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Review of Research On Guidance for Recovery from Pitch Axis Upsets

Stephanie J. Harrison
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December 2016

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Review of Research On Guidance for Recovery from Pitch Axis Upsets

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National Aeronautics and
Space Administration

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Nomenclature

AC	Advisory Circular
ADI	Attitude Direction Indicator
AOA	Angle-of-Attack
ASAR	Arc-Segmented Attitude Reference
BAI	Background Attitude Indicator
CAST	Commercial Aviation Safety Team
CFR	Code of Federal Regulations
DA	Dual-Articulated
EADI	Electronic Attitude Direction Indicator
EICAS	Engine Indication and Crew Alerting System
FAA	Federal Aviation Administration
HGS	Head-Up Guidance System
HUD	Head-Up Display
ICAO	International Civil Aviation Organization
LED	Light-Emitting Diode
LOC-I	Loss of Control-In Flight
MaH	Malcolm Horizon
MH	Moving Horizon
MP	Moving Plane
NASA	National Aeronautics and Space Administration
NDFR	Non-Distributed Flight Reference
NLR	National Aerospace Laboratory
PCG	Pitch Control Guidance
PFD	Primary Flight Display
PLI	Pitch Limit Indicator

PVD	Peripheral Vision Display
PVHD	Peripheral Vision Horizon Display
SV	Synthetic Vision
TLX	Task Load Index
UA	Unusual Attitude
UAR	Unusual Attitude Recovery

Abstract

A literature review was conducted to identify past efforts in providing control guidance for aircraft upset recovery including stall recovery. Because guidance is integrally linked to the intended function of aircraft attitude awareness and upset recognition, it is difficult, if not impossible, to consider these issues separately. This literature review covered the aspects of instrumentation and display symbologies for attitude awareness, aircraft upset recognition, upset and stall alerting, and control guidance. Many different forms of symbology have been investigated including, but not limited to, pitch scale depictions, attitude indicator icons, horizon symbology, attitude recovery arrows, and pitch trim indicators. Past research on different visual and alerting strategies that provide advisories, cautions, and warnings to pilots before entering an unusual attitude (UA) are also discussed. Finally, potential control guidance for recovery from upset or unusual attitudes, including approach-to-stall and stall conditions, are reviewed. Recommendations for future research are made.

1 Introduction

Despite continual improvements in aviation safety, between the years of 2003 and 2012, there were 75 commercial aviation accidents resulting in 4,408 deaths [1]. Under the taxonomy established by the International Civil Aviation Organization (ICAO) and the Commercial Aviation Safety Team (CAST) [1], loss-of-control in flight (LOC-I) was identified as the leading cause of fatal accidents involving commercial airlines, with a total of 18 fatal accidents and 1,698 total deaths (Figure 1). In response to these findings, government agencies and industry are investigating potential mitigations for LOC-I accidents [1].

