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Kinematic Effects in Large Transport Aircraft

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While many aspects of aircraft dynamics are easily modeled, there will always remain aspects that can be overlooked, especially if the particular dynamic can be masked by certain pilot technique. A review of several landing events contained in the databases of a number of accident investigative agencies from around the world (Australian Transport Safety Board (ATSB), British Aircraft Accident Investigation Board (AAIB), Japan Transport Safety Board (JTSB), Kingdom of Saudi Arabia General Authority of Civil Aviation (GACA), and United States National Transportation Safety Board (NTSB)) involving large transport aircraft revealed a pattern of pilot control inputs that appeared counter-intuitive. A review of the aircraft handling characteristics found no adverse handling qualities or anomalies that would have led to the accidents. Various aspects of the inputs were studied in an attempt to discern the reason pilots made these improper control inputs. One possible explanation is simply that humans will respond according to their perception of events. As is often the case with many incidents and accidents, perceptual cues can often be misleading and result in incorrect control and compensatory behaviors. An examination of transport aircraft landing accidents was conducted to evaluate what cues the pilots had that could lead to the observed pilot responses.

The Aircraft

Aerodynamic Overview

Large transport aircraft share a fairly common general plan form, with a relatively long fuselage, swept wings and horizontal stabilizer with elevator controls located at the tail of the aircraft. Due to the size of the aircraft, there is a significant amount of mass which, in turn, requires large amounts of force (push) to effectuate motion changes for both actual changes in the flight path or rotational motion in any axis. The aircraft motion itself is measured in reference to its center of gravity (CG), through and about which all aircraft motion takes place.

Swept wings are implemented to delay the onset of mach effects, improving efficiency. In addition, swept wings improve some stability aspects due to dihedral effect. A secondary factor resulting from swept wings is a flatter lift-curve slope, as illustrated in Figure 1 (Hurt, 1965, p. 228). The lift on the wing is altered by changing the angle of attack (α), and the most direct way to change the angle of attack is by changing the aircraft pitch (θ). As can be seen in figure 1, when the wings are swept, the amount of lift change for a given change of angle of attack is relatively smaller than it would be for straight wings. This means that before enough lift is generated to effectuate a change in flight path, there must be a relatively large change in pitch (Hurt, 1965, p. 229). While a change in aircraft speed will also change the amount of lift generated for a given angle of attack, this factor is not considered here due to the relatively long period of time required to accelerate a large aircraft enough to make a significant difference.

A change of pitch requires a force to be generated, and in a transport aircraft, the primary immediate means of creating this force is through an input to the elevator control surfaces. As these surfaces are located at the tail of the aircraft, in order to pitch the aircraft upwards, the tail of the aircraft must be *pushed* downwards, and vice versa.

What may be counter-intuitive is that when a force is applied to one end of the aircraft, the entire aircraft is moved in the direction of the force. This is due to the fact that the aircraft is not on a fixed support, but rather moving through the air, which is a fluid. The situation is not unlike that of a log floating on the water. If a weight is added to one end of the log, the log both rotates and (at its CG) sinks a bit. An aircraft acts in a similar manner. When the tail of the aircraft is pushed downwards in an effort to begin a climb, the *aggregate* force initially applied through the CG is actually downward, and thus the resultant movement of the aircraft is *opposite* of the *desired* change of flight path.

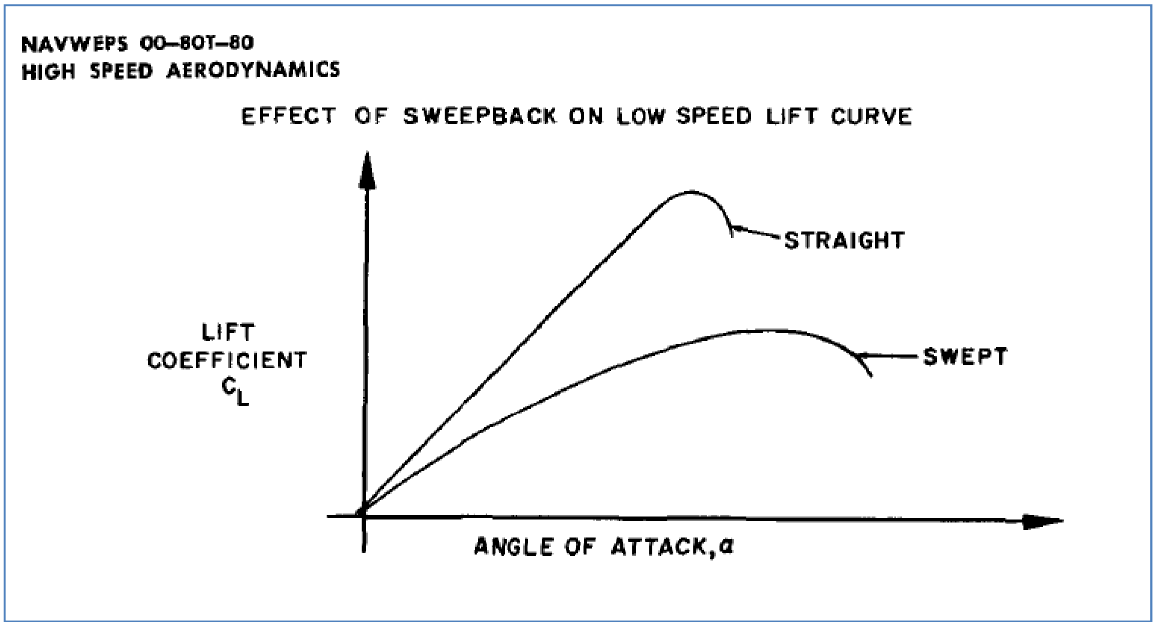

Figure 1. Low speed lift curves for straight and swept wing designs (Hurt, 1965, p. 228).

