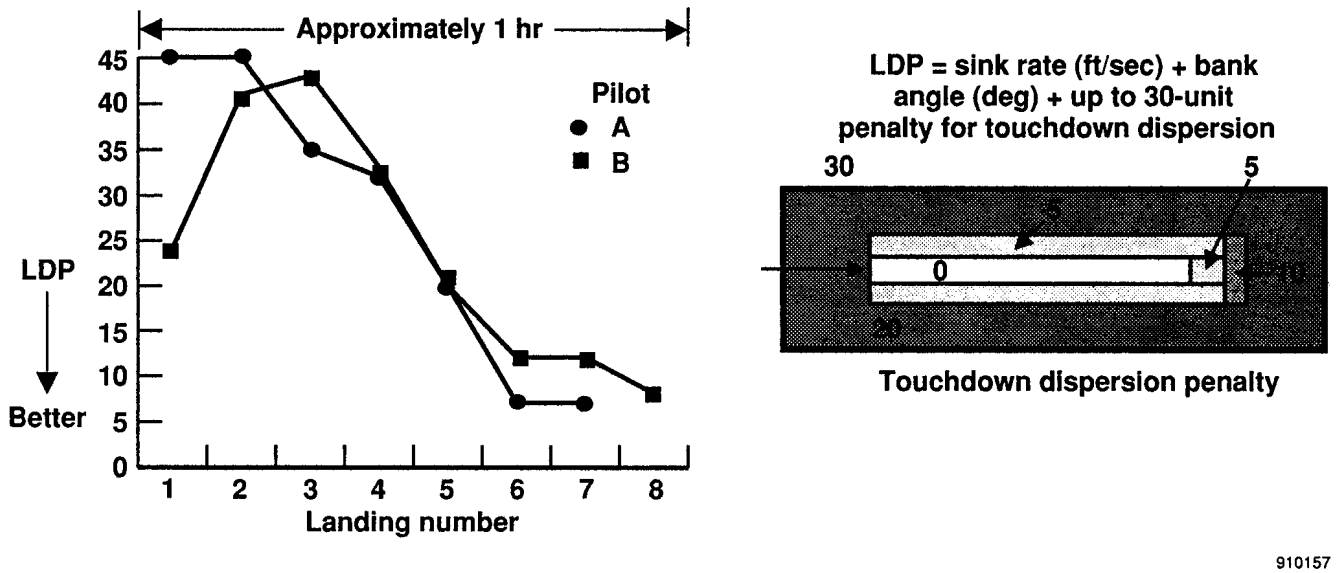

Figure 6. F-15 landing difficulty parameter for manual throttles-only landing.