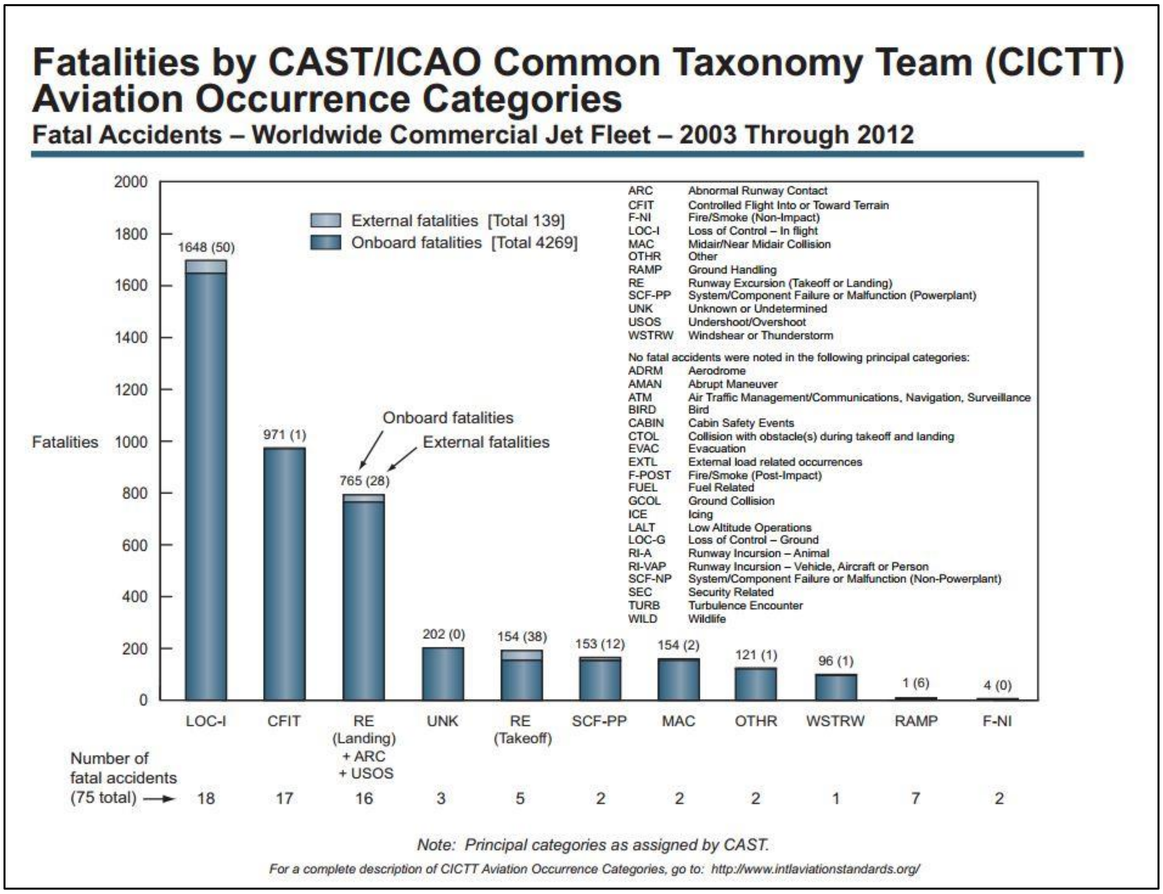

Figure 1: Aviation accident statistics for world-wide commercial jets 2003-2012

The CAST analyzed these LOC–I accidents and incidents to identify the contribution of the flight crew's lost awareness of their airplane's state, defined as:

- Attitude (pitch or bank angle or rate), or
- Energy (the combination of airspeed, altitude, vertical speed, thrust, and airplane configuration).

The review of worldwide transport airplane accidents over the past 10 years revealed that more than half of all LOC–I accidents and resulting fatalities involved flight crew loss of Airplane State Awareness (ASA) [2]. As a result, CAST has created safety enhancement plans for design, training, and research and development of new technologies for improved ASA and mitigation in the event of the flight crew's loss of ASA. One of the planned enhancements to develop and perform studies to assess algorithms and display scenarios which provide control guidance to aid pilots in recovering from upset conditions, including approach-to-stall and stall.

Primary flight instrumentation (i.e., full-time altitude, airspeed, and attitude displays) is already designed today to convey immediate attitude and energy state recognition and enable recovery from upset conditions for the flight crew [3]. Although this primary flight information reduces the risk of a loss-of-control incident, additional attitude awareness information, alerting, and control guidance may help to prevent these incidents and aid pilots in recovery during upsets.

Control guidance is defined as information provided to pilots to direct their manipulation of the controls to follow a course of action and, in the case of guidance for upsets, return the vehicle to normal flight conditions. Control guidance may also fulfill the intended function of an unusual attitude recovery (UAR) capability. In many respects, control guidance is integrally linked with the primary flight instrumentation. The primary flight information should provide immediate, discernible attitude and energy state recognition capability sufficient to prevent a loss of ASA [3]. Control guidance should complement this information and may play an essential part – another safety layer – in preventing the entry into or in aiding the pilot in the identification and recovery of an airplane upset. As such, it is almost impossible to solely discuss control guidance functions (i.e., information about required manipulation of the controls), without also considering the influences of attitude recognition. In the context of this report and in terms of pitch axis upsets, Pitch Control Guidance (PCG) literature is discussed as it would alert the pilot of the need to take action and provide control direction to recover from an upset condition, approach-to-stall, or stall.

This literature review was conducted to identify past efforts in providing PCG for aircraft upsets including stalls. This literature review was particularly focused on guidance systems employed to detect upsets and determine proper recovery response applicable to large commercial transport aircraft operations, including methods using: a) primary pitch control only, b) primary pitch control and pitch trim; c) primary pitch control, pitch trim, and thrust; and, d) other control strategies, as applicable [2].

Because guidance is integrally linked to the intended function of aircraft attitude awareness and upset recognition, it is difficult, if not impossible, to consider these issues separately. Accordingly, the literature review covered the aspects of instrumentation and display symbologies for attitude awareness, aircraft upset recognition, upset and stall alerting, and control guidance. The literature review covered numerous forms of symbology including, but not limited to, pitch scale depictions, attitude indicator icons, horizon symbology, attitude recovery arrows, and pitch trim indicators associated with upset and unusual attitude recognition and recovery. Further, different visual and alerting strategies that provide advisories, cautions, and warnings to pilots before entering an unusual attitude (UA) are discussed. Finally, the literature for PCG was investigated and recommendations for future research are made.