To initiate a climb (or reduce the rate of descent), the lift on the wings must be increased, requiring an increase in angle of attack if speed remains constant. To do this, the nose of the aircraft is pitched upwards, but this upward pitch only occurs because the tail is pushed downwards. What occurs then is that the force at the tail results in initially moving the aircraft downwards until enough lift is generated by the wing to overcome the combination of inertia and tail down-force which will start the aircraft moving upwards, in lag effect characterized as a *pitch transient* (Carpenter, 1997, p. 252).

In Figure 2, the lift is shown as a blue arrow, which must overcome the combined effects of weight and downward force imparted by the horizontal stabilizer with elevator movement. The resultant path of the aircraft is then to initially descend slightly before beginning to move upwards. Carpenter (1997) elaborates on this effect on large aircraft, stating:

> On a light aircraft…the pitching moment of inertia, I_y, is small, so that the rotation to the new attitude happens very quickly and the downward transient will often be unnoticeable. However, in the case of an airliner such as the McDonnell Douglas MD-80…with a very long and heavily loaded fuselage, or of a very large aircraft such as a Boeing 747, I_y is very substantial, and the pitching motion will take considerably longer, maybe a few seconds, during which a substantial amount of height will be lost (p. 252-253).

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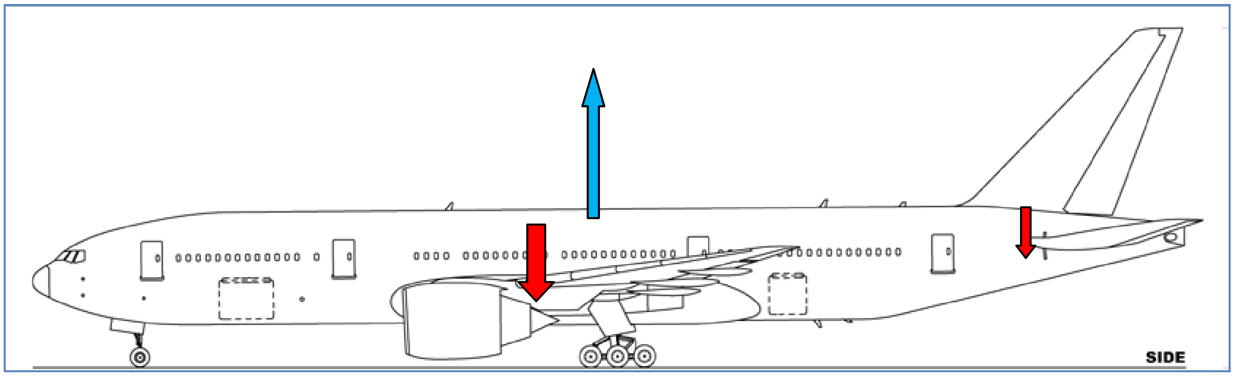

Figure 2. Lift (blue arrow) vs the combined effects of weight and downward force imparted by the horizontal stabilizer with elevator movement (red arrows). (Graphics added to Wikipedia, 2012)

The substantial inertia of a large and/or long fuselage requires a significant amount of force to initiate any pitch change, thus the flight path is going to be affected by both the time delay while changing pitch, as noted above, plus the magnitude of the force required, which is substantially more when large amounts of inertia must be overcome.

An additional aspect may also be a factor in certain designs. Aircraft that are designed with aft mounted engines will, by design, have a center of gravity (CG) that is closer towards the rear of the aircraft. This puts the elevator control in the equivalent of the short end of a teeter-totter. The short end has less "arm", so in order to balance that out, more *force* is required. This larger relative amount of force can, in some cases, exacerbate the pitch transient.

Kinematic Dynamics

Pitch transients have been understood for many years:

> It is, of course, a characteristic common to all planes having the control surfaces located behind the center of gravity to have a sign opposition between the change of lift force due to a deflection of the surface and the change of lift force sought by the pilot. The overall change reaches its correct sign only after a time interval during which the pitch has not changed sufficiently to counterbalance the immediate lift effect of the control surface (NASA, 1966, pp. 43-44).

The effect was quite prominent in some of the early jet fighter aircraft. Pilots sometimes used the “lag” to get a better shot, as an aircraft that is being pursued and attempting to rapidly climb or turn can find that its flight path vector actually moves *opposite* to the desired path. This could put it directly in line with the pursuing aircraft's guns, a problem particularly acute in delta wing designs (Carpenter, 1997, p. 253).

In smaller aircraft (as compared to large transport aircraft), the pilot is stationed within just a few feet of the aircraft center of gravity, so when the aircraft starts moving, the pilot can feel it, and if close enough to another aircraft, or the ground, the pilot can also see the effect visually. This is not the case for large aircraft, where the pilot can be 80 to 100 feet, or perhaps more, from the center of gravity.