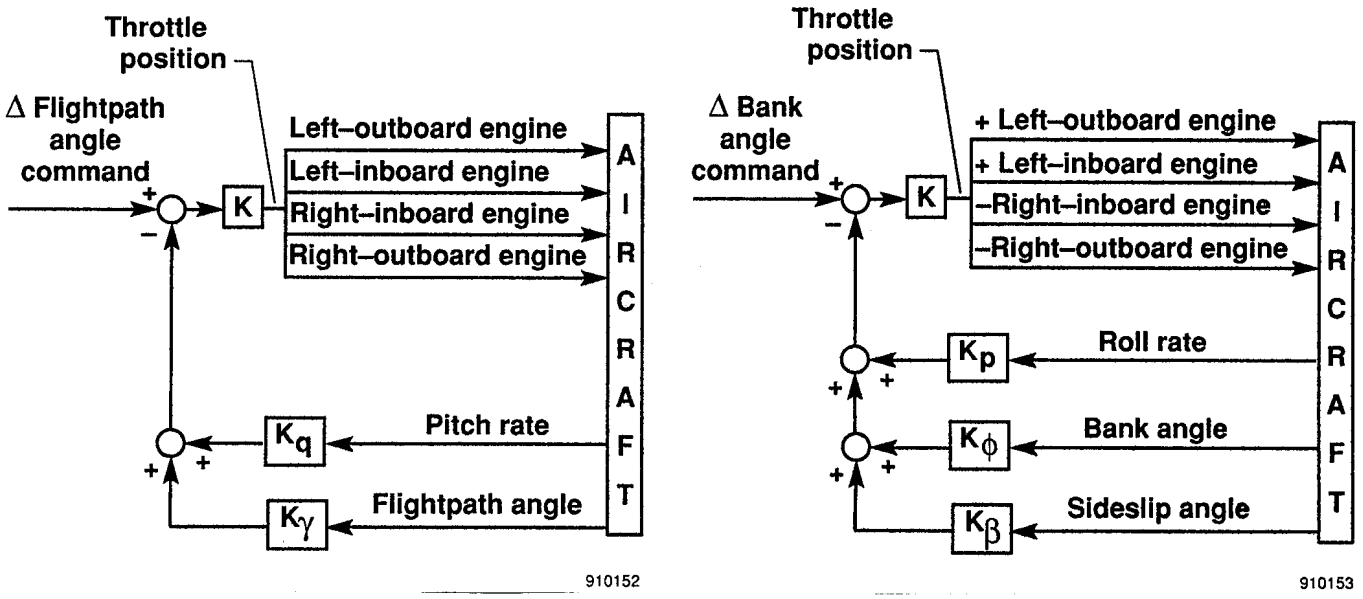

Figure 7. F-15 augmented control block diagram.

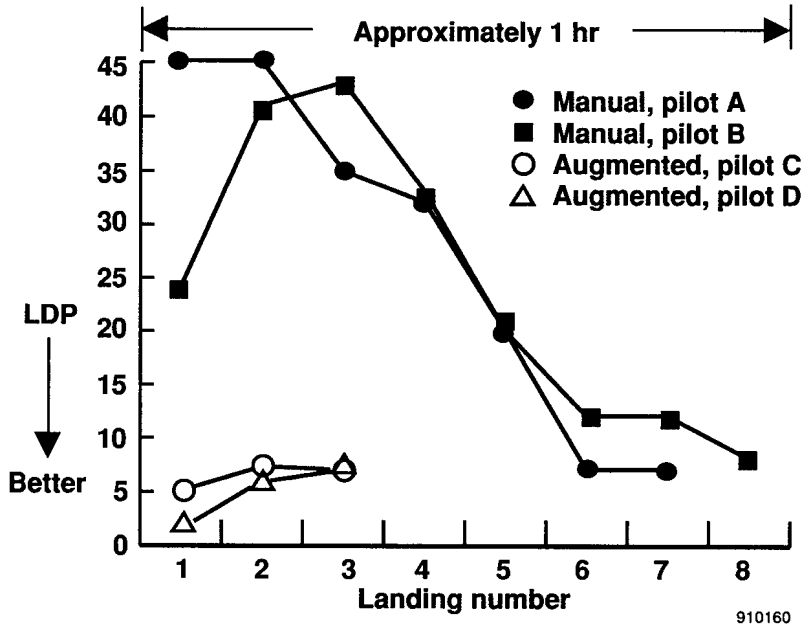

Figure 8. Landing difficulty parameter with augmented control.

