Aircraft Controllability and Primary Flight Displays
- Every Link is Important

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ABSTRACT

LOC-I accidents are occurring every year, and the recommendations from the accident investigation reports seem to have no effect. Up to now the Accident Reports do not seem to address the reasons for pilots losing control, other than focusing on need for better or more pilot training. Little or no focus has been directed towards why pilots are losing control. During last year's ISASI conference in Augsburg a paper was presented discussing *"A New Tool for Analysing the Potential Influence of Vestibular Illusions"*[1], like Somatogravic and Somatogyral illusions resulting in pilot spatial disorientation. The knowledge that the human brain is depending on strong visual cues for orientation and balance in a zero or offset gravity environment is well documented.

However, this knowledge seem to be absent in most LOC-I accident reports. During flight conditions in darkness or in instrument conditions pilots may be affected by Somatogravic, Somatogyral and G-excess effect illusions resulting in pilot Spatial Disorientation ("pilot vertigo"). The only effective cues to combat these sensory illusions are strong visual cues. An illustrating point in this respect is the example of an untrained private pilot who enters clouds. It will not take long until he loses control, but chances are that he will recover control when the aircraft exits the cloud cover and the pilot observes the natural horizon line in daylight visual conditions. In this situation the untrained pilot receives visual cues from the natural horizon line filling his windscreen and by use of his peripheral eye sight he receives the re-

[1] Reference 28

quired visual cues to combat the sensory illusions and restores aircraft control. This is an indication of the importance of a large and human factor centric artificial horizon on the pilot's Primary Flight Display.
During the last 25 years there have been investigated more than 18 LOC-I accidents and incidents globally where spatial disorientation may have been a factor. Still this was not a major focus by the accident investigations. This is an indication that the root cause of these accidents has not been identified. In none of these accidents did the accident investigation reports recommend improved Primary Flight Displays. The Air Asia QZ8501 is an example.

Several LOC accidents are related to aircraft stall. This may be an indication that the state-of-the-art Primary Flight Displays (PFD) are not presenting the aircraft flight condition in a most intuitive way, and not presenting the pilot with a clear indication of Angle of Attack (AOA). The Air France AF447 is an example in this respect.

Using today's technology, flight displays could be made more intuitive and easier to read in an unexpected and blurred flight situation. Also, by making flight control inceptors and autopilot modes more intuitive, and thus improve tactile feedback cues, the pilots may be kept in the loop and be more prepared to take control in an unexpected situation.

Regardless of how ideal the aircraft's handling qualities are, it is of limited value if the handling pilot becomes confused and disorientated during an unusual attitude (UA) or upset recovery (UR). Several of the recent accidents seem to be related to PFD's and the pilots knowledge and training in interpreting their displays. PFD is vital for the pilot's ability to keep Situational Awareness (SA) and it may be time for the manufacturers to focus on PFD's in addition to autopilot modes and aircraft handling qualities during test and evaluations.

The link between the pilots and the aircraft – the man-machine interface – should be improved and made more intuitive. Today's technology makes it possible to improve the displays and autopilot modes in aircraft based on Human Factor research.

INTRODUCTION

The global air accident statistics have gradually improved over the last 50 years. This has mainly been caused by gradual improvements in aeronautical engineering and technological innovations. Examples on this are improved Weather Radars (WR), Navigation Displays (ND), Vertical Displays (VD), Traffic and Collision Avoidance Systems/Airborne Collision Avoidance System (TCAS/ACAS), Ground Proximity Warning System/Terrain Avoidance and Warning System/Enhanced Ground Proximity Warning System (GPWS/TAWS/EGPWS), Category II/III Landing Systems, etc.

The latest technological advancements helped reduce the CFIT categories of accidents. However, the reduction in CFIT accidents led to increased focus on Loss of Control in Flight (LOC-I) accident statistics which seems to remain high.

ACCIDENTS

Typical LOC-I accidents

The common factors in most LOC accidents seem to be pilot confusions during unfamiliar flight situations, lack of pilot knowledge and piloting skills. From the CAST Team report in Figure 1 we see that most LOC-I fatal accidents are related to attitude and AOA control.

We see that in most LOC-I type of accident reports, the focus is on piloting knowledge and skills. No reference is made to possible loss of spatial orientation contributed by less than optimal Primary Flight Display (PFD) or lack of Angle of Attack indication. It is the author’s opinion that the progress in modern Glass Cockpit and Flight Display design have improved the navigation task, but not contributed to improving pilots’ attitude in space situational awareness. It may be argued that some of the modern Flight Displays are not very intuitive or helpful in a loss of control situation.

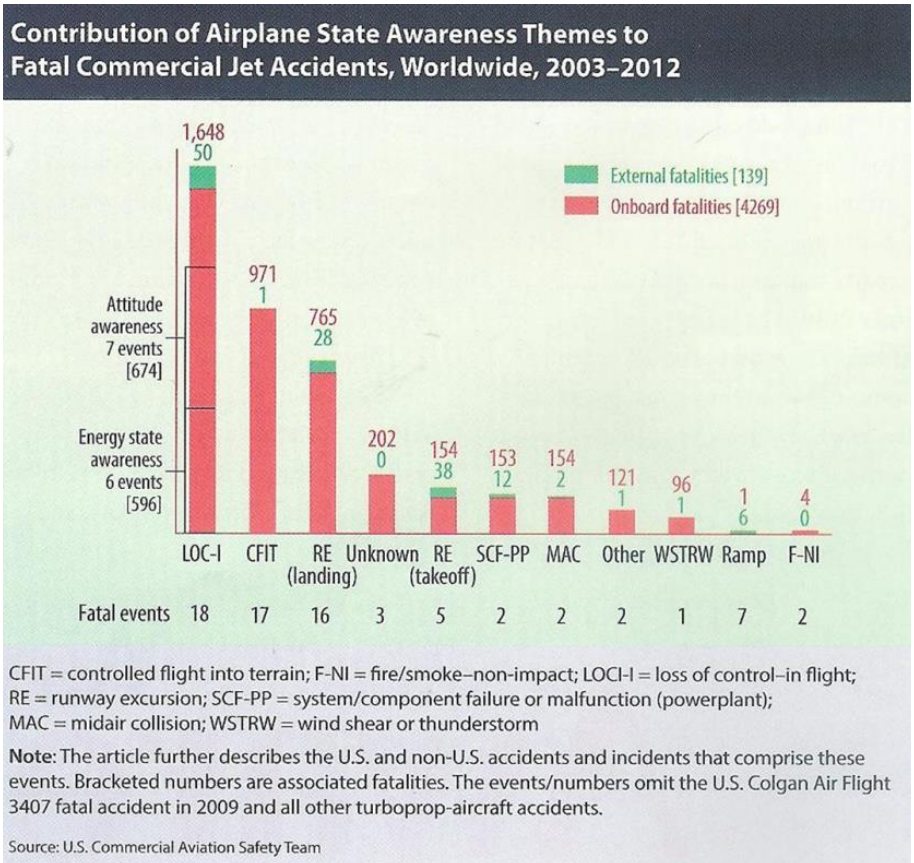

Figure 1. Commercial jet accidents, worldwide 2003-2012 (US CAST).

Further, the increased use of cockpit automation seems to have influenced the education and training of younger pilots. We have also seen that manufacturers advertise their airplanes as easy to fly (“*low workload”*) and *“unable to stall”*. Such statements are unrealistic and misleading to student pilots. Any student pilot should have a basic knowledge in physics and be taught from basic training that any heavier than air vehicle must always be aerodynamically controlled and may *“fall out of the sky”* if the flight conditions producing a sustainable lift are not maintained, i.e. a minimum airspeed, or more accurately, an Angle of Attack (AOA) below maximum allowable (below the stall AOA). Whether the airplane is stalling or out of control for other reasons does not matter.

Even though todays accident rates in aviation are quite low, the latest LOC-I accidents are avoidable and seem to be caused by a combination of inefficient PFD's and lack of knowledge and basic flying skills among the pilots. We find that LOC-I accidents results from stalls both during high altitude cruise and during approach.

These types of accidents are also happening to helicopters, as seen from the accident to a North Sea helicopter which crashed off Shetland. The helicopter lost airspeed and entered wortex ring state which may be comparable to a fixed wing stall.

In a typical LOC-I stall accident the pilots did not recognize the slow speed/high alpha flight condition and were not able to prevent the accidents. We see that these types of accidents are not only related to fixed wing aircraft. While airplanes may stall and enter controllable deep stall, helicopters may enter controllable Vortex Ring State (VRS) which, from a piloting point of view, may be comparable to an airplane stall. The recovery is similar - nose down to break the condition and increase power. However, a safe escape requires altitude just like an airplane stall at low altitude.

Other types of LOC-I accidents are related to pilot spatial disorientation which results in pilot confusion and loss of attitude awareness. The spatial disorientation may be caused by Somatogravic, Somatogyral and G-excess Effect illusions[2] causing the pilots to become spatial disoriented, and pitch or bank too much or in the wrong direction. Such mistakes may cause loss of control.

