MIXED MODE METHOD OF AIRCRAFT FLIGHT CONTROL

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The mixed mode method of flight control is one in which control of the flight path is mixed between manual and automatic means, an example of which is when one parameter of vertical flight path control (such as pitch) is controlled manually by the pilot while relying upon the second parameter (thrust) to be controlled by an automatic throttle. Many accidents and incidents have occurred while this method of flight path control has been used, but there has been little attention given to the fact that this method may be largely responsible for the problems.

If the aircraft is being controlled manually by the pilot then one hand, which controls the pitch axis, knows what the other, which controls thrust is doing, i.e., there is a coordinated input for flight path control. Likewise, if the vertical flight path is being controlled entirely by automatic means, the two channels talk to each other and the inputs are coordinated. When the channels are split, coordination does not exist and there can be problems caused by delayed reaction in correcting the vertical flight path. Because of the time delay in perceiving an inadequate response from the automatic controlled parameter, there is the opportunity to induce an aircraft pilot coupling (APC) event or a pilot involved oscillation (PIO) which are not the fault of the pilot.

MIXED MODE ACCIDENTS AND INCIDENTS

The following listed accidents and incidents are known or assumed to have occurred while the mixed mode of flight path control was being used. In the past, some airlines suggested[1] or required[2] their pilots to use the autothrottle on all manual landings. Some flight manuals have suggestions to "use the highest level of automation possible" and some flight instructors have interpreted this to mandate the mixed mode method. Since one manufacturer (McDonnell Douglas) advised "Autothrottles should be used for all landings."[3], its aircraft predominate in the below list because it is more certain the mixed mode method was being used.

Date	Aircraft	Operator	Location	Details
01/23/82	DC-10	World Airways	BOS	Long landing-overrun; retained autothrottle control during flare.
02/28/84	DC-10	SAS	JFK	Long landing-overrun; over reliance on autothrottle for speed control.
04/18/90	DC-10-10	FedEx	LAX	High pitch to arrest sink; tail strike.
02/11/91	A-310	Interflug	SVO	Violent pitch oscillations; eventual recovery.
12/21/92	DC-10-30	Martinair	FAO	High sink rate exceeding structural limitations; pitch instability; total loss.
04/26/94	A300-600	China Airlines	NGO	Confusion between automatic & manual functions; total loss.
08/19/94	MD-11	Alitalia	ORD	High pitch to arrest sink; four pitch oscillations; damage.
09/24/94	A310-300	Tarom	ORL	Violent pitch oscillations; eventual recovery.
01/04/94	MD-11	FedEx	MEM	Hard landing; tail strike.
11/04/94	MD-11	FedEx	ANC	High pitch to arrest sink; pitch oscillations; tail strike.
05/16/96	MD-11	FedEx	ANC	High pitch to arrest sink; three pitch oscillations; tail strike.
07/31/97	MD-11	FedEx	EWR	Pitch oscillations; NTSB says PIO; total loss.
12/25/98	MD-11	China Eastern	SHA	Tail strike; substantial damage. *
08/08/99	MD-11	China Eastern	SHA	Departed runway on landing; substantial damage. *

08/23/99	MD-11	China Airlines	HHP	Pitch oscillations; total loss.
12/18/03	DC-10-10F	FedEx	MEM	Hard landing; fire and total loss
02/07/08	B717	Qantas	DRW	Hard landing, structural damage
03/23/09	MD-11	FedEx	RJAA	Hard landing; structural breakup; fire; death of crew.

* Assumed mixed mode

A number of suspected similar events are not included due to inadequate information on whether or not a mixed mode procedure was being used. Some of these are listed below so that someone may perhaps fill in the blanks.

10/17/99	MD-11	FedEx	SFS	High speed; overran runway into Subic Bay; total loss.
11/20/03	MD-11	Eva Air	TPE	Bounce and damage.
09/19/04	MD-11	FedEx	MEM	Porpoise; tail strike.
09/14/06	MD-11	FedEx	SFS	Tail Strike

AIRCRAFT PILOT COUPLING (APC)

Aircraft Pilot Coupling or APC was defined by a National Research Council (NRC) Report of 1997[4] which states ".... APC events are rare, unexpected, and unintended excursions in aircraft attitude and flight path caused by anomalous interactions between the aircraft and the pilot." and "If the PVS [pilot-vehicle system] instability takes the form of an oscillation, the APC event is called a 'pilot-involved oscillation' (PIO)." The NRC report introduced a new meaning for PIO because the more traditional term, "Pilot Induced Oscillation", implies the event is caused by something the pilot did wrong.