In itself, the displacement from the center of gravity is not generally a large problem, although the greater heights involved can make it more challenging for pilots to see relatively small height changes. However, this is coupled with the kinematic effects of the change of aircraft pitch. The flight crew station will move vertically as the aircraft changes pitch (see Figure 3).

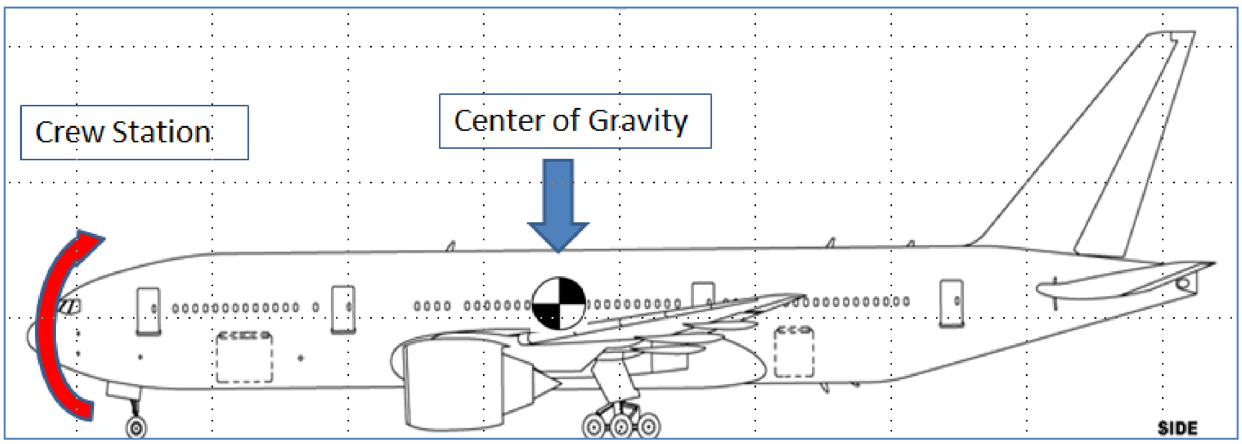

Figure 3. Relative direction of motion at CG vs. crew station location (Graphics added to Wikipedia, 2012)

As an example, if the distance from the crew station to the CG is 100 feet (not unusual for some of the larger transport aircraft), then a nominal 5º change of pitch will result in the pilot station moving almost 9 feet (100 TAN 5º). This is enough to create some interesting perceptual issues which shall be further discussed in the following section.

Human Perceptual Issues

Pilot Flight Control Response

Pilot control inputs fall into two general categories, the first being those inputs that are made in anticipation of what will be needed, and the second, those inputs that are in reaction to something the aircraft will be doing. Anticipatory inputs tend to be smaller amplitude and are generally classified as "low gain", while reactionary inputs tend to be higher gain. Very typically, reactions and control inputs from pilots who are unfamiliar with an aircraft platform and new to an airplane type will be higher gain as compared to those more experienced as they are not yet accustomed to the handling characteristics of the particular airplane. Higher gain is often referred to as "over controlling", where one input is too large, so then requires an opposite input to correct the first one, in a repeating or oscillating cycle until stability and control is

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reestablished. It is not surprising then that this is often a factor in aircraft-pilot-coupling (often commonly referred to as pilot-induced-oscillation) events (National Research Council, 1997).

Other factors can also move a pilot towards higher gain reactions and inputs. Consider the following discussion of an aircraft-pilot-coupling by the National Research Council (1997):

> Landing and derotation is a time of high pilot urgency and gain. For this reason it was assumed during control law development that fixed-base piloted simulations would not be adequate for realistic evaluation in this regime. One lesson from this event is that pilot urgency can be replaced to a significant extent by artificially boosting pilot gain via a suitable tight-tracking task. For example, on-runway attitude tracking showed clear trends in the time history and associated frequency response data. Derotation is a key flight phase and deserves special attention in preflight evaluation. The 777 simulator had the same characteristic as the airplane but was not evaluated as effectively prior to flight test. Also, none of the first five flight test pilots experienced any difficulty during landing, thus illustrating the need for carefully designed flight tests by as many different pilots as possible (p. 70).

Landing and derotation have been shown to increase pilot gain. Note also that there is a wide variation in pilot response, even when the sample set consists only of experienced test pilots. Pilot evaluations of the XB-70 showed similar variation (Berry & Powers, 1970, p. 17-27). The various factors can be seen in Figure 4 (National Research Council, 1997, p. 21).