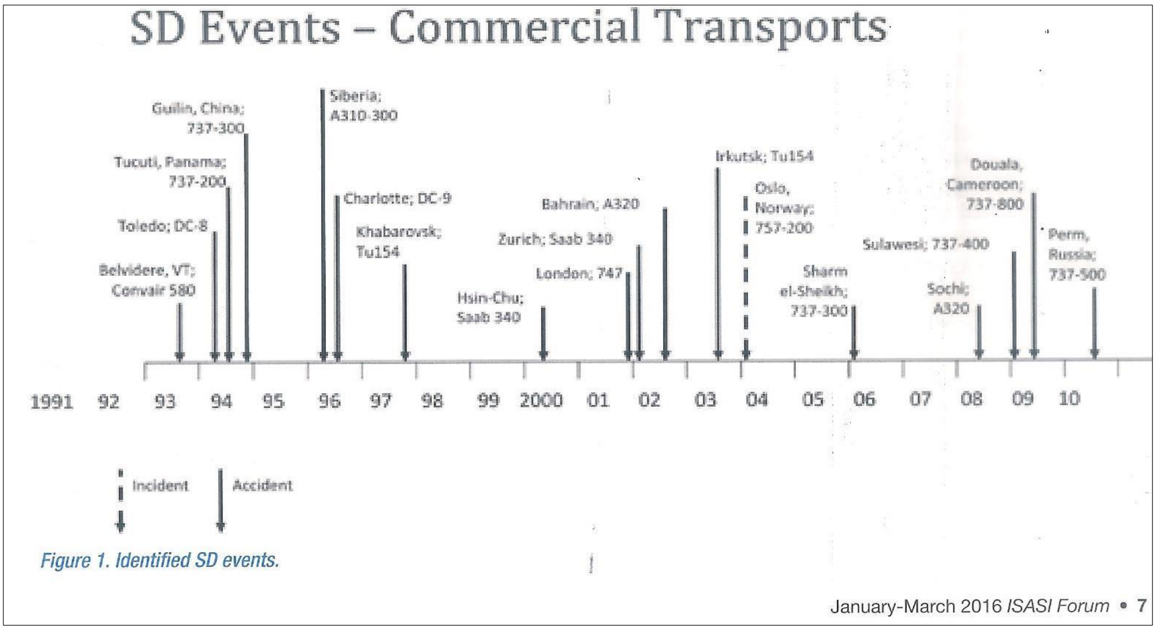

Figure 2. Spatial Disorientation in Commercial Transports (Dr. R. Mumaw et.al 2016). [3]

Accident Investigations

Historically, most LOC accidents were labeled «Pilot/Human Error».

[2] Reference 27

[3] Reference 28

Professor Dr. Sidney Dekker offers a "new view" on Human Error (2006)[4]:
The Old View: "*Human error is a cause of trouble*" (Bad Apple Theory).
The New View: "*Human error is a symptom of trouble deeper inside a system*".

Professor Dr. James Reason (1997)[5]:
"The Organizational model views human error more as a consequence than as a cause. Errors are the symptoms that reveal the presence of latent conditions in the system at large".

In modern accident investigation theory Human Error is not considered a cause of accidents. LOC-I accidents have several underlying cause factors and most LOC-I accidents are Organizational Accidents.

Figure 3 shows the typical operational and training flight envelope of today's commercial pilots. How can we expect pilots to cope with a flight upset situation involving more than 90° of bank, when they have only seen 60° during their training and are normally limited to 30° during normal operations?

Clearly then, we may label a LOC-I accident as an Organizational Accident and not just Human Error.

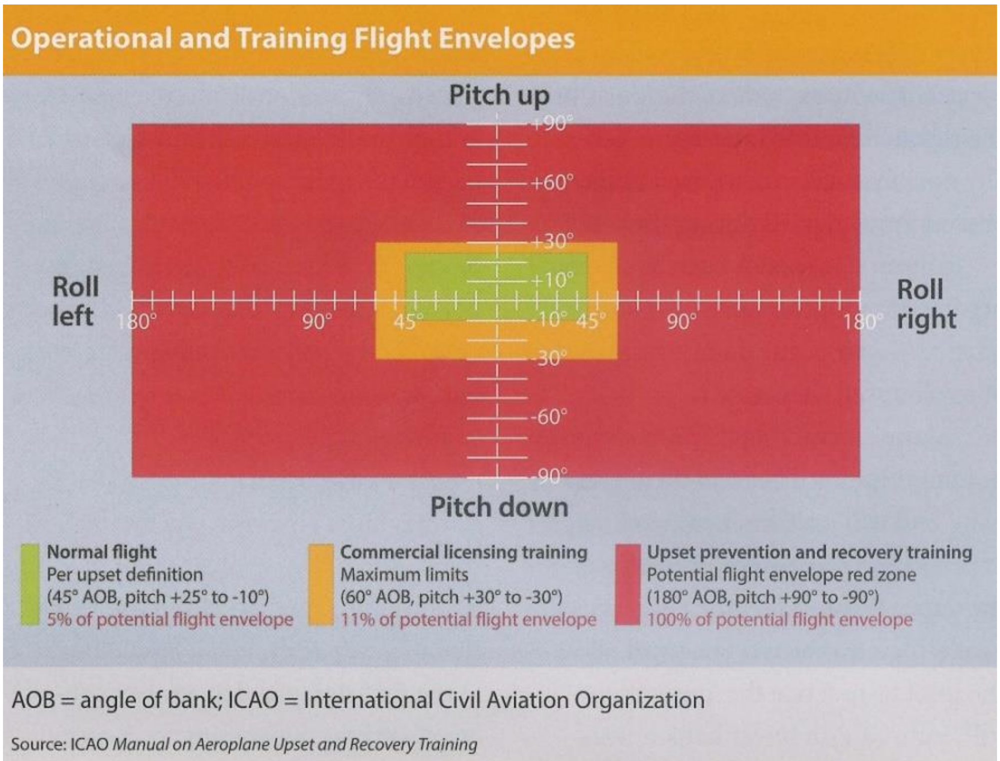

Figure 3. Operational and Training Flight Envelope (ICAO).

AREAS OF CONCERN

Coffin Corner

[4] Reference 14
[5] Reference 15

When flying at high altitude the air density is low; hence lift and thrust are reduced. The airplane angle of attack is increased to compensate for the loss of lift. The mach number[6] increases as a function of lower temperature and lower speed of sound. Thus the maximum cruise true airspeed (VMO) approaches the critical mach number (MMO) and must be reduced (mach buffet). Similarly, the true stall speed/mach increases. As the airplane climbs the maximum cruise TAS is gradually reduced and approaches the minimum flying speed or critical angle of attack (stall buffet). Hence, the margin between high mach buffeting and low speed buffeting becomes smaller and smaller with altitude. This flight conditions has been labeled the "*coffin corner*" due to the challenging flight conditions, Figure 4.
Hand flying at high altitude by reference to airspeed only is very challenging. It is very difficult to control the airspeed accurately and angle of attack indication is required for better airspeed control. Civilian trained pilots of today have not had basic training in this area ("pitch and power") and have limited hand flying skills.

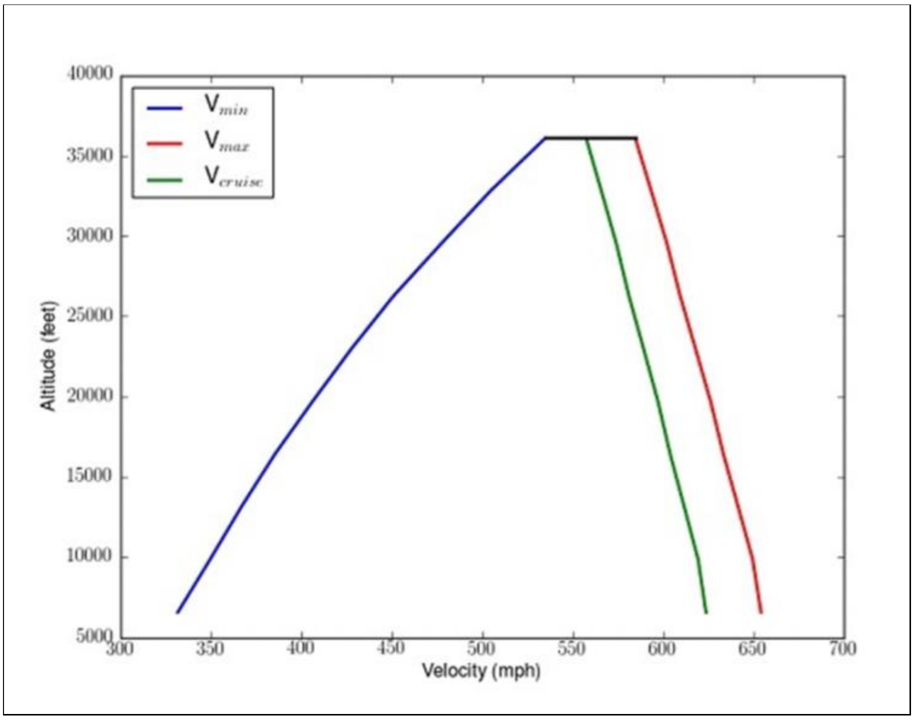

Figure 4. Coffin Corner (Wikipedia 2012).

Aerodynamic Stall and lack of AOA indicators

Aeronautical knowledge about the relationship between angle of attack and flying speed, and the necessary training has been basic pilot knowledge and training requirement for decades. However, based on the recent LOC-I accidents it seems that the focus on stall theory and training has diminished.

Aerodynamic stall occurs when the airspeed reduces below stall speed which varies according to flight conditions, Figure 5. However, it is not the airspeed itself but the angle of attack which is the critical factor, Figure 6. The airspeed is an indirect indication of the angle of attack in level flight. During maneuvering flight the wing will still stall at the $C_{L\ max}$ but at

[6] Mach number is the ratio TAS/Speed of Sound

a higher indicated stall speed[7]. Hence, it is only in level flight the pilots have a good reference to the actual stall speed. An angle of attack indicator will give direct indication in relation to the stall angle of attack. This is basic pilot knowledge, but for some unknown reason the aircraft manufacturers and certifying authorities have been reluctant to include an angle of attack indicator as a primary flight instrument.