A primary concern of the Committee was that fly-by-wire military aircraft have been known to have APC and PIO problems which were not discovered until after the aircraft were accepted into service. It was a purpose of the report to help prevent such problems with commercial fly-by-wire aircraft. During the course of the investigation it was discovered that the Airbus A-320 did in fact enter service with a PIO problem in the lateral control axis which was not corrected until after an investigation of a near accident[5]. Prior to the near accident there were approximately a dozen previous events.

Despite the focus on fly-by-wire, non fly-by-wire aircraft were also examined as they can also have such problems. Several examples of problems which occurred while pilots were flying in a mixed mode of control were noted with a suggestion that this procedure may be susceptible to an APC/PIO, when accompanied by a trigger event or condition. Some airlines have required their pilots to fly all manual (pseudo manual is more correct) approaches with manual control of the aircraft pitch and automatic control of the thrust. While landing with fully automatic means (autoland) requires certification of the aircraft, pilots and airport facilities, with operational limitations, no proof of concept was required for the use of the mixed mode procedure. The evolution of this method and the problems which are caused by such a method are discussed below.

PRINCIPLES OF VERTICAL FLIGHT PATH CONTROL

In the early days of aviation the principles for climbing or descending flight path control were well known and promulgated by notable experts such as Wolfgang Langewiesche with his book "Stick and Rudder". There are many other texts which also describe the fundamental equation of aircraft performance during climbing or descending flight, some of which are:

Airplane Performance, Stability and Control: Perkins and Hage
Aerodynamics for Naval Aviators: H. Hurt
Basic Aerodynamics: Tower
Fundamentals of Aviation and Space Technology: Univ. Institute of Aviation, Illinois
Engineering Aerodynamics: Diehl
Private Pilot's Flight Manual: Wm. Kershner
Learning to Fly: J.H. Holland
Aeronautics in Theory and Experience: Cowley
Flight Mechanics, Theory of Flight Paths: A. Miele

Basically, these texts point out that the primary control of flight path when climbing or descending is with thrust while angle of attack is the primary control of airspeed. The basic equation is universally accepted, but an opposite interpretation has evolved through the use of automatic systems and flight director guidance for pilots.

The most important element in understanding aircraft performance and control in the vertical plane is the Performance Equation which leads to an understanding of climb gradients, wind shear effects, noise abatement procedures, missed approach procedures, flight path control and obstacle clearance.

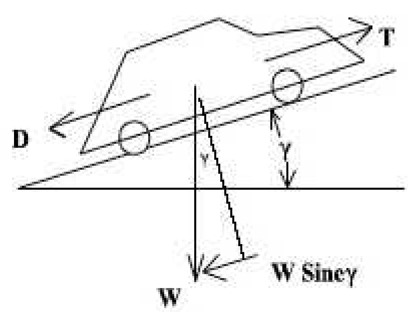

Figure 1. Forces Along an Inclined Path

Figure 1 shows an automobile on an incline at a constant speed. Thrust (T) is a force propelling the car up the incline while drag (D) is composed of friction and wind resistance. If the forces along the direction of motion are resolved and the angle of the incline is defined as gamma (γ), there is a force generated as a component of weight which tries to pull the car back down the incline. This force is obtained by multiplying the weight (W) by the Sine of the angle of incline. Thus: $T\text{-}D\text{-}W\text{Sine}\gamma = 0$ or:

$$(T-D)/W = \text{Sine}\gamma$$

Although the car illustration is obvious, what is less obvious is that an aircraft complies with the same basic formula, except that it can make its own hill within the limits of its capability to generate thrust and drag. Since Lift is defined as being normal (perpendicular) to the flight path, it does not appear in this equation which is the reason for using a car for the illustration. An aircraft's ability to generate lift should not be confused with its ability to fly a given flight path.