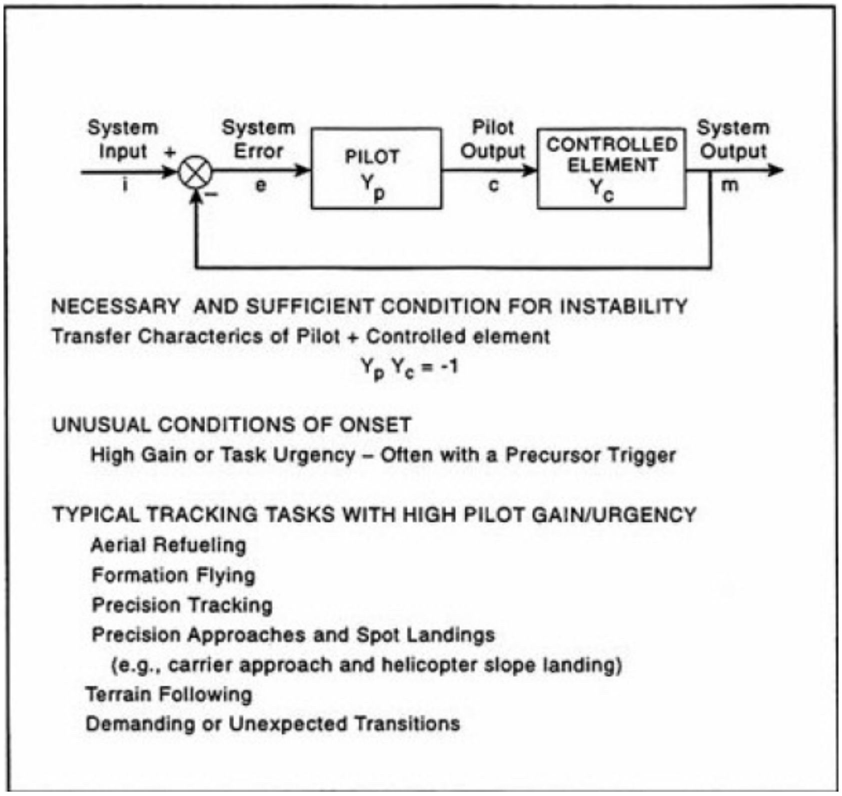

Figure 4. Typical factors associated with high gain reactions (National Research Council, 1997, p. 21).

A second factor that can increase pilot gain is known as the "startle effect". When a person is surprised or startled, their response tends to move towards a much higher gain, and over-control (Bureau d'Enquêtes et d'Analyses, BEA, 2012, p. 173), coupled with a period of time when they transition to a reactionary response mechanism, rather than a more cognitive process (Thackray, 1988, p. 3, 10-11).

The final few moments before and during landing happen very quickly, and aspects that do not go as expected require an immediate response. Many aspects of flying can be well planned in advance. Prior to the approach, pilots will discuss aspects of the approach and landing that may be pertinent, but it is impossible to anticipate every aspect. Pilots must react quickly to any unforeseen events during the landing phase, and this requires a response that would match the Recognition Primed Decision Making (RPD) model as described by Kahneman & Klein (2009, p. 523-525).

The RPD model, however, requires that the person has had the ability to "build" that response pattern in advance, either through direct experience, or mental "simulation", as further described here:

> An environment of high validity is a necessary condition for the development of skilled intuitions. Other necessary conditions include adequate opportunities for learning the environment

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> (prolonged practice and feedback that is both rapid and unequivocal). If an environment provides valid cues and good feedback, skill and expert intuition will eventually develop in individuals of sufficient talent" (Kahneman & Klein, 2009, p. 524).

Professional pilots are highly skilled, and thus have a vast amount of data ready to be utilized for RPD, however, there are limits to that skill. It is those times when pilots encounter situations that are very similar, but not quite like those that fit the RPD scenario that outcomes can be detrimental and potentially dangerous. If a pilot encounters a situation that superficially matches previous experience an error can occur. (Dismukes, Berman, & Loukopoules, 2007, p. 207).

It is also possible that a pilot will become accustomed to using a procedure that is not ideal, but will work under most conditions (Dismukes, et al., 2007, p. 104). This type of technique may go unnoticed and uncorrected absent the pilot encountering the corner-point scenario where the technique does not work as expected.

Finally, as described by Dismukes, et al., (2007, p. 297), people are vulnerable to making impulsive responses under stress and time pressure, particularly when they have not practiced the correct actions to the point of them becoming automatic.

Pilot Perceptions in the Landing Environment

The landing environment brings many challenges for the pilot. It can be said that it is here, during the landing phase, that all of the pilot's skills must coalesce. Pilots make control inputs based on their perceptions. Approaching the ground, the pilot must align the aircraft with the runway, and then decrease the rate of descent to accomplish a smooth touchdown. This also must occur within the designated "touchdown zone", which will enable the aircraft to have sufficient runway remaining to safely stop.

Advanced aircraft autopilots can also accomplish these tasks, but they are limited in their ability to anticipate rapid changes. In fact, autopilots are purely reactive in nature, adjusting the controls (very rapidly) to measured changes in the aircraft approach path. However, as a consequence of the limitations of the autopilot, they cannot be used in extremely gusty or windy conditions. Humans are still much better than computers at anticipating and compensating for unexpected events, and, coupled with RPD, and pre-planning, can generally operate in a much wider set of environmental conditions where highly non-linear conditions exist.

If conditions are such that they require the pilot to hand-fly the aircraft, the flight visibility must necessarily be high enough to allow the pilot to accomplish the task visually. Approaching the runway, the pilot must then accomplish the alignment and landing maneuver entirely through visual feedback of the runway environment. This requires that the pilot look far enough down the runway so that he or she can correctly ascertain the height of the aircraft and the relative changes in height during the landing maneuver. Once on the ground, the pilot of a transport aircraft will "derotate", or lower the nose of the aircraft to the ground and apply reverse thrust and brakes to stop the aircraft.

All of these aspects require that the pilot correctly perceive the alignment, aircraft height, acceleration/deceleration rates and other factors. This is an extremely dynamic environment, which requires an iterative cycle of perception, action, and feedback from the environment with multiple “last second” corrections. As there are only seconds, or fractions of seconds, available to make the correct control input, pilot reactions during landing will necessarily be based on an RPD model.