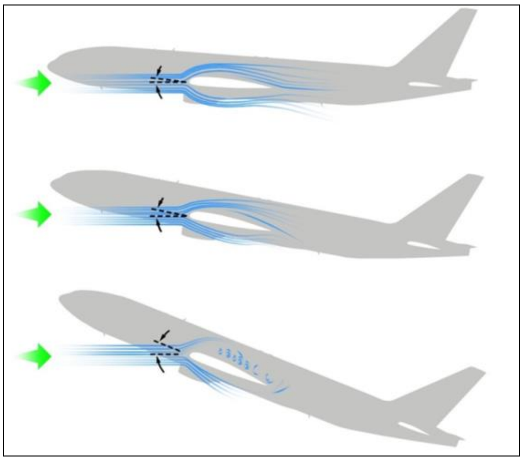

Figure 5. Aerodynamic Stall (D. Carbaugh, Boeing 2010).

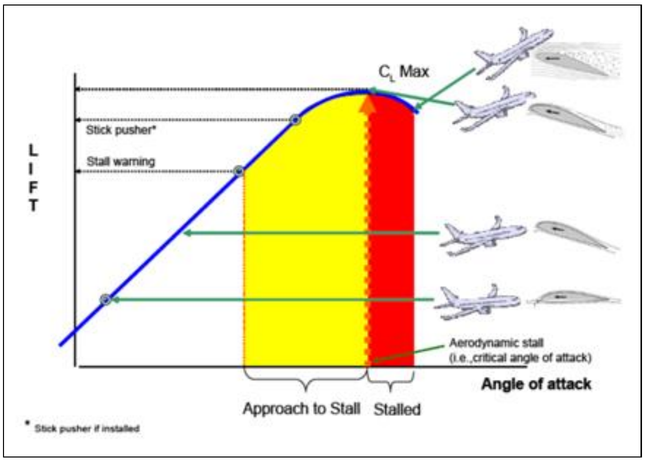

Figure 6. Airplane stall angle of attack (D. McKenney, ALPAI 2010).

Stalls can occur when performing any maneuver. The wing "does not know" about airplane attitude or airspeed, Figure 7.

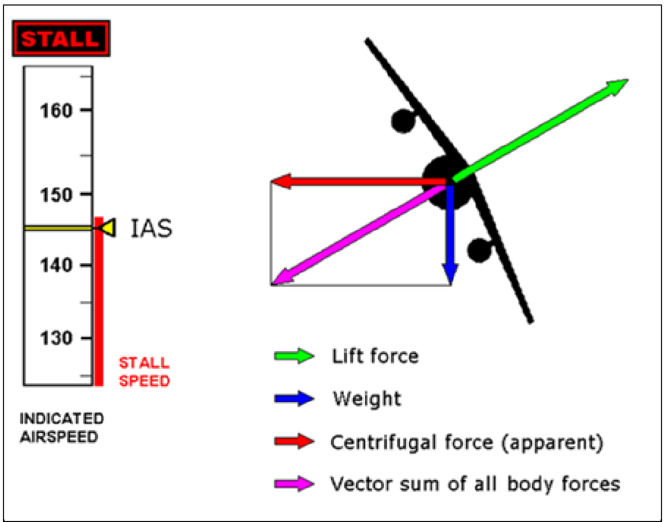

Figure 7. Stall during maneuvering (Wikipedia 2012).

The wing "stops flying" when the critical angle of attack is exceeded. Result is a stall - and if not properly educated and trained, the pilot may lose control. An Angle of Attack (AOA) indicator which clearly and intuitively tells the pilot the margin to stall or minimum control may mitigate such loss of control. This is the most fundamental and basic knowledge the student pilots are required to know, and that the airspeed indicator is just an "aerodynamic indicator" which does not tell the pilot how much lift margin he has, but is related to the forces acting on the aircraft. This has been an item for discussion for several decades. Tech-

[7] $V_{S2} = V_{S1} \sqrt{n}$

nically it is not complicated to install useable and intuitive angle of attack indicators in airplanes. This is merely a policy issue. US Navy and Air Force fighter airplanes have had alpha indicators installed for years, in addition to stall warning and artificial stall recovery systems.

Pilots used to alpha indicators found these very intuitive and useful, showing the lift and performance margin in maneuvering and accelerated flight as well in approach and slow speed flight conditions, Figure 14. However, for unknown reasons it appears that FAA, EASA, Boeing and Airbus have been reluctant to provide pilots with this information. Reference 18 describes flight in the SR-71A Blackbird. The author makes several references to AOA and instrument displays. From ref. 18 are some citations:

> *"Practically all high-speed military jets have an angle of attack (AOA) indicator in the cockpit."*
>
> *"AOA is an excellent indication of how well (or how poorly) an airplane is flying through the air."*
>
> *"Until AOA indicators were developed, pilots had to know their aircraft's flying characteristics at all gross weights, fuel loads, g-loads, flap settings, airspeeds, and other variables that affected the plane's stall speed. An AOA indicator took all those variables into account and became a reliable indication of how well the aircraft was performing. In high-speed fighter aircraft, this development was a tremendous improvement because the pilot had only to check his AOA indicator to see how his aircraft is performing. Once an aircraft reached its critical AOA, it stalled."*
>
> *"When I applied for the SR-71 program in 1973, part of the evaluation process at Beal consisted of two T-38 rides with an experienced SR-71 pilot making sure your flying skills and general airmanship were good. I had never flown the T-38 before and was somewhat apprehensive about how the plane handled. My acceptance into the SR-71 program was riding on how well I could fly it. I distinctly remember my evaluator telling me to fly the T-38 just like it was an F-4 and to use the AOA. Once he said that, I flew it easily."*

As a result of the many LOC-I accidents in recent years, there is a growing interest in installing AOA indicators as part of the PFD. This author, just as many other military trained pilots of the "cold war era", has flown several aircraft with AOA indicators. The experience gained is that AOA is a very intuitive primary flight indicator and just as valuable as the airspeed indicator.

The author has read several comments from pilots not used to AOA indicators, supplemented by some test pilots caution against reliance on AOA indicators, with reference to inaccuracies and limitations. AOA is measured on most modern aircraft and the data is used in the aircraft computers to calculate various flight parameters. Further, the AOA indication is of most importance when maneuvering or flying close to the stall AOA. Hence, the indication will be most useful during slow speed flight or during LOC and upset recoveries. However, the AOA must be a prominent and intuitive indication based on Human Factor and Aircraft Flight Mechanics theory which is taught in basic pilot training.

Boeing is offering AOA indicator as an option, Figure 8, but this is not the most efficient type of display.

Figure 8. Boeing AOA indicator (Boeing 2013).

DEVELOPMENTS IN FLIGHT DISPLAYS

LOC-I is not only related to pilot knowledge and skill, but just as much to Flight Displays, Control Sticks and Levers (inceptors/thrust levers), in other words the Human – Machine – Interface (HMI).

It is worth noticing that in the early days the pilots did not have a stand by attitude indicator available. To compensate the military pilots trained Partial Panel where the Attitude Indicator was covered or disconnected.

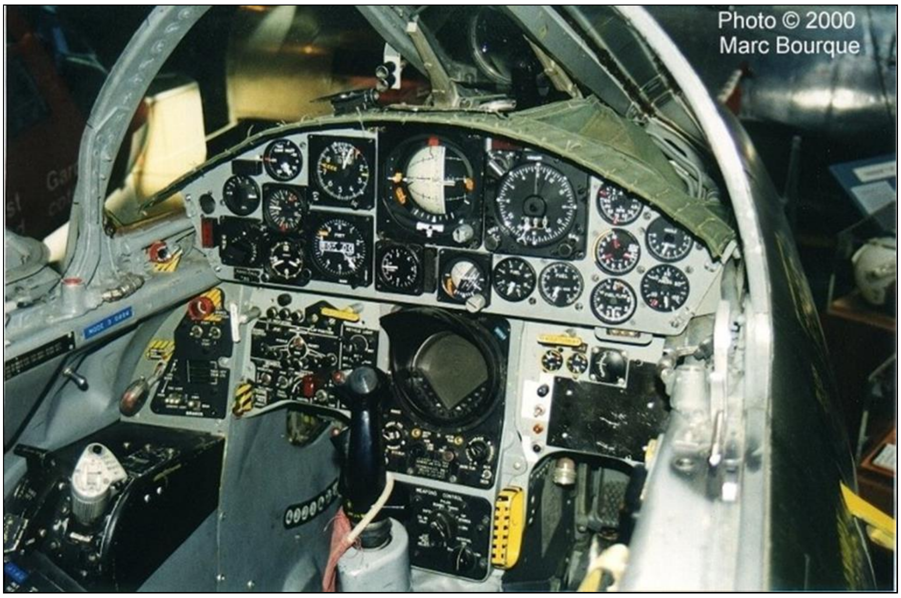

Figure 9. Lockheed/Canadair CF-104 (Photo: Marc Bourque via K. Lande).

With the introduction of gyro stabilized inertial platforms the stand by attitude indicator became standard, but there was still no instrument layout standardization, Figure 9. Note the large instrument sizes which made situational awareness in unusual attitudes easier. It is also worth mentioning the large Attitude Indicator (AI) with heading indication. With reference to just one indicator one got an instant "3D sense" of the flight attitude. This type of AI was used in several US aircraft, Apollo and Space Shuttle during the 1960's and 1970's. Compare this with today's electronic ADI which does not give the pilot the same "3D" sensation of "attitude in space", but only gives a "flat 2D" impression of attitude.

FAR 25 specified the flight instruments arranged in a T-shaped pattern, with the ADI in center, Horizontal Situation Indicator (HSI) below, airspeed located to the left of the ADI, altimeter to the right, with the vertical speed immediately below the altimeter. This arrangement became known as the "*Basic–T*".

Figure 10. Commercial Airliner (1970's) (K. Lande).