2 LOC-I Primary Causes and Recovery

2.1 Airplane Upsets

LOC-I may result from an airplane upset. The Society of Aviation and Flight Educators defines an airplane upset as "a departure from the intended flight profile that may or may not involve stalled flight and that typically involves an excess angle of bank, an excessive angle of pitch, or both, but that does not involve spinning" [4]. The Federal Aviation Administration (FAA) [5] explains that an airplane enters an upset when normal parameters are unintentionally exceeded, meaning:

- the pitch attitude is greater than 25 degrees nose up
- the pitch attitude is greater than 10 degrees nose down
- the bank angle is greater than 45 degrees, or
- the airplane is within these parameters, but flying at an inappropriate airspeed.

Ward and Moreau define airplane upsets as "unintentionally exceeding the parameters normally experienced in line operations or an event that alters the normal response of the airplane to pilot input such that the pilot must adopt an alternate control strategy to sustain or regain controlled flight" [6]. Upsets may lead to stall conditions if pilots are not aware of the situation and do not take proper action. Training, procedures, and current flight deck technologies work to reduce the risk of such an occurrence; however, further precautions need to be taken to decrease the threat of LOC-I accidents. Providing PCG to pilots may help decrease the likelihood of LOC-I accidents. Because the focus of this work involves large transport aircraft, PCG must consider the significant contributions of all pitch control effectors and factors, including primary pitch control, pitch trim, thrust, and other possible control strategies and influences (e.g., bank, yaw, flaps, and gear) as they may also help avoid or may be critical in effective recovery from these incidents as well as providing increased energy state awareness.

2.1.1 Pitch Axis Upsets

Pitch axis upsets result when normal parameters are unintentionally exceeded, generally defined as greater than 25 degrees nose up or greater than 10 degrees nose down. Prolonged upset attitude conditions can lead directly to critical, unsafe energy states (e.g., over speed or stall conditions). An aircraft in a pitch axis upset may approach or enter a stall condition if the angle of attack (AOA) becomes too high.

The AOA is the angle between the longitudinal axis of the airplane and relative wind, as indicated in Figure 2 [7]. Stated another way, the AOA is the angle between the nose of the aircraft and the flight path direction of the aircraft.

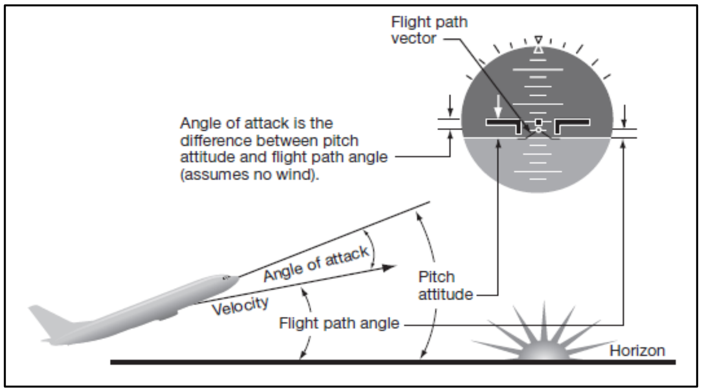

Figure 2: Angle of attack

The AOA at which an aircraft will stall is known as the critical AOA. The critical AOA of the aircraft varies depending on the aircraft design and configuration. Most aircraft have a critical AOA of approximately 15 degrees. Once this critical AOA is exceeded, lift will decrease, and the airplane will stall, regardless of the pitch attitude, speed, or altitude (Figure 3). Exceeding this AOA and remaining in prolonged upset attitude conditions can lead directly to critical unsafe energy states (e.g., over speed or stall conditions).