Large Aircraft Kinematics and Pilot Perception

Individual perceptions. Pilots operating large transport aircraft must contend with some unique issues. The pilot eye height on approach is significantly higher than smaller aircraft, with the pilot eye-height on touchdown being between 35 to 50 feet. This creates a challenge to ascertain the actual height of the aircraft prior to touchdown. As an example, if one changes height from 5 feet to 10 feet, they have doubled their height, and it is a very obvious change, but a change from 35 to 40 feet, while still only a difference of 5 feet, is much more subtle as the percentage change was much smaller.

FAA regulations allow for transport aircraft landing gear design to be based on the assumption that the aircraft's weight is being supporting by the wings entirely, (i.e., lift = weight) (Title 14 CFR 25.723, Federal Aviation Administration, 2001). If there is less lift than weight (as occurs when the aircraft pitch attitude is initially lowered), then the combination of kinetic energy and acceleration can quickly exceed the structural design ultimate limits. Designing for such a condition would require significantly more structure, resulting in a much heavier design.

Aircraft design is a balancing act between multiple requirements. While strength is important, once the aircraft meets the regulator requirements, the value of a lighter (and hence more fuel efficient) structure becomes the “driving force”. An aircraft dropped from just 5 feet results in enough force being generated to exceed the landing gear ultimate design loads as the acceleration of gravity will be sufficient in large transport aircraft to have it exceed regulatory requirements landing on both main landing gear symmetrically (CFR 25.723, Federal Aviation Administration, 2001; National Transportation Safety Board, 2000, p. 65; Shock Absorption Tests, Federal Aviation Administration, 2001, p. 4). If landing on just one main gear (such as a crosswind condition), the height is less. If the wings are supporting just 50% of the weight, then five feet would be enough to exceed to requirements for a touchdown on a single landing gear. This would equate to a fairly normal “derotation”, or “nose lowering” after landing – assuming the pilot knew they were on the ground.

Judging the height of the aircraft accurately becomes critical, and the task is a particular challenge when the *touchdown* eye height might be near 50 feet, making a 5 foot height change appear small. Further complicating the matter, many factors, such as aircraft vibrations, can be perceptually misleading, and may deceive a pilot in a very large aircraft to believe they are on the ground, particularly after a bounce.

Pilots may not understand the mathematics behind the design criteria, but they know a hard landing when they feel it. However, that requires that they do *actually* feel it. In a very

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large aircraft, that can be a challenge. The motion of the flight deck and flexure of the aircraft can significantly mask the forces that are imparted on the landing gear. The flight deck is rotating around the CG, and, depending on the particular dynamics, the force of the landing may be completely transparent to the crew, resulting in aircraft damage without the crew's knowledge.

Coupled with this facet is the issue of the pitch transient that was discussed previously. If an aircraft is approaching the runway and the pilot attempts to arrest the rate of descent with a rapid pitch change, the net result is that the aircraft's actual flight path can actually, very briefly, accelerate *downward.* If this occurs just prior to touchdown, there may be insufficient time for the aircraft's wings to create enough lift to preclude or mitigate a hard landing. The amount of acceleration will, of course, vary, and in many aircraft the amount of inertia is high enough that the flight path as measured from the CG will not significantly change in either direction—at least not in the time before the aircraft touches down.

While the flight path, as measured at the CG (or landing gear) may not be significantly altered, the aft "pull" on the controls by the pilot does result in the aircraft pitching nose-up. The pilot relies on the feedback from visual, vestibular, and haptic sensory inputs. When the aircraft rotates due to the pitch control input, the flight deck is changing its path, just as the end of a teeter-totter moves even though the base is stationary. The pilot will perceive this motion through visual, vestibular, and haptic sensations and perceptions, and from where the pilot is sitting, the pitch input is having its desired effect. Hence, although the aircraft's actual vertical motion has not changed, the flight deck *is* changing its vertical velocity. This can be seen directly by the graph in Figure 5. Notice the divergence between the flight deck (cockpit) height, the CG and the landing gear.

The difference in pilot eye height and landing gear height as pitch changes can be significant. It can be large enough that the pilot station is at a normal landing eye height while the landing gear is nearly 20 feet off the ground. This presents significant challenges to a crew in a highly dynamic situation. In smaller aircraft, the crew perception of aircraft height is always fairly close to the actual landing gear height, but in larger aircraft the changes in pitch can completely mask the height of the aircraft.