Figures 10 shows the FAA standardized flight deck of a commercial airliner of the 1970's. This standard "*basic–T*"[8] lay out is still a certification requirement for modern aircraft in FAR 25 and EASA CS-25, Figure 11.

[8] Reference 13

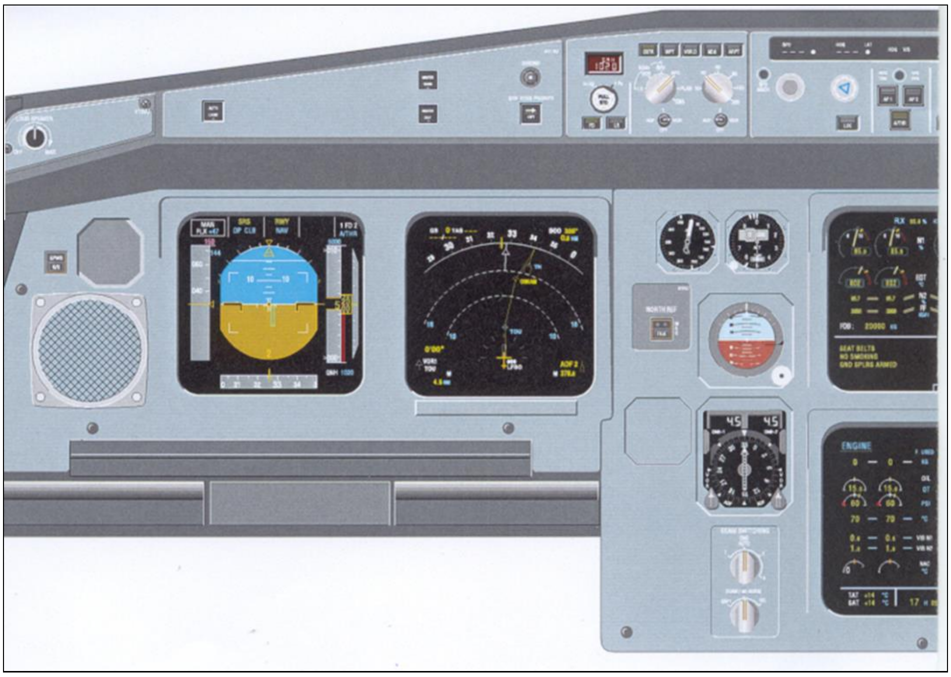

Figure 11. Airbus standard flight display layout (Airbus).

We see that the relationship between the ADI and the other flight instruments are retained in the "*basic–T*" fashion. However, it may be argued that even if the scan distance is reduced, so is the instrument readability.

Another aspect is the regulated installation of stand by instruments but no associated requirement for training in use of these instruments[9].

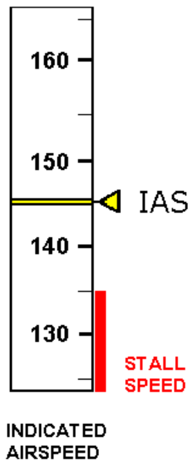

Figure 12. Conventional airspeed indicator (Wikipedia 2014). Figure 13. State of the art airspeed indicator (Wikipedia 2014).

In an unusual attitude situation the old fashion round dial airspeed indicator is easy to read, with large numbers, solid white needle pointer and a intuitive indication, Figure 12. With the pointer in the slow speed region on the right hand side of the airspeed indicator, a pull on the stick will increase the angle of attack and reduce the airspeed. The approximate position of

[9] Reference 8

the pointer in relation to the position and color on the scale give the pilot an approximate sense of the airspeed and the lift margin at a glance, in addition to giving the pilot a good rate of change in airspeed.

The same type of instrument could just as well display AOA, Figure 14. The instrument is intuitive in the sense that pulling on the control stick/yoke increases/rotates the indicator needle to a higher digit and vice versa (pull-increases AOA, push-decreases AOA). What can be more intuitive to a pilot than pulling on the stick that increases the AOA/reduces the IAS, and pushing on the stick that decreases AOA/increases IAS.

The human brain is analogue and there seem to be human factor indications that analogue round dial instruments may be easier and quicker to read/interpret than digital indications . This may be important during dynamic flight situations. A reminder to this effect is that most people use wrist watches with round dials and pointers (analogue round dial display) in lieu of watches with digits (digital display). Further, most aerobatic pilots prefer large round dial instruments for quicker scan.

Figure 14. AOA indicator (Wikipedia 2014).

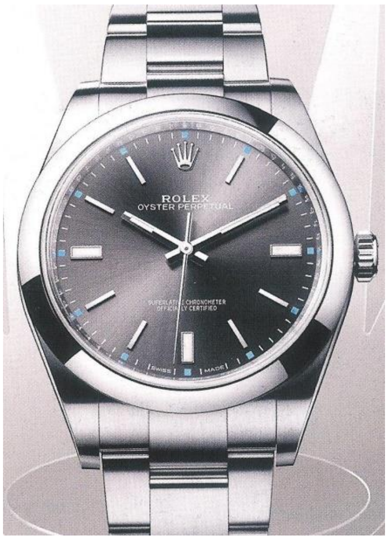

Figure 15. Typical analogue wrist watch (K. Lande).

Figure 15 show a typical wrist watch without numbers. The round dial analogue airspeed and AOA scales may be compared to a typical analogue wrist watch. It is so intuitive that numbers are not required. The user may see the approximate time at a glance. If more accurate time reading is required, a closer look may be required. This priciple works just as fine for aircraft PFD in a cockpit.

It is interesting to note the format developed by USAF in 1958, and introduced in operational aircraft such as F-105, F-106, F-111, C-141 and C-5, Figure 16. USAF research concluded that the airspeed scale digits should be increaseing downwards, i.e. “lower the nose, increase the airspeed” (“fly-to-principle”).[10]

[10] Reference 3

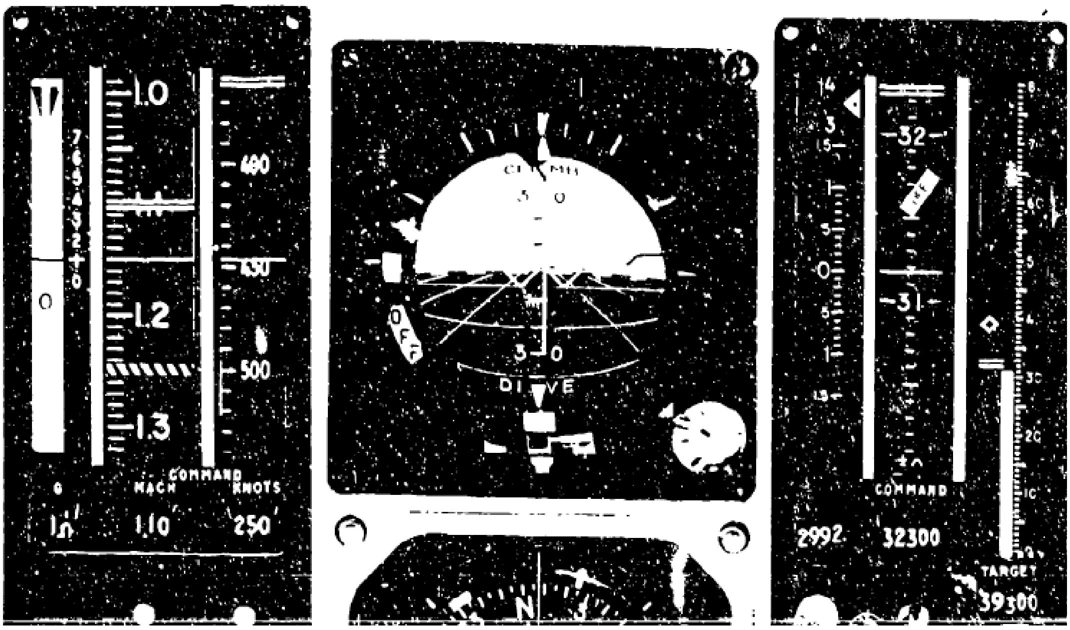

Figure 16. USAF Integrated Flight Instrument System (IFIS), 1958.

On the other hand, the present state-of-the-art airspeed indicator is not intuitive, even if they have a “speed trend indicator”. This is not optimal as a rate indicator, especially in turbulence. The scale numbers are increasing upwards. This is opposite to raising the aircraft nose (pulling on the stick). From basic training every pilot is taught that raising the nose will decrease the speed and lowering the nose will increase the airspeed.