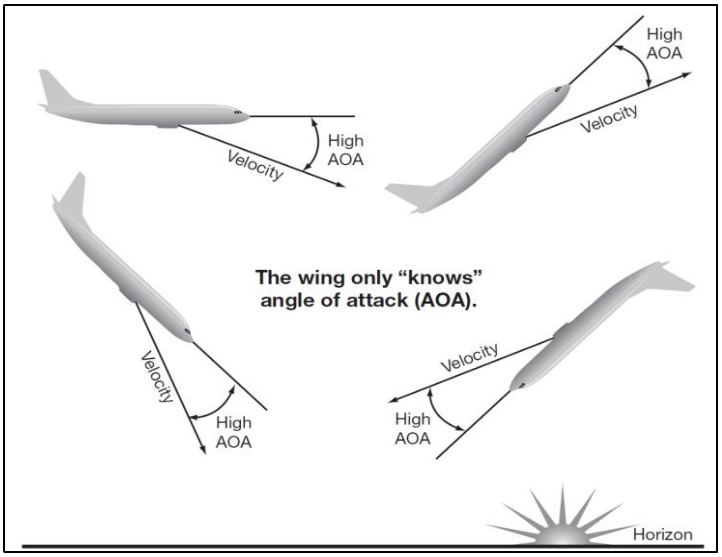

Figure 3: Pitch attitude and high AOA

2.1.2 Stalls

Stall conditions are caused by a decrease in lift resulting from the separation of airflow over a plane's wings. Stall parameters differ from aircraft to aircraft. However, for a given aircraft at a given configuration, the AOA at the stall is always the same; that is, the aircraft will always stall at the same AOA regardless of the airspeed, weight, load-factor (G), power setting, or density altitude [8]. The AOA at stall may differ depending on the flap setting and gear position. Stalls are often characterized by buffeting, lack of pitch authority, lack of roll control, inability to control descent rate, or a combination of these factors. Moreau and Priest point out that stalls can be characterized in three ways: an uncontrollable pitch down of the airplane, the control column reaching the operational limits, or the buffeting of the airplane. Buffeting is the state of an airplane in which the airplane shakes, sometimes violently, as a result of the airplane reaching the design limits. Buffeting often results from the airplane reaching the stall speed, not the stall AOA [9].

Stalls are not to be confused with approach-to-stalls, also known as impending stalls. Impending stall conditions are considered controlled flight conditions, whereas stalls are departures from controlled flight. AC 120-109 points out that the first natural or synthetic indication of a stall is the initial aural, tactile, or visual sign of an impending stall [10].

Pilots' understanding of stall characteristics allows for proper identification of approach to stalls and stalls. During stall conditions, it is important for the pilot to first recover from the stall prior to applying other recovery techniques [11].

2.2 Upset and Stall Recovery

Primary flight instrumentation is installed on aircraft to provide full-time airspeed, altitude, and attitude information to the pilot for constant awareness of airplane state. Pilots are trained to use this primary flight information for full-time awareness, as well as to recognize and recover from upset attitude conditions, approach-to-stall, and stall should they occur.

2.2.1 Upset Recovery

In 2008, the Industry Airplane Upset Recovery Training Aid Team [7], including government and industry partners, established pilot control recovery procedures for airplane upsets for large swept-wing turbofan airplanes typically seating more than one hundred passengers. These included nose high and nose low recovery techniques.

For nose high, the following recovery procedure has been established:

- Recognize and confirm the situation
- Disengage autopilot and auto throttle
- Apply nose-down elevator
    - Use nose-down stabilizer trim should stick forces be high
- Use appropriate techniques to control pitch or get nose-down pitch rate:
    - Roll aircraft to bank angle to obtain a nose-down pitch rate
    - Reduce thrust (underwing-mounted engines)
- Complete the recovery:
    - Approaching the horizon, roll to wings level
    - Check airspeed, adjust thrust
    - Establish pitch attitude

For nose low, the following recovery procedure has been established:

- Recognize and confirm the situation
- Disengage autopilot and auto throttle
- Recover from stall, if necessary
- Recovery to level flight:

- Apply nose up elevator
- Apply stabilizer trim, if necessary
- Apply thrust and drag as necessary

Moreau and Priest [9] explain that although these procedures provide general guidance into the issues associated with UAR, they do not provide insight into how to control the airplane when primary flight controls are lacking, nor do they provide insight in how to mitigate the original cause of the UA once this has occurred. Alternative control strategies may in fact be required.

2.2.2 Stall recovery

In 2014, an advisory circular (AC 120-111) with associated regulations was issued by the FAA to codify upset recovery and stall training. The principles of the AC are stated as developing a training curriculum that "provides pilots with the knowledge and skills to prevent an upset, or if not prevented, to recover from an upset". [5]

The training identifies the importance of timely action by the flight crew to avoid progression toward a potential upset by actively scanning the internal and external environment. Further, the importance of identifying and being alert to factors that may lead to divergence from the desired flight path are described [5].

The training also identifies the importance of prompt recognition and timely action to recover from an upset or divergence from the intended flight path or uncommanded changes to the aircraft flight path. Recovery procedures, largely similar to that established by the Industry Airplane Upset Recovery Training Aid Team, are specified.

3 Upset and Stall Control Guidance and Recognition

Flight crew awareness is critical to accident prevention as the first step to preventing such an occurrence of upset or approach-to-stall and stall by creating flight crew awareness and if not sufficient, alerting the crew. In addition, the design of the primary flight instruments, installed to provide full-time awareness of airplane state, significantly impacts the form, format, and design of any algorithms or display scenarios for pitch control guidance.

Awareness is nominally provided by the primary flight information. However if this awareness is not sufficient or if non-normal conditions and events occur that warrant and/or require flight crew awareness to maintain good flight crew decision-making and responses, alerts should be used with the level of alerting dependent upon the severity and criticality of the condition.