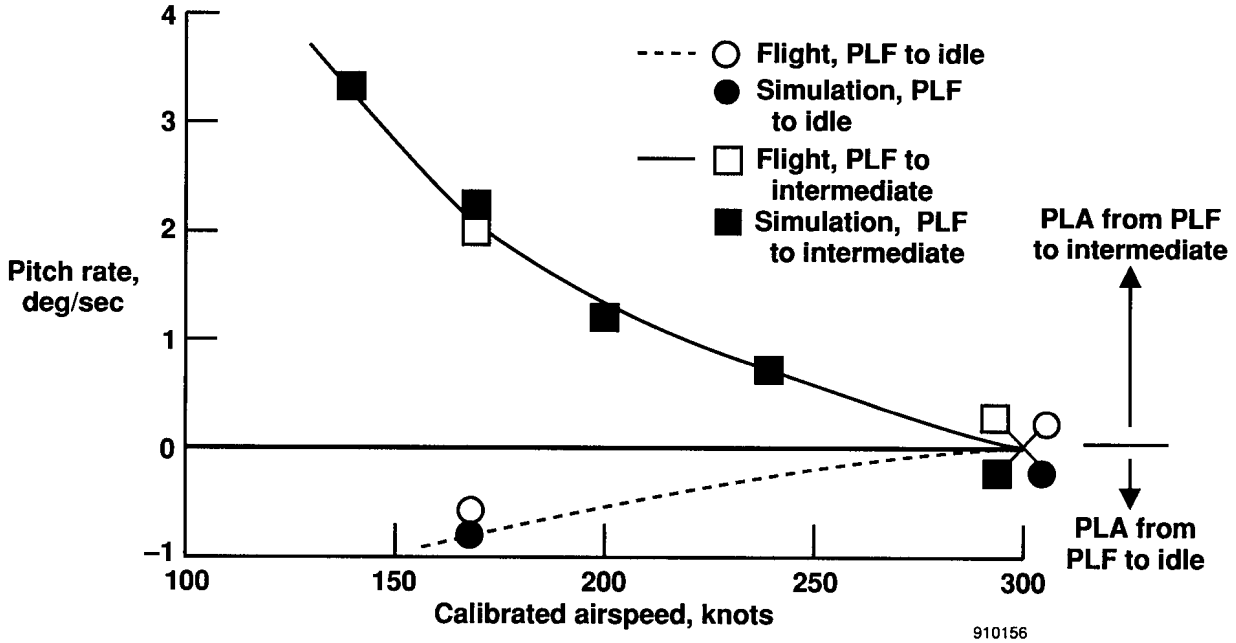

Figure 9. Effect of calibrated airspeed on pitch rate, flight, and simulation for F-15 airplane.

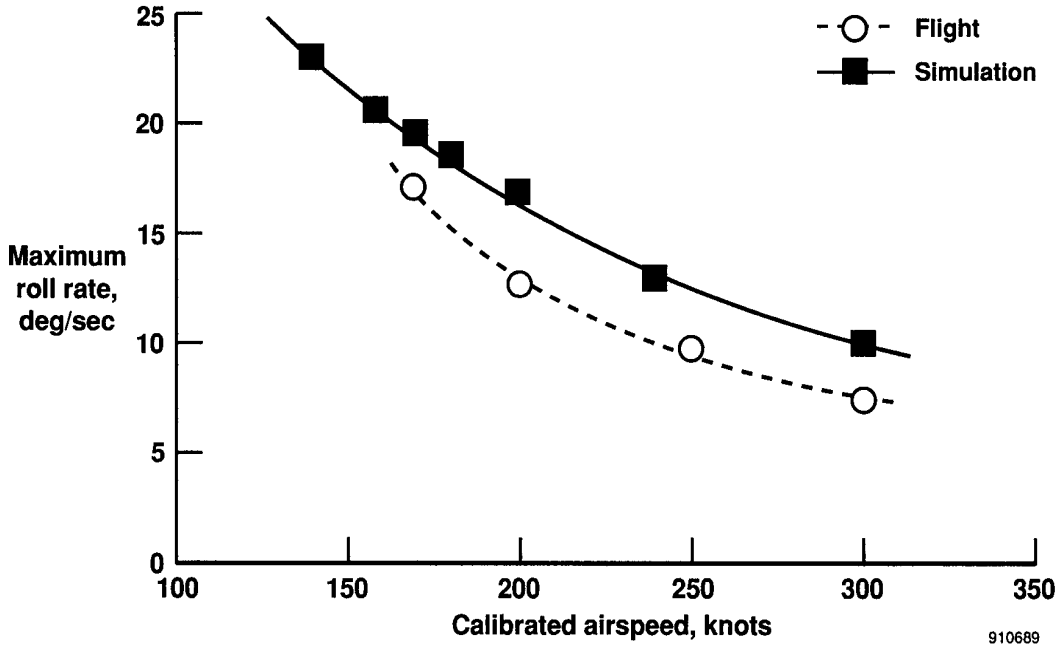

Figure 10. Effect of calibrated airspeed on maximum roll rate for F-15 flight and simulation.