The above equation is for non-accelerated flight. If an aircraft accelerates or decelerates along its flight path then Newton's second law of motion enters the picture which says that the net thrust (minus drag) will cause an aircraft to accelerate or decelerate along its flight path such that T-D = MA where M is mass and A is acceleration. Since Mass is equal to Weight divided by the acceleration due to gravity (g), the complete performance equation can be written as:

$$\mathbf{(T - D)/W = Sine\ \gamma + A/g}$$

What this equation says is that the net thrust weight ratio of an aircraft can cause it to climb or descend and/or accelerate or decelerate. The flight path angle portion of this equation is relative to the airmass while the acceleration is relative to Earth, i.e., inertial so the terms have a mixed reference which is especially important in wind shear.

A more sophisticated analysis of aircraft motion requires the use of more complete equations of motion as used by Professor Angelo Miele of the Aero-Astronautics Group at Rice University in the studies of Optimal Trajectories in Windshear[6]. However, the above embodies the most essential elements and accounts for more than 90 percent of the solution for vertical flight path performance. Thrust is offset from being parallel to the flight path by angle of attack and installation angle, but within the normal range of flight, there is little difference. A complete analysis for a particular aircraft would require aircraft data which is usually considered "proprietary" by the manufacturer.

The above does not account for the force required to change the direction of motion of an object. This force acts normal to the direction of motion and is called Centripetal Force. It is a function of centripetal acceleration which is commonly called "g load" in aircraft.

From the above, it should be obvious that if an aircraft should be attempting to fly on a glide slope but below the desired flight path at the proper airspeed then an increase in thrust is required to fly a more shallow flight path at the same airspeed. However, this will require a slight momentary increase in centripetal force to change the aircraft's trajectory so the pitch should be increased to provide this force and will thereafter be slightly higher in order to preserve the desired angle of attack. Thus, it can be argued that the flight path is changed by pitch inputs and maintained with thrust inputs, or it can be argued that trust is the primary input to vary the flight path while pitch is used to regulate the angle of attack. Regardless of how one looks at this, it is impossible to fly different flight paths at the same angle of attack without different thrust levels.

AUTOMATIC CONTROL

During the evolution of approach couplers, designers first used only pitch inputs in an attempt to fly the glide slope, with the pilot left to control airspeed by varying the thrust. This form of mixed mode, exactly opposite to the current problem, worked reasonably well because flight directors directed this form of control; pilots could monitor the pitch requirements and learned to anticipate thrust requirements. The first autothrottles did not work well because they were entirely independent from the pitch channel. Improved versions were designed which responded to angle of attack changes, but they were still unsatisfactory. It wasn't until pitch anticipatory circuits were installed which allowed the automatic system to have coordinated inputs that a satisfactory system was developed. Even then there were operational limitations placed upon these systems such as crosswind limits, etc. One problem is that the systems used inertial accelerometers to modulate their response rates. In windshears the response rates are modulated exactly opposite to what they should be[7] which is one reason why they have not proven satisfactory during windshear encounters, contrary to some claims.

Through the evolution of automatic systems, an unreasonable belief in their superiority has led to recommendations for the mixed mode procedure. Because there are many who believe automatic systems will always be better than human control, recommendations have been put forth to use all of the automation which is available at a given time. This coupled with a misunderstanding of the proper method of flight path control in which it is assumed that thrust is used only to control airspeed has resulted in the mixed mode method of flight path control.

That there are limitations to this procedure is evident in the safety record of those aircraft on which the procedure is being used. Because of the high number of tail strikes on landing there are special recommendations and training to prevent tail strikes when in fact they would most likely not occur if the pilots were not using a mixed mode procedure.

A special case of mixed mode control occurs when climbing and using autothrottles to maintain a climb thrust level. In this case the thrust is held relatively constant while the pilot may manually control the pitch to control the angle of attack. The resultant flight path angle is whatever it is. However, it is especially important for pilots to be aware of mode changes or failures because there have been accidents when the autothrottles didn't do what the pilots expected.

Humans are very poor monitors of automatic systems, but automatic systems are excellent monitors of themselves and/or humans. There are a number of cases of accidents (not on the above list) where the automatic systems were doing something opposite to what the pilots expected. In most cases they could have warned of a failure or conflict if programmed to do so.

FLY BY WIRE

For those who believed that pitch controls the vertical flight path and thrust controls airspeed as independent functions, the arrival of the Airbus fly-by-wire control system seemed to prove their point. The Airbus system is designed to maintain a desired flight path based upon what would normally be pitch channel inputs while an autothrottle maintains a desired airspeed. The pilot is really controlling an autopilot in a control wheel steering mode for flight path control. Although, it may appear that the same can be done with a standard system where the pilot controls the pitch channel and an autothrottle controls airspeed, the Airbus system is unique in its operation in that acceleration normal to the flight path (g load) is monitored and corrections are applied to control the flight path. This system integrates pitch and thrust requirements whereas the mixed mode procedure separates the channels.