Flight crew alerts are roughly categorized based on the urgency of flight crew awareness and response as follows:

- Advisories – for conditions that require flight crew awareness and may require subsequent flight crew response
- Cautions – for conditions that require immediate flight crew awareness and subsequent flight crew response
- Warnings – for conditions that require immediate flight crew awareness and immediate flight crew response

Title 14 of the Code of Federal Regulations (CFR) §25.1322 and AC 25.1322-1 outline the regulations enforced when incorporating alerts into the cockpit [12, 14].

Alerts may come in the form of visual, aural, and/or tactile alerts depending upon the alert severity level and following the guidelines in AC 25.1322, including color where warnings are indicated by red and cautions by yellow or amber.

In the event that specific crew actions are warranted or required, control guidance may be appropriate. Control guidance is defined as information provided to pilots to direct their manipulation of the aircraft controls to follow a course of action.

The PCG function for primary pitch control is depicted within the primary flight instrumentation of the aircraft and its required attitude indicators. Attitude direction indicators (ADIs) are "inside-out" displays replicating the motion of the outside world on a display on the flight deck. "Outside-in" displays are sometimes used for attitude indication as well. These displays replicate the motion of the airplane on a static image the outside world. Both "outside-in" and "inside-out" displays have been investigated for use in UARs [15]. PCG for control effectors other than the primary flight control may be annunciated by other means and through other displays (visual, tactile, or aural) as discussed in the following.

The next sections outline various types of PCG that have been researched in past years. Because pitch guidance is integrally linked to the intended function of upset and UA recognition and recovery, it is difficult, if not impossible, to consider these issues separately. As such, the literature is reviewed for:

- Upset and UA recognition,
- Upset and UA alerting (i.e., cautions and warning used to increase aircrew awareness of current or impending UA conditions in the event that the aircrew are not recognizing the situation),
- And finally, PCG which is information provided to pilots to aid or direct the pilot's manipulation of the controls of the aerodynamic forces to maintain vehicle stability and, in the case of guidance for upsets, approach-to-stall, or stalls, return to normal flight conditions.

3.1 Upset and UA Recognition

According to the United States Air Force manual on instrument flying -

> "Aircraft performance is achieved by controlling the aircraft attitude and power. Aircraft attitude is the relationship of its longitudinal and lateral axes to the Earth's horizon. An aircraft is flown in instrument flight by controlling the attitude and power as necessary to produce the desired performance."

Pilots use control instruments that display attitude and energy state indications, specifically monitoring control using the ADI. A centrally-located ADI is a primary flight instrument and serves as the pilot's primary reference for pitch, bank and command steering information [3].

One of the intended functions of the primary flight instruments is to ensure flight crew awareness of the aircraft attitude and energy state, including upset attitudes. MIL-STD-1787C for Aircraft Display Symbology [16] outlines that primary flight reference symbology must provide sufficient cues for attitude reference to support immediate recognition and recovery from UA. As such, cues shall clearly distinguish between climb and dive attitudes and provide a full time horizon reference. The display must provide pilots with attitude awareness and the ability to recover effectively should the airplane enter an unusual or unexpected attitude [16].

UA recognition can be thought of as being analogous to an advisory flight deck alert, providing the first level of awareness to a pilot. Advisory alerts give the pilot an overall situation awareness of the airplane's attitude. Under 14 CFR §25.1322, an advisory alert is defined as "a condition that requires flight crew awareness and may require subsequent flight crew response" [14]. AC 25.1322-1 recommends that an advisory alert should be visually provided within the flight crews' normal scan patterns [13]. An advisory alert should enhance the situation awareness of the crew, allowing them to avoid upset situations. Much of the advisory symbology research discussed below involves symbology that is displayed at all times in order to advise the crew *before* an UA is reached.

3.1.1 Attitude Symbology

Attitude symbology should provide a clear and intuitive display of attitude to the pilot. Knowledge of an aircraft's attitude can help to ensure that a pilot recognizes an UA at an early stage, before a stall is imminent. How this information is conveyed to the flight crew, however, is not standardized and has been the subject of significant research.

The fundamental requirements for a "bank and pitch indicator" is outlined in 14 CFR §25.1303. Beyond this basic functional description, implementation details are contained in guidance material such as SAE AS396B, "Bank and Pitch Instruments" [17] which states that

1) The method of displaying bank and pitch attitude shall be as specified below:
   a) Bank attitude shall be displayed so that the true relationship between aircraft bank attitude and the actual earth's horizon is clearly presented over the range of indication.
   b) Pitch attitude shall be displayed so that a change between the aircraft's pitch attitude and the actual earth's horizon is clearly presented in the proper relationship over the range of indication.
2) Indicating Requirements:
   a) Indicating Range: The range of indication in pitch shall be at least plus or minus 25 degrees. The range of indication in bank shall be at least plus or minus 100 degrees.
   b) Indicating Graduations: Right and left bank graduations shall at least be provided at 30 degrees.
   c) Pitch Attitude Reference: A zero pitch reference shall be provided.