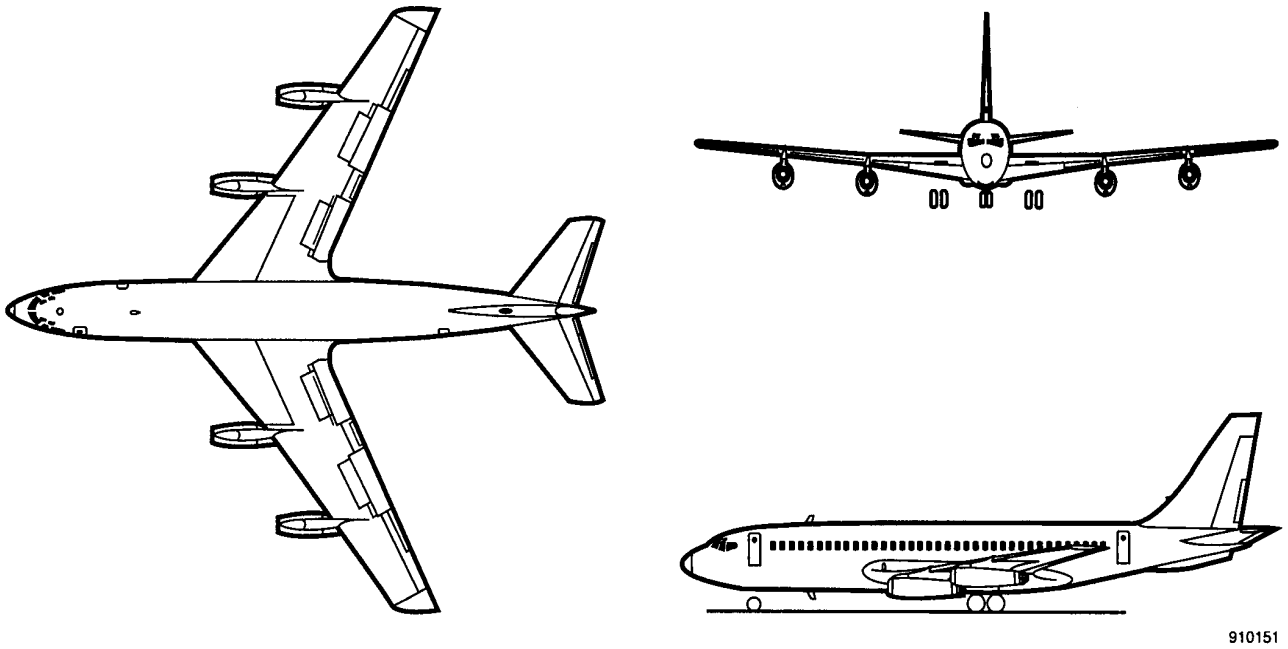

Figure 11. B-720 three-view.