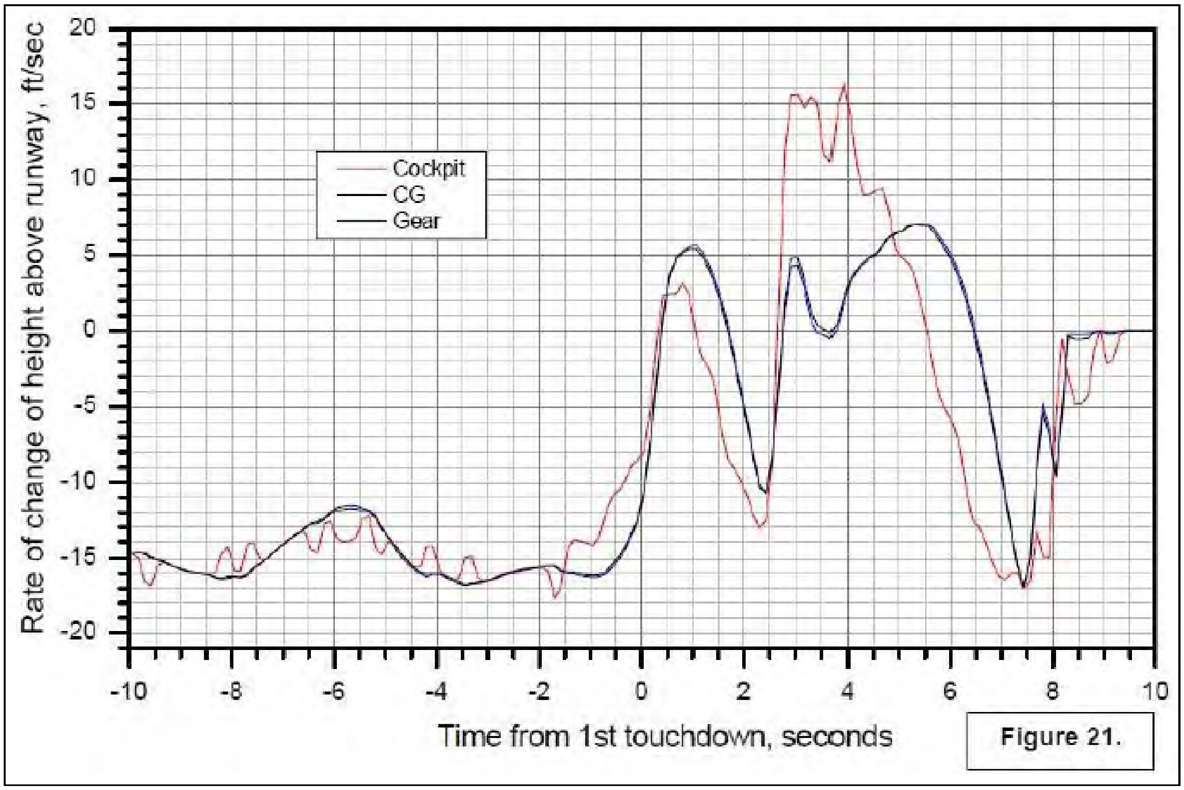

Figure 5. Differences in rate of change of height above runway for three different locations on the aircraft (Kingdom of Saudi Arabia, 2010, p. 66).

In another aircraft landing mishap, the aircraft, a McDonnell Douglas MD-11, bounced to a height of just 5 feet (main landing gear height), and at that height had a pitch attitude of about 2º. That is roughly 4º lower than the nominal landing pitch attitude for the MD-11 at that weight and CG, which placed the *pilot eye height* 7 feet lower than it would have been if the pitch attitude had been at the nominal value. The pilot control inputs are necessarily based on the pilot's perceptions of height and aircraft dynamics. In this event it resulted in the aircraft exceeding the design loads (NTSB, 1997; NTSB, 2000, p. 53, 116).

Further exacerbating the situation is the lack of external cues for pitch attitude awareness. The changes can be subtle, and in a dynamic situation, easy to miss. This means that pilots who are making large pitch changes near to the ground may not be aware of the fact that the pitch is changing significantly, and that those pitch changes are masking the actual aircraft height. This means that the feedback the pilot is receiving from visual, haptic, and vestibular sensations and perceptions are not aligned with the actual aircraft state.

The pilot that attempts a late flare can, therefore, inadvertently land hard as a result of the sensory impression that the descent is arrested, while the landing gear path remains constant, or even accelerates downwards as a result of the pitch transient. This was described in a report by the ATSB describing an incident involving a Boeing 717, stating "at about 30 ft, the copilot made an abrupt rearward movement of the control column resulting in the main landing gear moving faster downwards" (ATSB, 2008, p. 23).

Unfortunately, the problem does not end there. The unexpected hard touchdown can result in a startle factor, increasing the gain response of the pilot. Now the pilot may over-compensate. Most large aircraft are susceptible to tail strikes, and a review of the event reports indicates that they are not particularly rare (JTSB, 2011a, p. 22-23; JTSB, 2011b, p. 16, 18). Pilots, aware of this, are also trained to know that a tail strike can easily follow a hard landing, and are particularly cognizant of any pitch up on landing. It would not be surprising to see pilots react with a high gain "over control" in such a scenario, and even a superficial survey of such landing accidents supports this conclusion (Hradecky, 2012; NTSB, 1999, Thackray, 1988).

Crew interaction. Most landings are routine, so pilots can become comfortable with a somewhat mechanical response. This will work as long as the response matches the situation, but can lead to precarious outcomes if it does not. Unfamiliar situations requiring very rapid reactions put the pilot in a situation where no automatic response is available. If the pilot does not have time to assess the appropriate response the probability of an error increases (Dismukes, et al., 2007, p. 297).

One of the strongest safeguards against pilot error is the other pilot. The realization of this fact, coupled with the fact that 70% of accidents were the result of error, led to the creation of crew resource management (CRM) training starting in the early 1980s (Cooper, White, & Lauber, 1980). Despite this training, the problem persists, with 79% of accidents involving errors of monitoring and challenging between 1978-2001 (Dismukes, et al., 2007, p. 287). Further, monitoring and challenging other crewmembers is a lot more difficult than it might appear to someone in the "arm chair quarterback" position (Dismukes, et al., 2007, p. 191).