Having made this distinction, it should not be concluded this is an endorsement of the Airbus fly-by-wire control logic, but merely an identification of the differences of this system. Aside from the controversial subject of not having moving autothrottles, the Airbus method removes the tactile feel a pilot has of positive longitudinal stability which is evident in all other aircraft, i.e., an aircraft trimmed to a given angle of attack will not diverge far from the trimmed condition without a pilot push or pull force or re-trimming. In certification, an aircraft is allowed to oscillate about the trimmed condition, but not diverge. The Airbus system takes a pilot input to direct a new flight path angle and holds that new angle within certain limits. The tactile feel of having diverged from a trimmed condition is not present. In addition, pilots may be seduced into believing the only purpose of thrust is to maintain airspeed as the changes to thrust requirements for varying flight paths are obscure.

The ability of the Airbus system to operate in this manner should not be considered as a reason to operate other aircraft (conventional or fly-by-wire) in a mixed mode.

MIXED MODE APC AND PIO

In the previously mentioned accidents and incidents, certain cases appear to be clear PIO cases which were identified at the time. Others resulted from APC events which may have had oscillations but were of a longer period than is typical of a PIO. These are the ones where there was confusion between what the pilots were attempting to accomplish and what the automatic system was doing. The China Airlines A-300 crash at Nagoya, Japan on 4/26/94 is a good example, as are the two dramatic cases of out of phase operation between pilot manual pitch inputs and autothrottle inputs, being a Tarom A-310 at Orly on 09/24/94 and an Interflug A-310 at Moscow on 02/11/91. In all three cases there were very high pitch values which resulted in a total loss in the first one and eventual recovery in the second and third after the pilots took the autothrottles out of the loop. There is a very suspicious additional case, not on the above list, which was a China Airlines A-300 executing a missed approach at Taipei on 02/16/98. There was a 35 to 40 degree pitch, autopilot disengagement, stall and crash which was fatal to 196 persons. Implicated in some accidents is an autopilot which will trim against a manual pilot input which is further reason to not attempt to mix the modes.

A computer simulation of the Interflug incident at Moscow, created by Flightscape, inc., shows how dangerous the event was. Pitch attitudes as high as 80 degrees were recorded.

For mixed mode operation, the time delay in recognizing a problem and reacting is within the range required to cause a PIO event if a high gain task requiring rapid, precise control is demanded. The NRC report considers the total pilot vehicle system (PVS) where input to output delays in the aircraft control system are an important component of the time delay. Modern control systems, especially fly by wire, can be rate saturated by pilot commands for a faster rate of control surface movement than the surface can provide. Rate saturation has been evident in a number of PIO incidents.

In demonstrating PIO events with the Calspan Corporation Learjet during the NRC study the lateral axis control of the aircraft was tailored to have a time delay with the possibility of rate saturation. In normal flight this was undetectable from the unmodified system, but when a high gain task was required, the pilot would get out of phase with the system. To set up the requirement for a high gain task, the pilot with modified controls was instructed to approach for a landing parallel to the runway but about 300 feet offset from the centerline. At about 150 feet agl, the control pilot called for a landing on the runway. This required rapid and precise control inputs (a high gain task), which were easy to accomplish with the unmodified system; but with the modified system the result was a lateral PIO with rate saturation. The NRC report identifies this as having a cliff like characteristic, like stepping off a cliff. In a subsequent approach with identical conditions, the pilot was able to avoid the cliff with slightly less aggressive control inputs which illustrates how pilots can adapt once they know the cliff is there. This doesn't eliminate the cliff; sooner or later a lateral PIO will happen again as long as the PVS has this characteristic.

Many military pilots have seen movies of the first attempt at in-flight refueling of an F-18 in which the pilot lost control at the last moment. Up to the point of stabbing the probe, the task was not high gain, but it then became so, which was the trigger for the APC event.

Landing an aircraft can be a high gain task in the vertical axis. There can be many normal landings using the mixed mode method, but a trigger event requiring a high gain task can result in an APC/PIO. If the mixed mode method had been tested according to Calspan procedures, it is likely it would never have been approved.