From these requirements, modern ADIs and primary flight instruments have evolved under Advisory Circular guidance (such as AC25-11) and range in implementations from electronic replicates of mechanical ADIs such as that in Figure 4a to those using Synthetic Vision backgrounds and Head-Up Display (HUD)-like symbologies (Figure 4b).

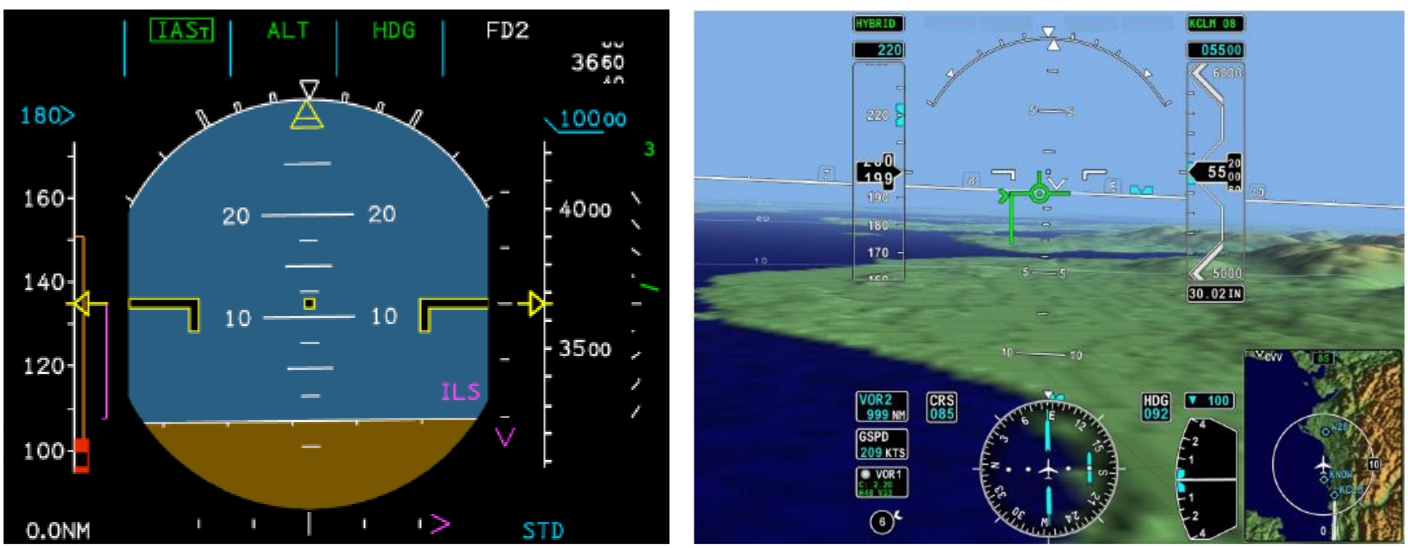

Figure 4: (a) ADI (b) Synthetic Vision Background with HUD Symbologies

The literature review of how these different symbologies promote basic attitude awareness and UA recognition are described. This review discusses both HUD and head-down display research since both display devices may be used as a primary flight reference and the core principles for attitude awareness are shared across the devices.

3.1.1.1 Articulated Pitch Ladders

Articulated pitch ladders, also known as angled or slanted pitch ladders, have been proposed to provide pilots with increased attitude recognition and a possible form of pitch guidance during upset recovery. Articulated pitch ladders are identified by pitch bars that funnel towards the horizon with the bar angles being more acute as the aircraft's pitch increases. In a nose high attitude, the pitch bars point in the down direction (such as in Figure 5). Similarly, in a nose low, the pitch bars point up toward the horizon.

Taylor in 1984 investigated articulated pitch ladders as a part of a series of experiments he conducted [18]. Three of the four experiments will be discussed in section 3.1.1.3 below. The fourth of these experiments investigated the utilization of pitch bars for roll and horizon interpretation. Roll orientation information and the direction to the nearest horizon is key during upset recoveries. Forty-eight non-aircrew subjects were presented with three display formats incorporating solid and dashed pitch lines for positive and negative pitch bars, pitch bar tails, and inclined pitch bars that funnel to the nearest horizon. The subjects were asked to correct either a pitch or roll attitude as quickly as possible. Results for the pitch tasks indicated that the pitch bars funneling toward the horizon were superior to other formats. This format of pitch bars was not found to enhance or degrade unusual roll attitude recoveries [18].