In the landing scenario described, the challenge is even greater than many other phases of flight. As previously described, the aircraft kinematics can effectively mask the actual state of the aircraft where perceptions of height and pitch attitude are not easily discernible, particularly when operating as the monitoring pilot with associated duties in addition to monitoring the aircraft flight dynamics, such as system monitoring, communicating with air traffic control, reading checklists, etc.

Pilots are hesitant to be critical of each other (regardless of power-distance or crew position issues), and this, coupled with the lack of salience of the critical nature of the aircraft state, can result in the pilot monitoring remaining somewhat passive. This attitude is additionally supported by the fact that it is not uncommon for pilots to experience situations that are a little outside of their expectations, a virtual certainty in the highly dynamic environment of flight, and these situations typically turn out fine. So, while the pilot who is monitoring is often in a position to prevent a problem, for a combination of reasons, they appear to generally remain silent during a landing event as has been found in several accidents (NTSB, 2000, p. 110-112; AAIB, 2008, p. 57; Dismukes, et al., 2007, p. 125).

Mitigating Kinematic Induced Misperceptions

Crew Training

Training offers the most immediate mitigation to problems related to kinematic issues. The first portion of training should concentrate on teaching the aerodynamic and kinematic effects of elevator control inputs near to the ground. Pilots should understand the visual illusions that can be presented as a consequence of the changing pitch attitude. This training should be included as part of ground training prior to any work in the simulator.

The perceptual problem is a consequence of the pilot use of pitch/elevator input in an attempt to arrest a high sink rate. Due to the combination of the flat lift-curve slope inherent in swept wing designs, pitch transients and perceptual issues due to kinematic aspects and tail strike risk, the use of pitch to control flight path when near to the ground should be approached with extreme caution. This puts more emphasis on the only other control that can affect flight path, and that is power. This is a technique that has been embraced by pilots of highly swept wing aircraft for many years, and is also utilized for aircraft landing on aircraft carriers. If autothrottles are used, they will need to be over-ridden or turned off to allow the pilot to directly control the thrust.

The perceptual problems are a direct consequence of the pitch changes masking the actual aircraft dynamics. The flight deck is literally moving on a different path than the aircraft CG and landing gear. If the pilot minimizes the pitch changes, the flight deck will, by definition, be tracking the same flight path angle as the rest of the aircraft. The pilot will now have direct visual feedback that accurately matches what is occurring, and so can more accurately respond to any path deviations that are perceived.

Through maintaining a relatively constant pitch, the technique will also serve to mitigate any adverse handling characteristics. Maintaining a relatively constant pitch (as long as the pilot does not turn it into a tight tracking task by maintaining a precise pitch), will serve to move the pilot to a *lower gain* state, mitigating aircraft-pilot-coupling (National Research Council, 1997, p. 31).

The simulator can be an excellent tool to teach this technique. The position can be "frozen", while the pilot then maintains a constant pitch attitude and utilizes the power to adjust the aircraft height.

Display Technology

When the autopilot is conducting an automatic landing, it is utilizing the aircraft pitch control to maintain flight path, and the throttles are being used to maintain speed. At some point during the landing phase, the throttles are reduced to idle at a programmed rate, and the autopilot continues to maintain the flight path utilizing the pitch commands. Unlike the human pilot, the autopilot is not subject to the illusions of height change created by kinematic issues, so all pitch changes are appropriate to maintain the landing gear flight path on the programmed path. As previously discussed, autopilot landings are limited to relatively benign conditions in terms of wind and gust factor. While the autopilot has fairly rapid pitch response, the autothrottle response is much slower, and neither the autopilot nor autothrottle are capable of moving the controls as rapidly as a human pilot, thus trusting only the autopilot to compensate for windy conditions absent human input can put the aircraft outside safe operating margins.

The use of Heads Up Guidance Displays (HUD) can provide the human pilot with the flight path corrections that the autopilot would use, while still maintaining the rapid proactive control responses of an experienced pilot. Several manufacturers have developed HUD landing guidance systems. These include a "flare cue", which displays a landing trajectory very similar to the one utilized by the autopilot, as well as warnings for exceedances, such as "tail strike"(see Figure 6). Utilizing the flare cue, the pilot can quickly see if the pitch attitude has diverged from safe parameters.