An NTSB report[8] of an accident where the mixed mode was being used, cites as a cause a PIO in the vertical axis, but with no recognition of why it may have occurred or that the mixed mode method of flight control might be a causal factor. In another report[9], the NTSB notes that during the investigation, while performing a demonstration flight, a pilot got into a PIO (presumed to have been mixed mode as this was a requirement of the operator). This fact was dismissed because the pilot was not rated on the aircraft.

Figures 2 and 3 are taken from a Boeing submission to the NTSB regarding the FedEx accident at EWR on 7/31/97. They show the variations in pitch attitude for the FedEx crash and the Martinair crash at Faro, Portugal on 12/21/92. Both are suggestive of an APC/PIO event.

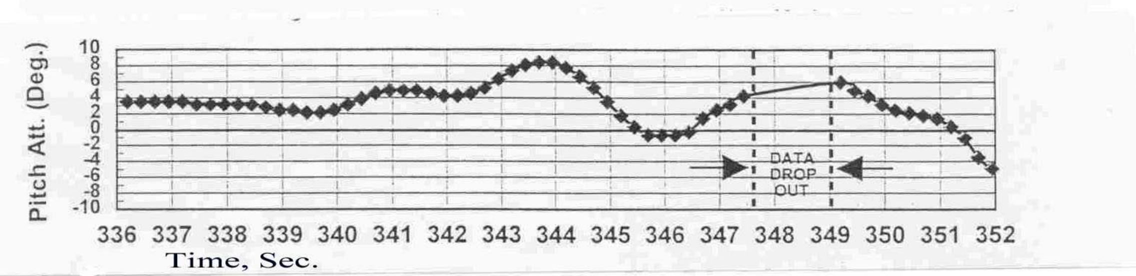

Figure 2. FedEx MD-11 at EWR, 07/31/97

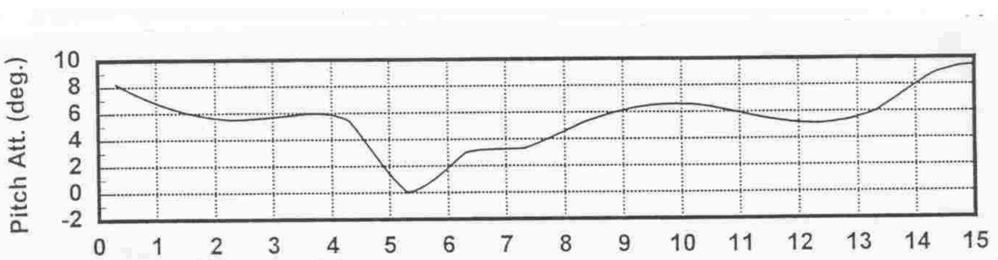

Figure 3. Martinair DC-10 at Faro, Portugal, 12/21/92

In the Martinair accident, the trigger event was probably a high gain task caused by atmospheric conditions. There were documented microbursts in the area and at the time of impact the crosswind exceeded the certification limit of the aircraft. The FedEx EWR accident occurred in a low wind condition, but the trigger event resulting in a high gain task causing the PIO was probably the pilots concern over getting the aircraft onto the runway as close to the threshold as possible. The landing was being made on a wet, marginal length runway with one of the thrust reversers locked out.

The NTSB accident report (AAR-05/01)[10] of the DC-10-10F at MEM on 12/18/03 has a pitch/time history of the accident aircraft (Figure 4) which shows pitch oscillations similar to Figures 2 and 3 above. The previous two landings are shown on the same graph and they also show similar pitch oscillations. Although the accident aircraft had a much higher vertical descent rate, if these pitch oscillations are indicative of normal landing technique in the mixed mode, there should be cause for alarm; the landings were flown by two different pilots.