Further, by raising the nose and hence reducing the airspeed, the moving scale should move downwards with decreasing digits from the top[11]. This is in line with Human Factor spesialist recommendations. In its present format the state-of-the-art airspeed indicator is not intuitive and the vertical scale should be reveresed. Pushing the aircraft nose down would then result in increasing airspeed. This is also recommended by Don Bateman of Honeywell.[12]

[11] References 9

[12] Reference 21

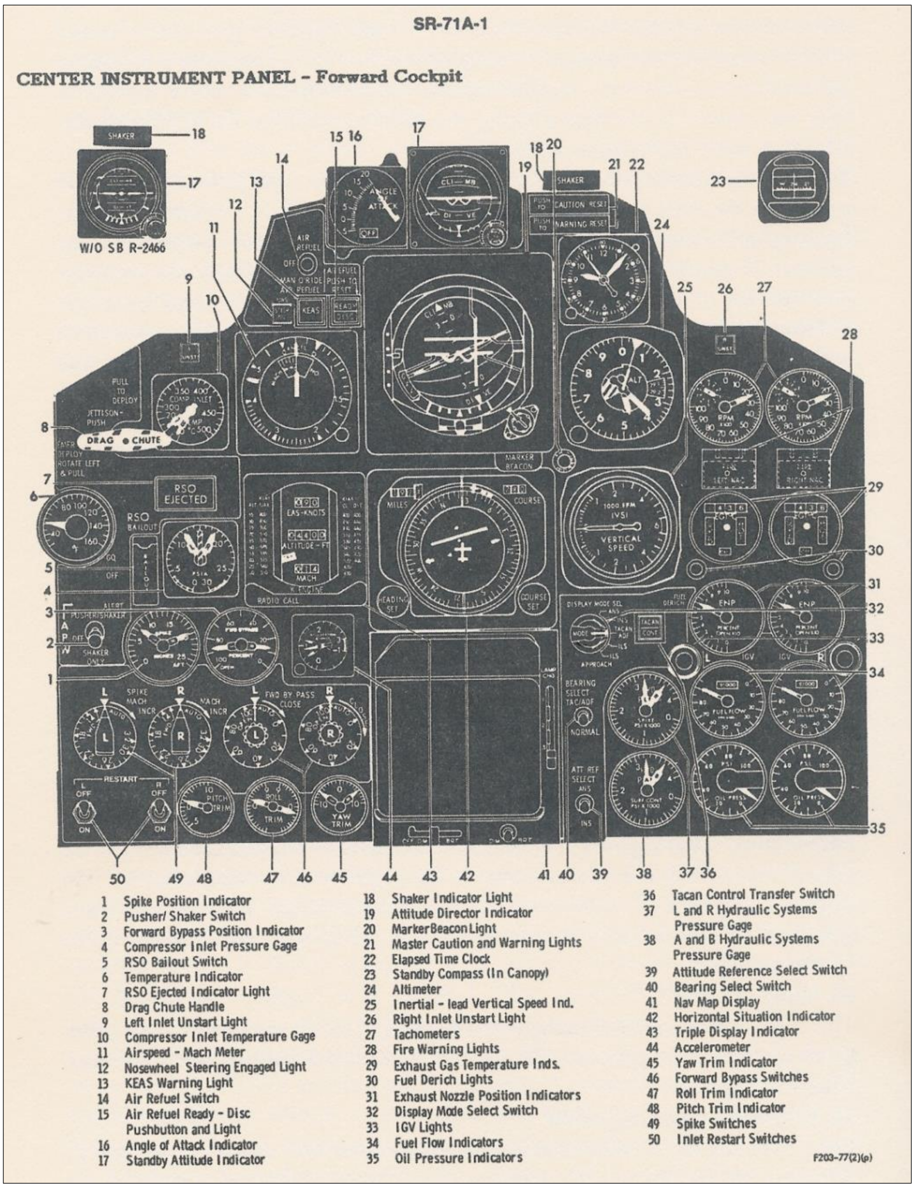

Figure 17. SR-71A Instrument panel (T.O. SR-71A-1).[13]

Figure 17 show the instrument panel of the SR-71A. This was a very challanging aircraft to fly and demanded good pilot knowledge and flying skills. It was an aircraft which needed continous pilot attention to attitude and AOA. This was a USAF aircraft with an instrument panel developed concurrently with the previous mentioned IFIS. Still we see a conventional "Basic-T" layout with round diales. We see that a large portion of the instrument panel area was devoted to the primary flight instruments. Compare this to Figure 11 which is a state-of the-art primary flight display. We also see the prominent location of the AOA indicator close to attitude and airspeed. The large round dials with prominet pointers allowed easy reading and permitted use of the peripheral vision registering the relative position of the pointer. It allowed the pilot to interpret the flight condition without necessarily reading the exact number.

Initially, SR-71 pilots were sceptical to night flying, and there were some incidents where

[13] Reference 18

pilots overcontrolled in bank during turning at Mach 3. This was caused by a sensory illusion called G-Excess Effect, Figure 18. To compensate for this Lockheed developed a device called Peripheral Vision Display (PVD). It projected a laser generated, thinly red line parallel to the horizon, across the pilot's instrument panel. The PVD was not intended to be part of the pilot's instrument crosscheck. Instead, the pilot perceived the laser line indirectly by peripheral vision and subsconciously supported spatial orientation, just as visible outside horizon supports orientation during daytime flying. As the aircraft pitched and rolled, the red horizon line also pitched and rolled across the instrument panel and gave the pilot instant orientation. The horizon line flashed to warn the pilot if the pitch or bank angles exceeded certain limits.

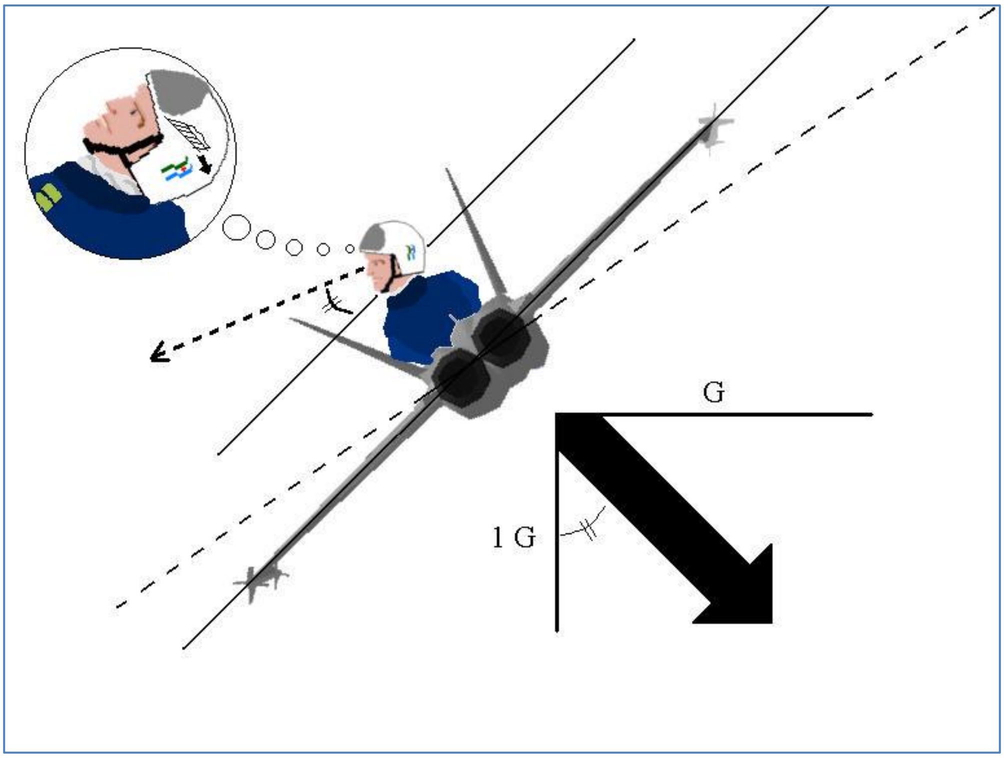

Figure 18. G-Excess Effect during turns (Dr. Bob Cheung, (DCIEM) Canada.[14]

The digits on state-of-the-art flight instruments are also smaller than previously and not so easy to read in a "blurred" and dynamic flight (LOC) situation. The same may be said about the altimeter and vertical speed scales. Such scales are more suited to computers than to aircraft displays. These types of displays were introduced during the 1980's and were driven by the avionics manufacturers. I have seen limited research reports documenting the benefits and efficiency of the modern primary flight display indicators, other than engineering and cost benefits[15]. According to available litterature regarding vertical scale instruments and movement, the benefits of todays flight displays in a LOC situation is doubtful[16]. I am convinced that modern glass flight displays have improved the horisontal navigation and helped reduce CFIT accidents. However, they are less intuitive and efficient in resolving the pilots sense of the "3D attitute in space" in a LOC situation (unusual attitude or upset

[14] Reference 27
[15] References 7 and 9
[16] References 4, 5, 7 and 9

situation), and may have contributed to several of the recent LOC-I accidents. With todays digital technology it should be possible to design more functional and intuitive Flight Displays.

The flight displays in most commercial aircraft of today were introduced during the 1980's and have not changed much, even though todays digital technology make most designs possible, Figure 19. Figures 20 and 21 show state-of-the-art flight decks which will be around for the next 20-30 years. The layout is basically the same as developed 30 years ago, and is also, with a few exceptions, standard in modern helicopter cockpits. Considering the number of LOC-I accidents worldwide, it may be time to reconsider the present PFD layout and do some HMI research and development of flight displays and controls. It may be time to look for new types of displays which are more intuitive, based on human factor considerations and basic flight mechanics principles.

Figure 19. Airbus 320 Flight Deck (Airbus1982).

The author has several hundred flight hours with similar types of displays, but was not introduced to any recommended scan pattern. The general idea was that all the information is included on one display, "right in front of you". However, several LOC-I accidents in recent years may indicate that the state-of-the-art PFD's are not as efficient as thought of in the industry.

Figure 20. Airbus Flight Deck (Airbus 2012).

Figure 21. Boeing Flight Deck (Boeing 2015).

Figure 22. Modern Flight Displays (Internet 2016).

These types of PFD's are satisfactory only during benign flight conditions and autopilot operations, but not during a dynamic or upset flight situation leading to an unusual attitude. In such flight conditions all flight parameters are changing and the human brain may be saturated by changing parameters and digits that need direct readings and interpretation. Further, todays PFD's become more and more cluttered with non-flight-control-essential indications which may tend to distract the pilot's attention.

Today's state-of-the-art instrument panel seems to have lost some of the benefits of the older "classic" panel. The panel seems very clean and is certainly saving space (and money). It is quite sufficient during routine benign flight conditions within 15° of pitch and 30° of roll attitude, but not optimal during a dynamic unusual attitude (LOC-I) recovery situation.
It seems that the larger the screens the more data are included, making the PFD very cluttered.