Zenyuh and colleagues investigated the use of articulated pitch bars, as well as the use of a multicolor HUD, in their research in 1987 [19]. This work examined the effectiveness of articulated pitch bars versus standard pitch bars and monochromatic versus multicolored HUDs. In order to accomplish this task, sixteen military pilots from the US Air Force, Air National Guard, US Air Force Reserve, and others from Wright Patterson Air Force Base performed twelve UARs using one of four HUD formats in a generic advanced fighter cockpit simulator. These four formats included a standard monochromatic HUD, standard multicolor HUD, articulated pitch bar monochromatic HUD, and an articulated pitch bar multicolor HUD. The articulated pitch bars tunneled toward the horizon, with pitch scale numbers moving inward as the aircraft became inverted and outward as the plane became upright. The multicolor HUD display provided cyan colored pitch bars above the horizon, green pitch bars below the horizon, with a white horizon line. The flight path marker was colored green, with all other symbology being white and enclosed by a cyan box. Performance metrics including initial response times, task initiation time, completion status, and total event time were recorded. Results showed that the use of both angled pitch bars and a multi-colored display provided for improved flight performance metrics during extreme attitudes. During non-extreme attitudes where the horizon line was visible, the standard symbology was sufficient. Zenyuh and colleagues noted that the better performance may have been attributed to the combination of the multi-colored display and angled pitch bars providing a clear indication of the direction of the horizon [19].

In 1988, Reising, Zenyuh, and Barthelemy investigated the use of an articulated pitch ladder in their research on HUD symbology for UAR (see Figure 5) [20]. This research was done in an advanced fighter concepts cockpit. The articulated pitch ladder was incorporated into all concepts tested. As such, pilot preferences in regard to the articulated pitch ladder were not reported.

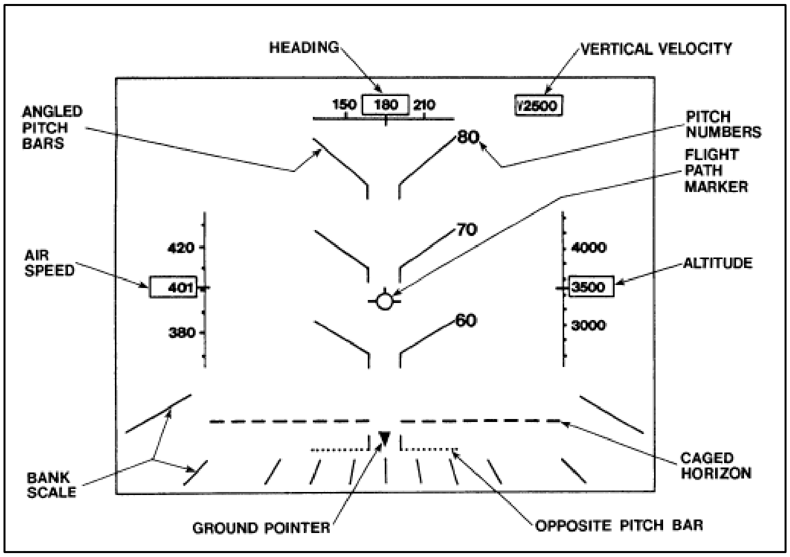

Figure 5: HUD symbology for articulated pitch ladder

In 1988, Newman conducted an UAR experiment. In this experiment, six operational pilots performed UARs in a fixed-base flight simulator using the HUD for flight information [21]. As part of this work, Newman investigated pitch ladder variations of HUD symbology during spatial disorientation. A baseline, conventional pitch ladder, articulated pitch ladder, and pitch ladders with both vertical and lateral asymmetry were investigated. Control inputs, airspeed, heading, attitude, and subjective measures were recorded. Articulated pitch ladder provided slightly faster reaction times than the other pitch ladder variations. Subjective results showed that subjects preferred the articulated pitch ladder with lines slanted toward the horizon. Subjects did not indicate a preference for the asymmetrical pitch ladders [21].

In 1989, Roust [22] discussed her research of different HUD formats for the F/A-18. She conducted two surveys with the purpose of looking at the strengths and weaknesses of specific HUD symbology. The first survey examined individual HUD symbology elements and characteristics. The second survey explored different display formats incorporating the preferred symbology elements and characteristics from the first survey. The elements and characteristics questioned in the first survey included pitch bar angles, locations of pitch angle numerals, the usefulness of negative signs, types of velocity vector symbols, and the word readouts of “CLIMB” and “DIVE” commands. The second survey investigated which direction a so-called “Augie Arrow” should point, the presentation of word cues on the HUD, the use of the velocity vector while at extreme attitudes, a “sawtooth” pitch ladder, and different ADI formats. Sixty pilots responded to the first survey, and 56 pilots responded to the second survey. All pilots were F/A-18 pilots at Lemoore Naval Air Station in California. The survey data indicated that pilots preferred an articulated pitch ladder funneling toward the horizon. Additional results of these surveys will be discussed in Section 3.1.1.3 and Section 3.3.2 [22].