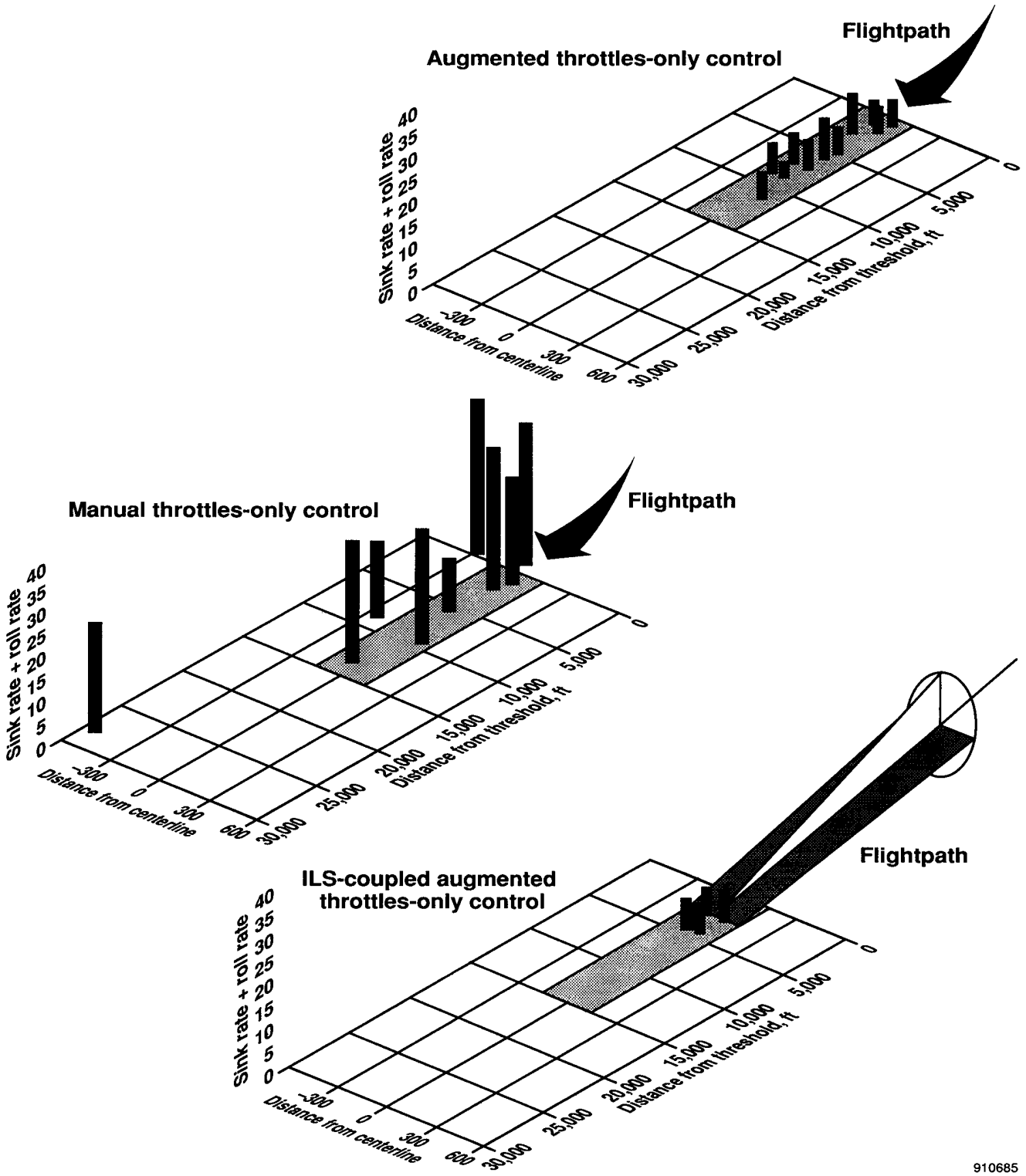

Figure 12. Landing results for the B-720 simulation for manual, augmented, and ILS-coupled control; 160 knots, light turbulence, flaps up, gear down.