A large screen with wide horizon line from the synthetic picture of the terrain and transparent round dials with pointers, including AOA indicator, will enhance the pilot's situational awareness.
Being an experienced flight and aerobatic instructor the author has seen the reactions of students with limited or no outside references. During such flight conditions the student pilots loose aircraft control very quickly. However, once visual reference to the outside terrain and horizon is regained, they may regain aircraft control within reasonable time and altitude loss. It follows that many of the recent LOC-I accidents might have been avoided if the pilots had visual sight of the underlying terrain.

Therefore, future Primary Flight Displays should be based on a synthetic picture of the outside world with overlaid prominent and transparent primary round dial flight instruments, including a prominent AOA indicator. Figure 22 shows two later PFD displays for fixed wing aircraft.

AAIB[17] investigated a LOC-I incident that happened to a single pilot aircraft which stalled at high altitude in 2013. Quote from the AAIB report[18]:

"The pilot then recalled a violent and very confusing rolling departure from controlled flight. The aircraft almost immediately entered high cirrus cloud, obscuring the horizon. The pilot was unable to interpret the PFD attitude indicator, which he described as presenting information that he could not recall having seen before. He did not recall exactly how long this persisted but he did recall checking both the left and right PFD displays, which were similar in appearance.
The pilot made several attempts to recover the aircraft, although he could not later recall what control inputs he made. He recalled selecting idle thrust and achieving almost level flight at one point but, he had not increased thrust and the aircraft slowed rapidly and again departed from controlled flight. During the period that the aircraft was out of control it descended into clearer air between cloud layers, with a visible external horizon allowing the pilot to regain control."

In most LOC-I accidents the pilots do not survive to tell their story. Here we have an example of a pilot who stalled his aircraft and was not able to interpret his state-of-the art PFD. It is clear that the pilot was totally confused, and only regained control when he could refer to the natural horizon. He survived and could tell the investigators his experience.

Figure 23 shows an Advanced Flight Systems (AFS) type of PFD installed in some GA airplanes. The positive feature is the display of the terrain and transparent flight instruments, but the negative features are the strip indicators and all the added information making the PFD cluttered.

In 2010 NTSB issued a Study Report on accidents in GA airplanes with Glass Cockpit compared to airplanes with conventional flight instruments. The report shows that accidents in the 2002-2008 periods resulting in fatalities were 16% with conventional flight instruments, compared to 31% with Glass Cockpit.
On average, glass cockpit aircraft had:

- More accidents during climb, cruise, and approach
- More loss of control in flight, collision with terrain, and weather encounters
- More personal/business flights
- Longer flights
- More IFR
- Accident pilots were older, with more flight hours and higher certificates/ratings.

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17 Aircraft Accident Investigation Branch (UK)
18 AAIB Bulletin: 1/2015 N380CR EW/C2013/12/05

Figure 23. Advanced Flight Systems (AFS) PFD (A. O. Frog, March 2014).

AIRCRAFT CONTROLLABILITY

With reference to the previously mentioned accidents it is also worth mentioning the role of control sticks (inceptors) and handles. These should be even more intuitive than modern controls. It is important that pilots receive feedback cues from the controls which help them assessing the flight situation and giving the pilots better situational awareness without total reliance on sight and visual readings[19]. It may be argued that the PM (pilot monitoring) in AF447 could not see the control input of the PF. Hence, it is not clear if he was aware that the PF held full aft stick and was holding the aircraft in a controllable deep stall.

The pilots use several information cueing channels during aircraft control, Figure 24. The visual cues are most effective, but tactile cues are also of great importance during certain flight conditions (i. e. moving controls/inceptors give pilot feedback cues).

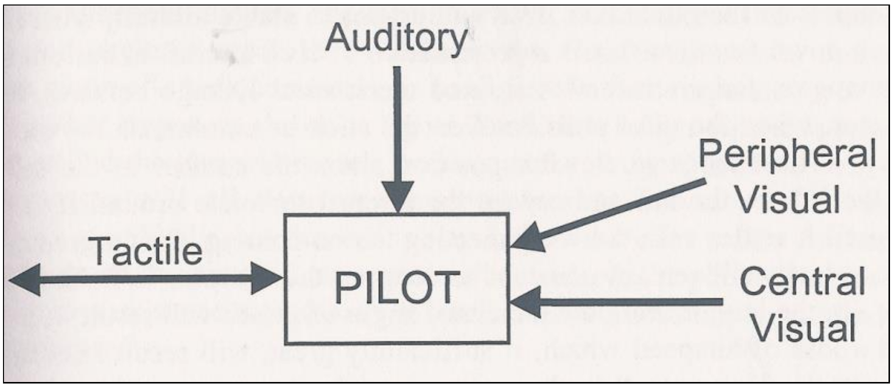

Figure 24. Pilot information cueing channels[20].

[19] References 9 and 10

[20] References 9

The basic piloting model is "the series pilot model" as described by Field 2004[21], Figure 25. The model describes basic piloting technique as student pilots are taught during basic training. The model is intuitive and is the most effective model during low speed manual handling of aircraft. The flight displays and controls (inceptors) should be based on this model.

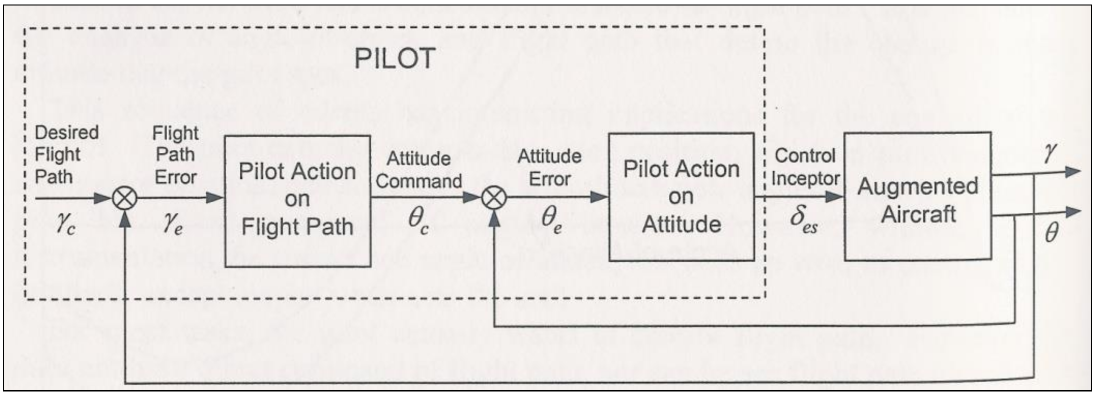

Figure 25. The series pilot model[22]

It may seem that todays pilots' knowledge about basic aircraft performance is not adequate. During the 1950-60-era, when the jet aircraft was introduced, it was focused on "operations on the back side of the power curve". This was a result of several approach accidents, both in the military and commercial aviation.

Pilots became quite familiar with the theory of aircraft performance, where pitch attitude controlled the airspeed and power controlled the rate of climb and descent:

$$\mathbf{V = \sqrt{(2L / C_L \varsigma S)}}$$

R/C = T –D (V/W) **R/D = D –T (V/W)**

Today manufacturers have made flying more complicated than necessary with too many autopilot modes and pilot's increased reliance on automation. How difficult is it to control an aircraft? Today basic aerodynamic principles seem to be forgotten by airline pilots normally controlling the aircraft through the autopilot. Modern aircraft are equipped with autopilot and autothrottles. The original intent was that pilots should use these automated systems in combination to reduce cockpit work load. When flying an autopilot coupled approach, the autopilot controlled the pitch and roll and the autothrottles controlled the rate of descent. The idea was that the PF should disconnect both when flying manual. However, some pilots developed the habit of disconnecting the autopilot and control pitch and roll manually and let the autothrottle maintain speed. Hence, the auto throttle controlled the speed and the pilot controlled the pitch and roll. Ref. Asiana Flight 214 accident.

"Pilots normally try to land at the target speed, in this case 137 knots, plus an

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[21] References 10

[22] References 10

> *additional 5 knots, said Bob Coffman, an American Airlines captain who has flown 777s. He said the briefing raises an important question: "Why was the plane going so slow?"*
> *The engines were in idle and the pilots were flying under visual flight rules, Hersman said. Under visual flight procedures in the Boeing 777, the autopilot typically would have been turned off while the automatic throttle, which regulates speed, would been on until the plane had descended to 500 feet, Coffman said. At that point, pilots normally would check airspeed before switching off the autothrottle to continue a "hand fly" approach, he said."*[23]

It seems that Asiana Flight 214 accident may be similar to the Turkish Airlines B737 accident in Amsterdam, where the throttles were in idle (due to intercept of glide path from above) and the autopilot was trying to compensate with increasing AOA, instead of PF handflying the aircraft manually during the final visual part of the approach. This seems to be a reversion to the type of aircraft accidents which occurred during the early 1960-ies, with the introduction of passenger jet aircraft. Older airline pilots were not familiar with jet aircraft performance characteristics with approach speeds "on the back side of the power curve".

> *"The instructor pilot told investigators that at 500 ft. altitude, he realized the aircraft was below the PAPI's visual glideslope and told the left seat pilot to "pull back" on the control yoke. "He had set the speed at 137 kt. and assumed the autothrottles were maintaining the speed," the NTSB says. Depending on the auto-flight mode selected, autothrottles, if armed and turned on, should automatically control engine thrust to maintain a preset speed, in this case 137 kt., the reference landing speed for the 777-200ER that day*."[24]

This control technique is opposite of basic piloting principle, and eventually the pilots may develop a habit of controlling the aircraft's vertical flight path in this manner. We may also see the effect of this habit in the AF447 accident, where the PF was pulling on the control stick (in stead of lowering the nose) and adding full thrust and thus trying to "fly out of the high AOA condition". This would be in line whith his previous training with Airbus systems, where he normally is protected by autothrust if approaching stall AOA (Airbus quote; *"our airplanes do not stall"*).
Hence, an AOA indicator should be a mandated supplement to the airspeed indicator, and by the same token it would be logical to have an airspeed scale with decreasing digits with increasing stick pull ("fly to - principle"), or even better, a transparent round dial as shown in Figure 12. The combination of intuitive flight displays, controls (inceptors) and autopilot modes, should be related to basic flight mechanics principles learned during basic pilot training.