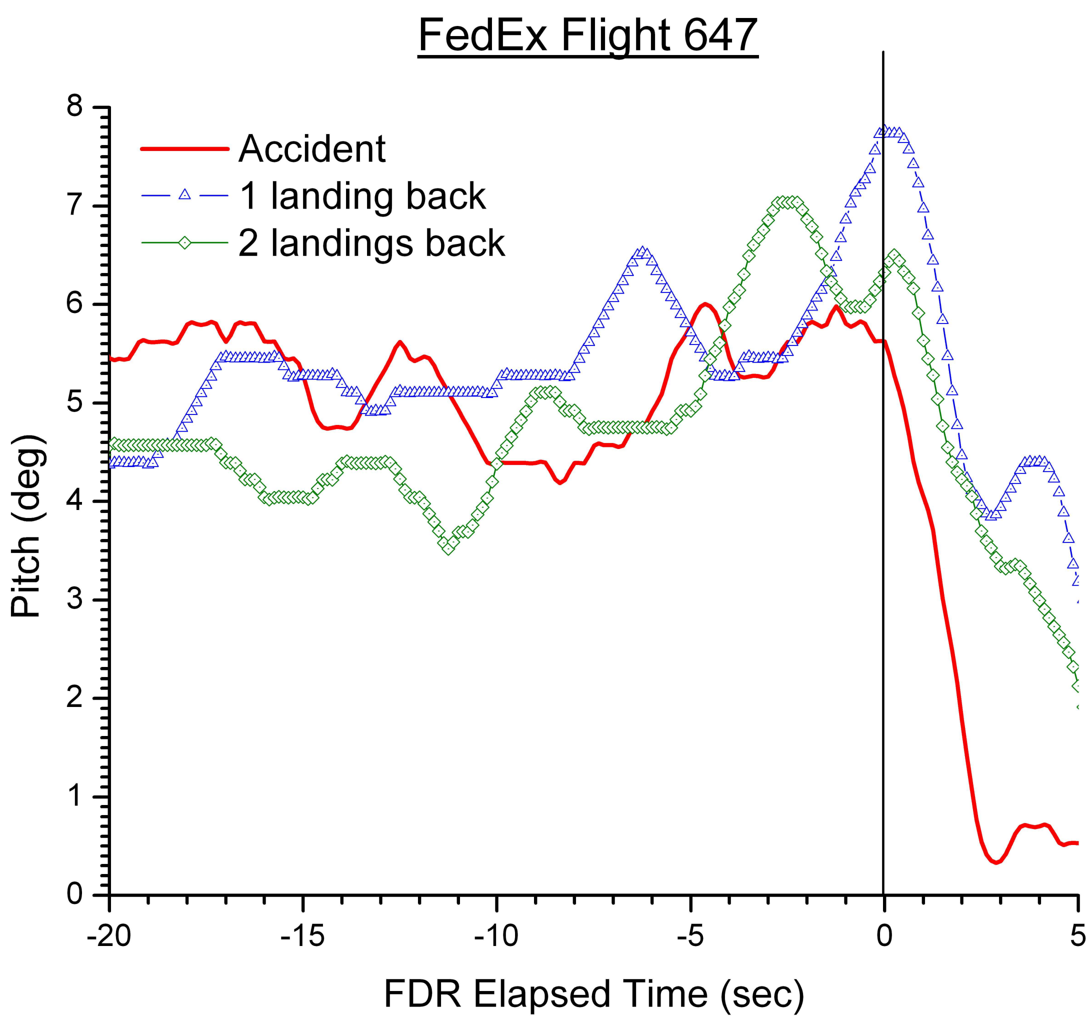

Figure 4. FedEx DC-10-10F at MEM, 12/18/03

Below (Figure 5) is the FDR pitch plot versus time in seconds of the FedEx MD-11 crash at Narita, Japan on March 23, 2009 (Japanese accident report AA2013-4). First impact occurred at the zero time point.