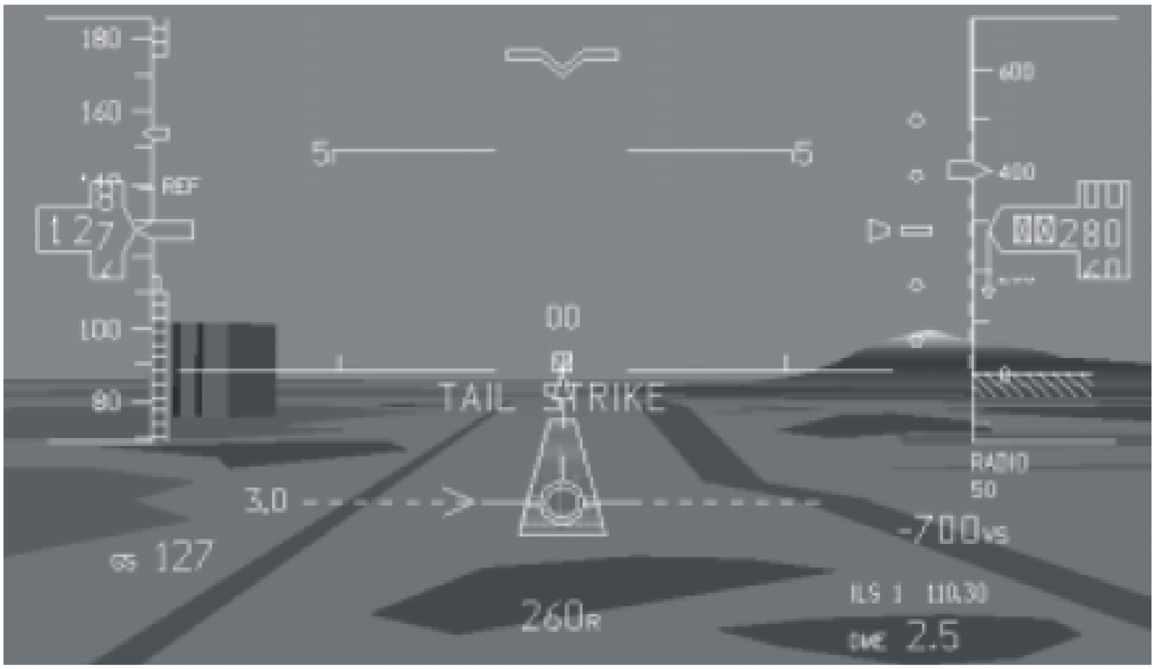

Figure 6. Typical Heads Up Display (HUD) with illustration of “tail strike warning (Hoh, Arencibia, & Hislop, n.d.. p. 18)

Design Criteria

Aircraft designers face many constraints. After safety, they must counter balance efficiency, runway limitations, airport and gate limitations, passenger comfort and many other aspects. Safety is always a primary concern and designers do what is possible to mitigate known issues. However, kinematic issues cannot be “designed out”. Large aircraft will be susceptible to kinematic issues simply because they are large.

As noted in the discussion of training, one of the simplest ways to mitigate the kinematic issue is through the use of power to control vertical path. As the aircraft approaches the runway the power is removed either through the autothrottle system or through manual inputs. If the autothrottle is used, the algorithm is the same as that utilized for automatic landings. The system has many constraints; high among them are the runway length limitations. If power is left on too long the result will be an excessive amount of runway required for landing. This can exceed certification requirements and is a constraint the designer must contend with.

As previously discussed, the autopilot will utilize pitch control to maintain flight path, which is exactly opposite the recommendation to mitigate kinematic perceptual issues. However, as the autopilot is not faced with problems of perception, it has no problem with this factor, thus the designer is free to constrain the autothrottles as required for the runway length performance constraint.

If the autothrottles were actively maintaining aircraft speed through touchdown the pilot would be less likely to make large pitch changes to compensate for unexpected sink rates as the sink rates are a result of a loss of energy generally due to a gust or a cross-control input. Unfortunately, this is often not an option due to the performance constraints of runway length. That stated, it is possible that lowering the altitude at which the throttles are reduced to idle may mitigate some of the kinematic effects.

Another approach was stumbled upon by Lockheed, which was actually a side effect of the designers working to mitigate another issue. During certification of the Lockheed L1011, low visibility landings were constrained by the high pitch attitude of the aircraft on approach, as the high pitch reduced forward visibility both due to the height and slant-view out the windshield. In order to mitigate this, the designers created a system called Direct Lift Control (DLC), which maintained a constant pitch attitude on approach. The system utilizes the aircraft spoilers to maintain flight path (Throndsen, n.d., p. 780). While not an intended benefit, clearly such a system would help to mitigate kinematic issues. Unfortunately, such a design increases fuel consumption due to the higher thrust required to offset the spoiler deployment.

Conclusion, Recommendations, and Suggestions for Future Research

The issues regarding landing kinematics, once identified, can be seen to be a factor in many transport aircraft landing incidents and accidents. The combination of circumstances for this to manifest into a problem is uncommon, and it is possible that some pilots will never experience it, leading to potentially faulty RPD models for some pilots. Still, the incident and accident rate demonstrates that the risk of aircraft damage and loss of life as a result of failure to mitigate the problem is real.

Although humans are very good at dealing with unanticipated problems, pilots, like all other humans, cannot be expected to mitigate a problem they do not know about all the time. Due to the kinematics of large transport aircraft, pilots are placed in a position where their perceptions may not match the actual aircraft dynamics. Most pilots will not become aware of the problem without training. Post event interviews with pilots that have experienced this revealed that the pilots were still not aware that their perception of events did not match the actual aircraft dynamics (NTSB, 1997).

The use of display systems, such as the HUD, can provide the visual feedback to help ensure that the pilot is aware if the pitch attitude has diverged from a safe parameter. The pilot reaction to such a divergence should be with thrust as that will minimize the amount of pitch change required to maintain the desired flight path.

The aircraft designers are extremely constrained in their ability to mitigate the problem, with the balance between cruise and landing performance, the designers are effectively boxed in. This leaves training and display technology as providing the most return on investment in terms of mitigation strategies.

Operators of large aircraft should incorporate training concerning kinematic issues for pilots, as well as training on how to mitigate the issues. Absent such action it is probable that there will continue to be accidents and incidents as a consequence of this issue.

Further research should be conducted to explore other possible mitigating factors. Perhaps design changes can be made. Systems such as Lockheed's Direct Lift Control can be shown to mitigate the kinematic issue, but at the cost of higher fuel consumption. It may be possible that there are other solutions with fly-by-wire technology.

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