DEVELOPMENTS IN PILOT EDUCATION AND TRAINING

Instrument flying ("*blind flying*") was first introduced by Jimmy Doolittle in USA in 1929.

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[23] Curt Lewis & Associates, Flight Safety Information, July 15, 2013.
[24] Curt Lewis & Associates, Flight Safety Information, July 15, 2013.

However, it was not until World War II that instrument flying became standard pilot proficiency. After the war instrument flying was continuously developed by improved instrumentation and pilot procedures. The concept of Attitude Flying was introduced. The basic principle is that the pilot controls the airspeed by lowering or raising the nose attitude of the aircraft. He/she controls the heading by banking in the wanted direction of flight and thus turning to the required heading. These are the basic and intuitive piloting principles both in visual and instrument flight. In visual flight the pilot uses the natural horizon as reference, and in instrument flight he/she uses the attitude indicator ("*artificial horizon*").

This concept was further developed into categories of instruments; Control Instruments consisting of Attitude and Power Instruments, Performance Instruments and Navigation Instruments. The principle was simple and intuitive; the pilot controlled the attitude of the aircraft by reference to only two instruments (Attitude and Power) and monitored the performance and navigation instruments for proper response, Figure 26.

A special pilot instrument cross check was developed, Figure 27, where the main instruments were the Attitude and Power indicators (Control Instruments). Improper cross check technique could result in chasing the performance indicators preventing stabilized flight. The student pilots were trained according to these principles and learned to scan the instruments in a certain scan pattern, where the Attitude Indicator was in the center and the most frequent scanned instrument. The faster this scan could be developed, the better situational awareness for the pilot.

During basic and advanced flight training, both in visual and instrument flight, it was emphasized that the primary Flight Control Instruments were the Attitude Indicator and the RPM/Power instrument – Pitch controlles airspeed and Power controlles acceleration, climb and descent according to:

$$\mathbf{V = \sqrt{(2L / C_L\, \varsigma\, S)}}$$

$$\mathbf{R/C = T - D\ (V/W)} \qquad \mathbf{R/D = D - T\ (V/W)}$$

This knowledge was also the fundamental basis for controlling an aircraft during any emergency or upset flight condition:

- Maintain aircraft control (by use of attitude and power) (Aviate)
- Analyze the situation (Navigate)
- Take proper action (Communicate)

Today's pilots seem to forget this, possibly because authorities and manufacturers allow design and operational use of conflicting control laws and operational practice.

Figure 28 shows the T-shape instrument scan of modern strip PFD. This scan will take longer as the eyes must be directed to one focal point at a time and the pilot fails to see more than one parameter at a glance as opposed to round dial instruments and pointers. With larger round dials and pointers the pilot may use his peripheral vision giving him/her an overall quicker scan.

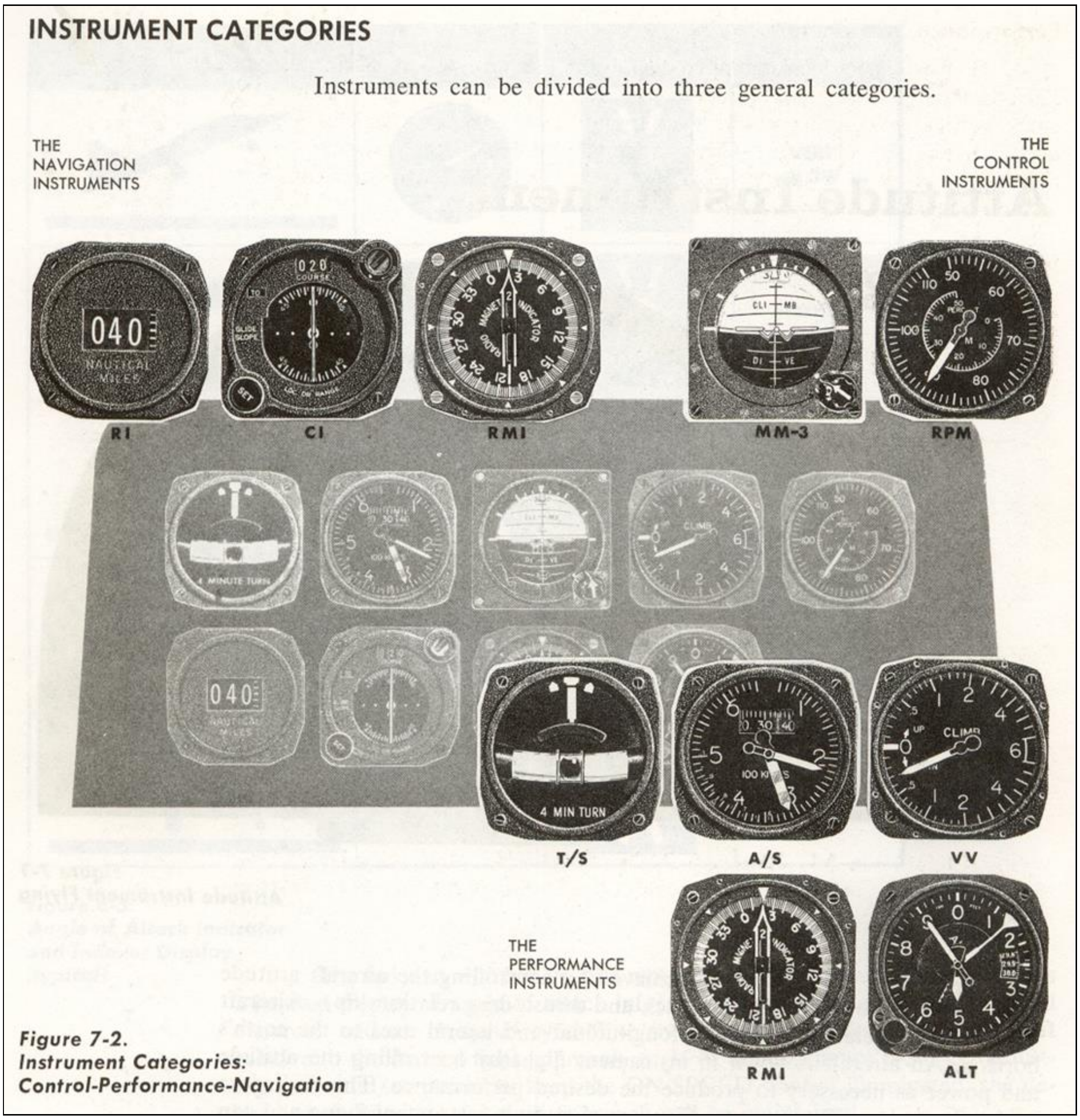

Figure 26. Flight instrument categories (US Air Force Manual 51-38, 1954).

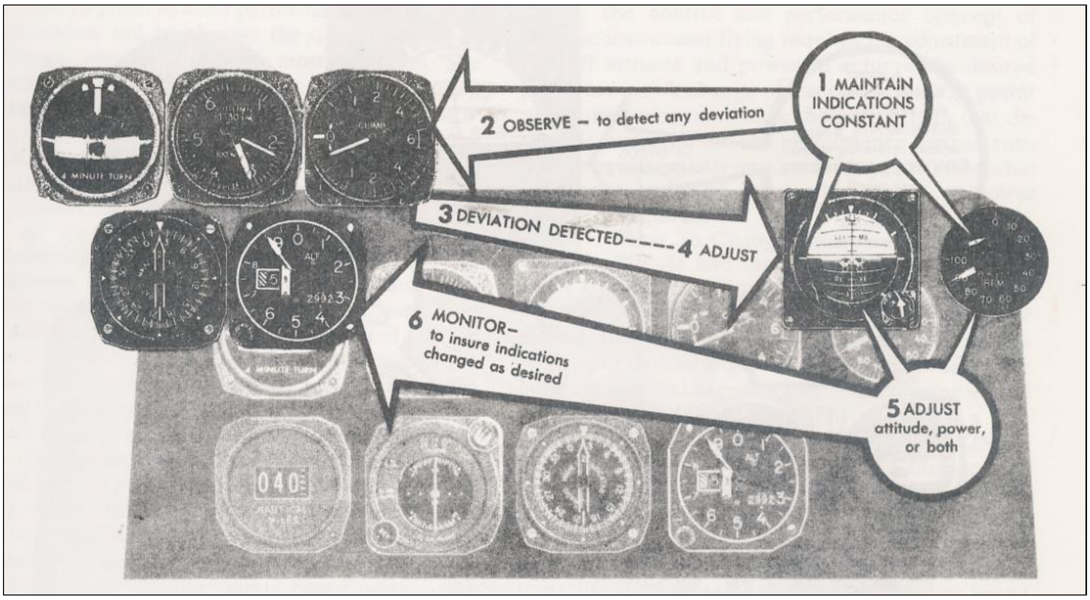

Figure 27. Instrument cross check technique (US Air Force Manual 51-37, 1979).