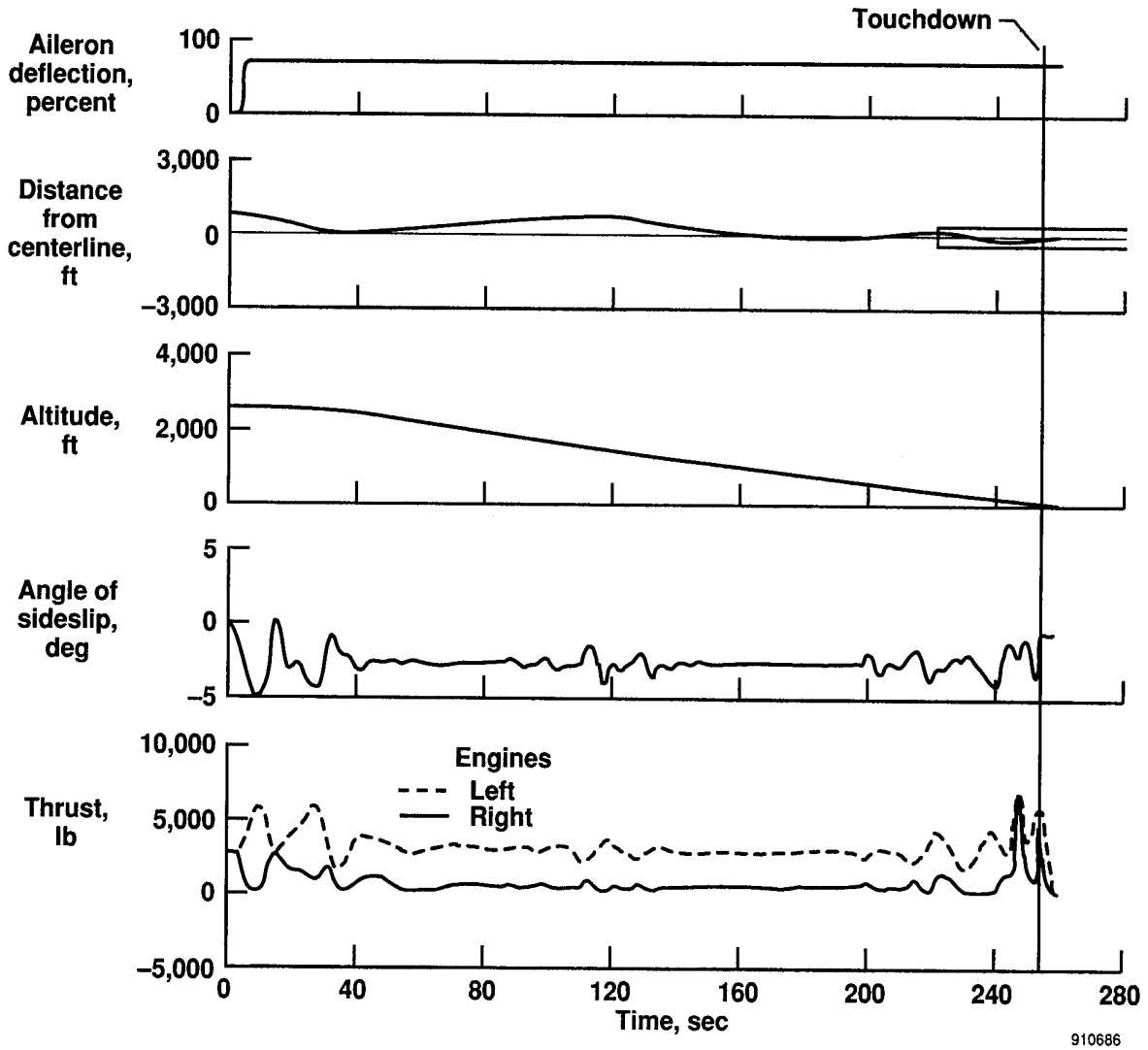

Figure 13. B-720 simulation augmented landing time history with 65-percent aileron input locked in; 160 knots, flaps up, gear down.