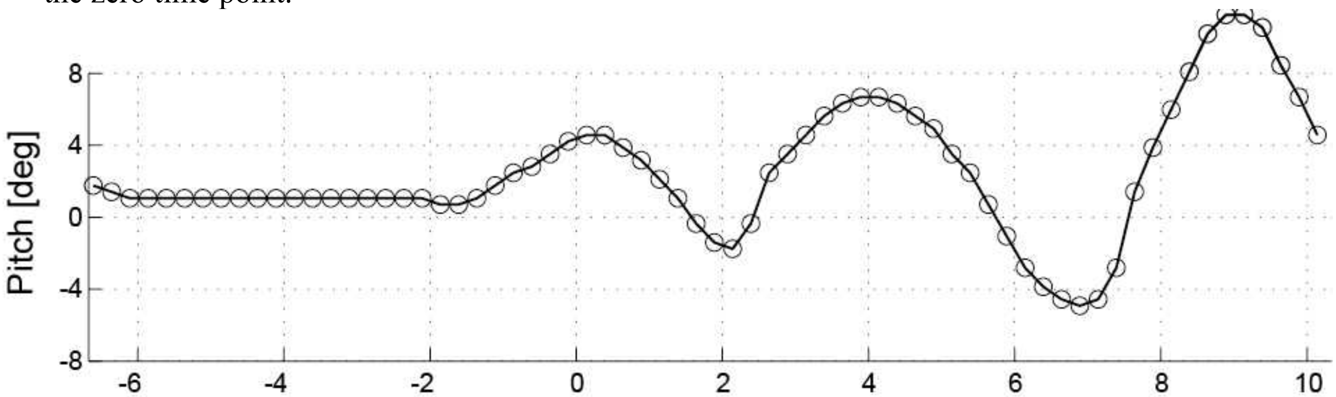

Figure 5. FedEx MD-11 at RJAA (Narita), 03/23/09

Another accident, the Lufthansa MD-11 at Riyadh, Saudi Arabia on July 27, 2010 is interesting because Lufthansa had a policy of requiring disengagement of the ATS (auto-throttle system) at no less than 200 feet agl (above ground level). However, in this case the PF (pilot flying) performed the same as the ATS would have done, by significantly reducing thrust and using pitch control alone to effect the landing; in this case, a crash. There is a report (2X003-10) in English at www.bfu-web.du/EN which is a translation of the Saudi Arabian report. The below, Figure 6, is taken from that report. Pitch angle is the top curve.

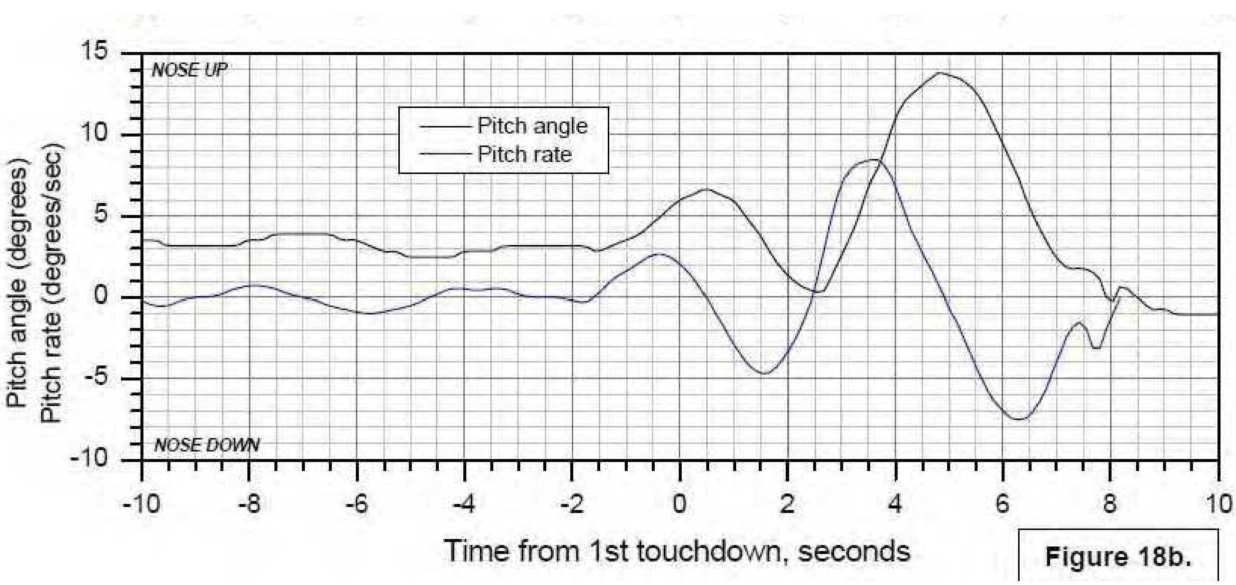

Figure 6. Lufthansa MD-11 at KKIA (Riyadh), 7/27/10

The report recommends:

"The FAA should require Boeing to revise its MD-11 Flight Crew Operating Manual to reemphasize high sink rate awareness during landing, the importance of momentarily maintaining landing pitch attitude after touchdown and using proper pitch attitude and power to cushion excess sink rate in the flare, and to go around in the event of a bounced landing (A-11-68)." and states:

"Safety Action was taken by Boeing on 15 February 2011. The MD-11 Flight Crew Operating Manual was revised by Boeing in accordance with the stated recommendation A-11-68."