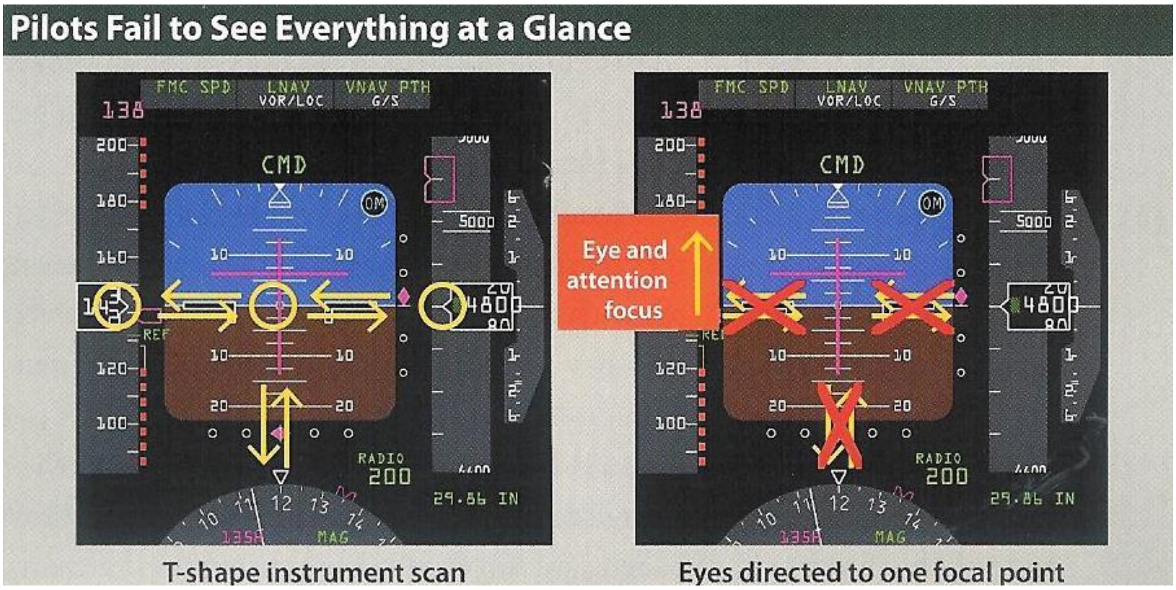

Figure 28. T-shape instrument scan (Boeing 2014).

COCKPIT DISPLAYS – TEST AND EVALUATION

Reference 20 addresses test and evaluation of cockpit displays:

> *"There have been a number of papers and articles written about operational difficulties with modern display and other cockpit systems. As we see it, the problem has been a series of discontinuities between the users and the designers, between the designers and the testers, and between the users and the testers.*
> *As a result of <u>the first discontinuity</u>, between users and designers, inadequate design requirements are established. This is particularly unfortunate as systems can be (and are being) designed with greater and greater capabilities in terms of automatic flight and guidance and flight control. Without adequate requirements, it is hardly surprising that there are problems encountered in operational use.*

<u>The second discontinuity</u>, between designers and testers, reduces the opportunities for feedback to the designer. In fact, with today's economic setting, many systems are practically committed to production by the time they reach flight test. Only if there are very serious problems, will these systems be corrected.

<u>The third discontinuity</u>, between users and testers, results in inadequate test criteria. As a result of this discontinuity, we are left with highly subjective criteria which vary from tester to tester. Or we have inappropriate criteria."

*"**The display design** must consider **why the pilot needs the data** and **what the pilot is expected to do with the data**. According to Singleton, several questions must be answered during development of a display:*

- *Does the **pilot's need** justify the display?*
- ***What data does the pilot need** that has not been provided?*
- *Can the **average pilot** obtain what is required easily?*
- *Does the **display conform to the real world**?*
  - *To other cockpit displays?*
  - *With previous pilot habits and skills?*
  - *With required decisions and actions?"*

RESEARCH ON PFD AND INCLUSION OF AOA INDICATOR

Figure 29 is described in Reference 4 as the results of a research program related to readability of different types of airspeed and altitude displays on HUD's.

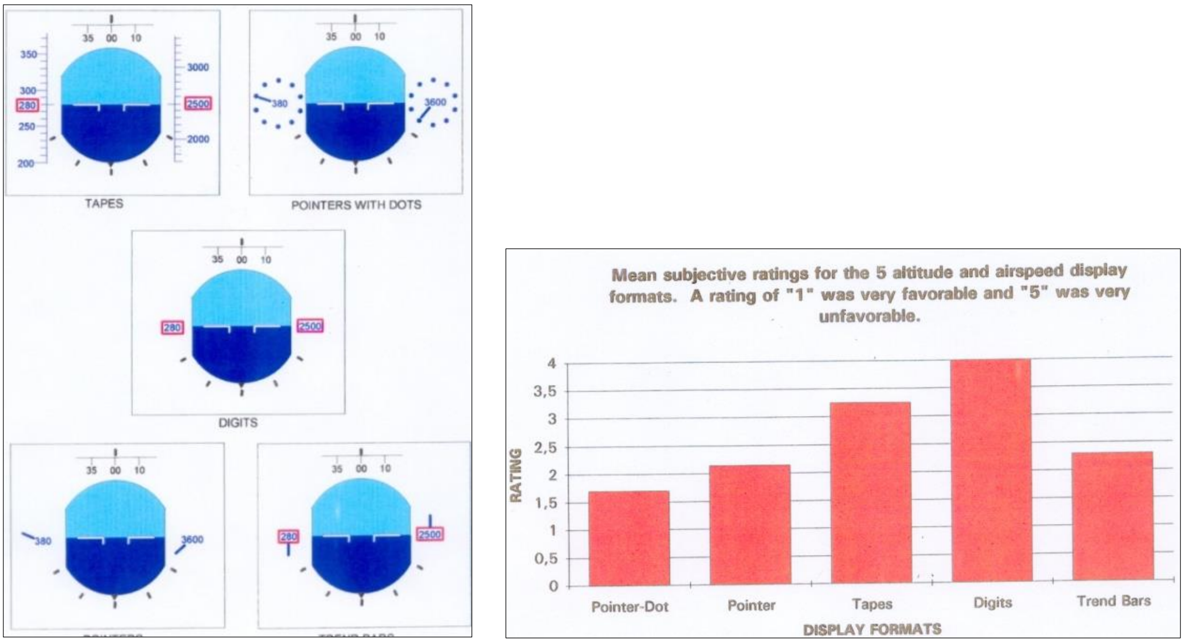

Figure 29. Different types of Airspeed and Altitude displays with Mean Subjective Ratings.[25]

[25] Reference 4

We see that a pointer is more intuitive and quicker to read and interpret at a glance. This indicates that round dial and pointer is more human adaptive than tapes and digits.

Figure 30 shows a PhD study at the Swinburne's Aviation Simulation Laboratory, Swinburne University of Technology's, Australia. The initial results into a study of the way pilots look at digital and analog instruments suggest experienced pilots facing an emergency will spend twice as much time looking at their instruments as novices. The study is testing volunteers in Swinburne University of Technology's flight simulators to see how pilots cope with the switch between digital and analog cockpits.

There is evidence indicating that pilots who have trained on analog instruments generally find it easier to move to a digital cockpit than vice versa. The author has not seen any research data supporting the human factor benefits of the state-of-the-art PFD's of today with strip indicators. However, there are indications that digital round dial indicators are more intuitive and quicker to read at a glance than strip indicators. The PFD's of today are 30 years old and it is time to develop new PFD based on human factor research and technological advancements.

Figure 30. PhD study at Swinburne's Aviation Simulation Laboratory, Australia 2014. Source: Supplied.

In the future there might be novel aircraft control systems available to help the pilots in a LOC-I situation [26] but so far the most rational solution is to make the PFD, autopilot modes and control inceptors more human factor centric and intuitive, combined with a prominent AOA indicator and relevant pilot training in stall and upset recovery.

CONCLUSION

[26] Reference 24

Several recent LOC accidents indicate that the human factor related aspects of primary flight displays, lack of AOA displays, flight control and inceptor design, and pilot education and training[27], play a significant role in the pilot's handling of an aircraft.

It is recommended that the industry initiate more human factor based research within these areas.

Quote: *"If you keep on doing what you do – you get what you got".*[28]

[27] Curt Lewis & Associates, Flight Safety Information, October 16, 2014
[28] Captain Tore Hultgren, AIBN

ABBREVIATIONS

AAIB - Aircraft Accident Investigation Branch (UK)
ACAS - Airborne Collision Avoidance System
ADI - Attitude Director Indicator
AI - Attitude Indicator
ALA - Approach and Landing Accidents
AOA - Angle of Attack
ASAR – Arc Segmented Attitude Reference
GA – General Aviation
CFIT - Controlled Flight into Terrain
CS-25 - Certification Specification Part 25 (EASA)
DCIEM - Defence and Civil Institute of Environmental Medicine Canada
EASA- European Aviation Safety Authority
EFIS – Electronic Fligh Instrument System
EGPWS - Enhanced Ground Proximity Warning System
FAA - Federal Aviation Administration
FAR 25 - Federal Air Regulations Part 25 (US)
GPWS - Ground Proximity Warning System
HMI – Human Machine Interface
HSI - Horizontal Situation Indicator
HUD - Head Up Display
IAS – Indicated airspeed
IATA - International Air Transport Association
ICAO - International Civil Aviation Organization
IFIS - Integrated Flight Instrument System (USAF)
ITQI - IATA's training and qualification initiative
LOC-I - Loss of Control in the air type of accidents
MMO - Max Operating Mach number
ND - Navigation Displays
NGAP - ICAO's next generation aviation professionals
NTSB - National Transport Safety Board
PF - Pilot Flying
PFD - Primary Flight Displays
PM - Pilot Monitoring
PVD - Peripheral Vision Display
TAWS - Terrain Avoidance and Warning System
TCAS - Traffic and Collision Avoidance Systems
UA - Unusual attitude
UR – Upset revovery
VD - Vertical Displays
VMO - Max Operating airspeed
VRS - Vortex Ring State
VSI - Vertical Speed Indicator
WR - Weather Radars

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