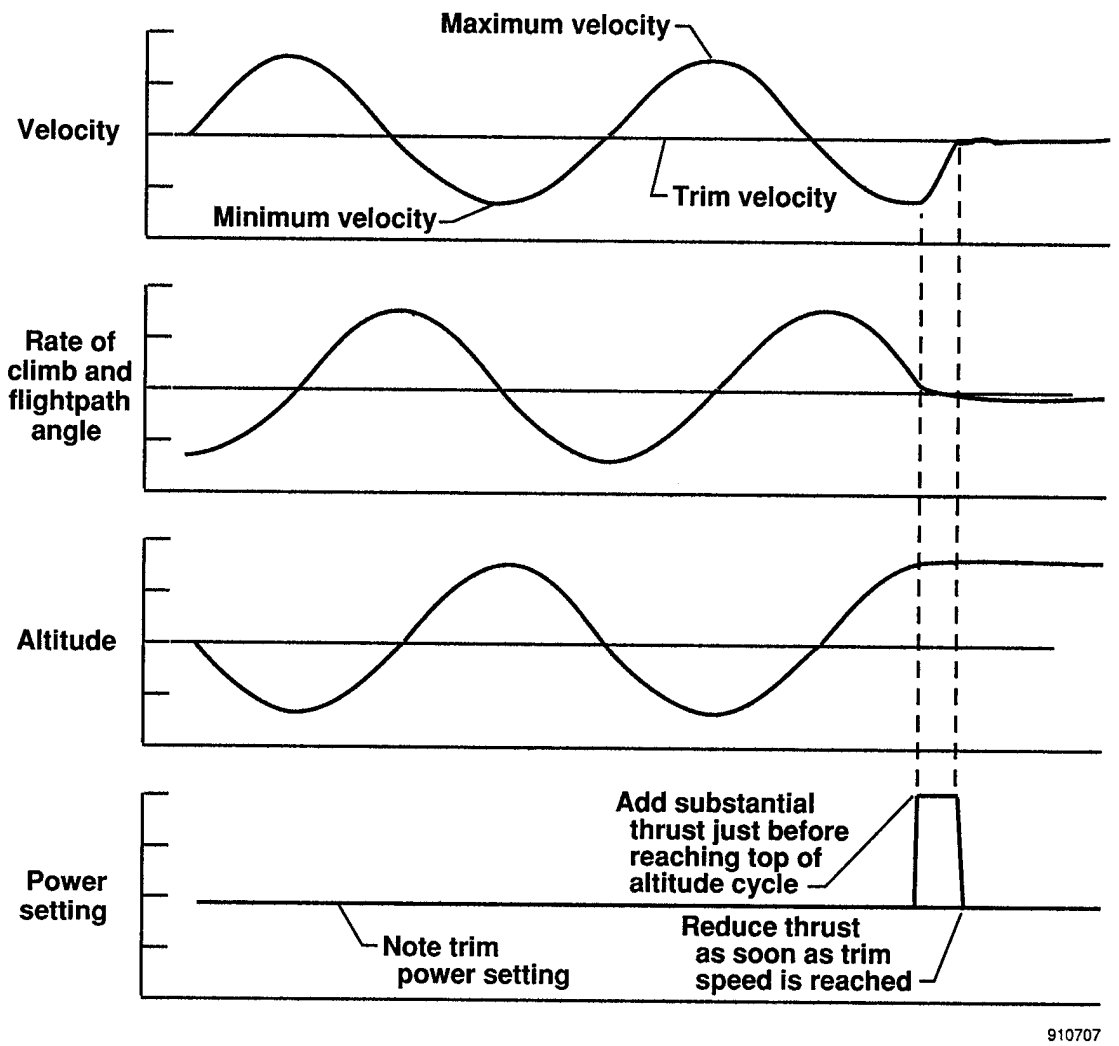

Figure 14. Phugoid damping technique.

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13. ABSTRACT *(Maximum 200 words)*

A multiengine crippled aircraft, with most or all of the flight control system inoperative, may use engine thrust for control. The NASA Dryden Flight Research Facility conducted a preliminary study of the capability and techniques for emergency flight control. Included in the study were light twin-engine piston-powered airplanes, an executive jet transport, commercial jet transports, and a high-performance fighter. Piloted simulations of the B-720, B-747, B-727, MD-11, C-402, and F-15 airplanes were studied, and the Lear 24, PA-30, and F-15 airplanes were flight tested. All aircraft showed some control capability with throttles and could be kept under control in up-and-away flight for an extended period of time. Using piloted simulators, landings with manual throttles-only control were extremely difficult. However, there are techniques that improve the chances of making a survivable landing. In addition, augmented control systems provide major improvements in control capability and make repeatable landings possible. Control capabilities and techniques are discussed.

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