Although, to be technically precise, the correct term is "thrust" and not "power", this is a significant departure from a recommendation of using autothrottles for all landings, but the recommendation only addresses MD-11 aircraft. Considering it comes 14 years after the NRC report identified mixed mode operation as having a potential for APC/PIO events and the large amount of substantiating evidence, it is an inadequate response to the issue. Lack of recognition by the NTSB of the larger problem is not because they haven't been told. NTSB recommendation A-11-68 & 69 can be found at www.ntsb.gov. and contains some information about the Riyadh accident which is not in the report.

The NRC report states. "If an aircraft has an APC tendency, sooner or later someone will encounter a problem. Pilots naturally hesitate to admit they have problems flying an aircraft that other pilots have flown without difficulty. With an APC prone aircraft, the superior test pilot is the one who can detect a problem. A line pilot who discovers an APC characteristic may prevent a tragedy by sharing that information. Thus, it is important to educate both test pilots and line pilots about APCs and to encourage them to report suspected APC events."

SUMMARY

The mixed mode method of flight control is suggested as a possible combination for an APC/PIO event in the National Research Council report. There is abundant evidence that APC events have been present in many accidents and incidents when this procedure was being used. It is believed that one reason there aren't more problems with the mixed mode procedure is that many pilots have learned to not trust the autothrottle and override it during landing. In the accident report referenced above (AAR-05/01), a check airman ". . . . reported he guards the autothrottles and does not let the throttles retard on the MD-10 during the flare and touchdown." (page 41).

Recommendations in one airline's operations manual to override the autothrottle in the event of unsatisfactory performance presumes the pilot will recognize a need to override prior to acting. This leads to the problem of perception before response which increases the PVS time delay, further increasing the probability of an APC event. Despite whatever can be alleged the pilot(s) did wrong, the accidents/incidents would probably not have happened if mixed mode operations were not being conducted.

A combination of factors may be leading to the high number of accidents and incidents where the mixed mode method is being employed. While the method itself leads to an APC/PIO potential, especially when a high gain task is required; scheduled autothrottle thrust reduction depending upon radio altitude above the ground may be adequate for some circumstances and not for others.

Influence of accelerometers in the automatic systems may be causing problems, especially in windshears. The effect of the Longitudinal Stability Augmentation System (LSAS) in the case of the MD-11 may have some effect in combination with other factors. However, the author believes this cannot be a factor alone because, having had some experience with this aircraft, he found it to have excellent landing characteristics when being flown with coordinated pitch and thrust inputs.

As has been shown, thrust is the most important parameter in controlling a flight path. Glider pilots control their landings by regulating drag with a spoiler which has the same net effect on the flight path as regulating thrust. Why should a pilot ever consider not having instant control of thrust, or drag in the case of gliders, at the most important time?

References:

1 Martinair Holland NV, for example.

2 FedEx prior to June 30, 1998; still a suggestion.

3 “Know Your MD-11", Douglas Aircraft Company, April 14, 1993, page 4.

4 Aviation Safety and Pilot Control–Understanding and Preventing Unfavorable Pilot-Vehicle Interactions, National Research Council–National Academy Press, 1997.

5 National Transportation Safety Board report no. CHI-95IA-138, Northwest Airlines approach to Washington National Airport, April 27, 1995.

6 A. Miele, T. Wang and W. W. Melvin, “Aero-Astronautics Report No. 191-Optimal Flight Trajectories in the Presence of Windshear, Part 1, Equations of Motion” Rice University, 1985. Also, many subsequent technical papers.

7 W. W. Melvin, “The Dynamic Effect of Wind Shear”, Pilot Safety Exchange Bulletin, Flight Safety Foundation, November/December 1975; Also, “Windshear—Optimum Trajectory, Human Factors and Miscellaneous Information”, SAE paper no. 901995, SAE Aerospace Technology Conference and Exposition, October, 1990.

8 NTSB report AAR-00-02, FedEx MD-11 at EWR, 07/31/97.

9 NTSB report ANC95FA008, page 1d, FedEx hard landing at ANC, 11/04/94.

10 http://www.ntsb.gov/publictn/2005/AAR0501.pdf

Note: Adapted from AIAA paper no. 2003-6705, Nov. 2003.

August, 2009; revised May, 2013