Ward and Hassoun also investigated the use of articulated pitch bars for UAR evaluations in 1990 [23]. Twelve F-16 pilots evaluated HUD symbology for UAR in an F-16 simulator. Subjects performed UAR using an F-16 HUD with a partially articulated pitch scale, or a fully articulated pitch scale. The partially articulated pitch scale showed articulated pitch bars below the horizon line, funneling toward the horizon. Performance data including reaction time, recovery time, correct response, altitude change, subjective workload data, and situation awareness data were collected and analyzed. Results showed that the partially articulated format that provided sloped pitch bars below the horizon line yielded the best performance, quickest mean reaction time, and quickest mean recovery time. Pilot participants reported that they preferred the partially articulated pitch ladder in high workload scenarios, however, the fully articulated pitch ladder was preferred during normal flight conditions [23].

In 1991, Weinstein and Ercoline studied various climb/dive ladder configurations for UAR [24]. Articulated pitch bars provided asymmetry between above-the-horizon and below-the-horizon, which increased speed and accuracy for attitude recognition. In addition, the articulation provided an indication of the direction of the horizon and better spatial orientation during steep pitch down situations where the articulation of the bars increased with increasingly negative pitch. They conducted a study investigating the effects of articulated pitch bars compared to parallel and tapered pitch ladder lines. Twelve HUD-experienced military pilots performed UARs across four pitch ladder concepts (Figure 6). The four conditions compared articulated and parallel lines, tapered lines, and static versus dynamic climb/dive marker. Accuracy, reaction time to the initial input, and subjective measures were recorded. The parallel, tapered top, articulated bottom with moving climb/drive marker resulted in significantly lower accuracy, however, there was no significant differences in reaction times using the four displays. Subjective data showed mixed preferences. Seven subjects preferred the articulated bottom with parallel tapered top and a fixed pitch reference (Figure 6b), while four subjects showed preference for the articulated top with parallel and tapered bottom with a moving pitch reference (Figure 6c). One subject had no preference. Although most subjects showed preference for a particular display, performance data did not correlate with their preferences. Speed of recovery from a nose-down UA was unaffected by the pitch ladder configurations. It was concluded that using parallel lines below the horizon line of the pitch ladder provides for more consistent and accurate bank information. The authors concluded that asymmetry of the pitch ladder to indicate horizon position enhances spatial orientation [24].

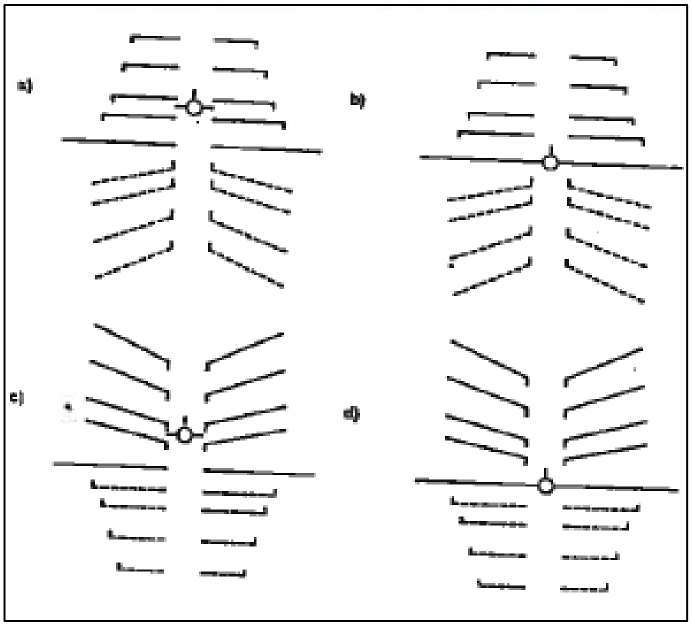

Figure 6: Pitch Ladder Configurations

Deaton, Barnes, Lindsey, Greene, and Kern investigated two different HUD pitch ladder formats in 1992 [25]. The HUD pitch ladder is often criticized for not providing enough information during critical flight operations, such as recovery from UAs. The two HUD formats included: a standard format and an enhanced format. The standard format contained dotted, parallel pitch bars at negative pitch attitudes. The enhanced format included the use of "sawteeth" at negative pitch attitudes. This format is an example of partially articulated pitch lines below the horizon. The "sawteeth" would start to appear at 30 degrees pitch down and gradually grow in size at 60 degrees pitch down (figure 7). Subject pilots were put into an UA while sitting with their head down. Once the UA was achieved, the pilot was told to look up and recover the aircraft. The enhanced display format resulted in improved recovery time and higher subjective preference ratings. Following the completion of all scenarios, the pilots completed a debrief questionnaire. This questionnaire asked pilots about the ease in determining the airplanes attitude given the standard HUD or enhanced HUD. Pilots found the enhanced HUD to be more helpful when compared to the standard HUD when recovering from UAs [25].

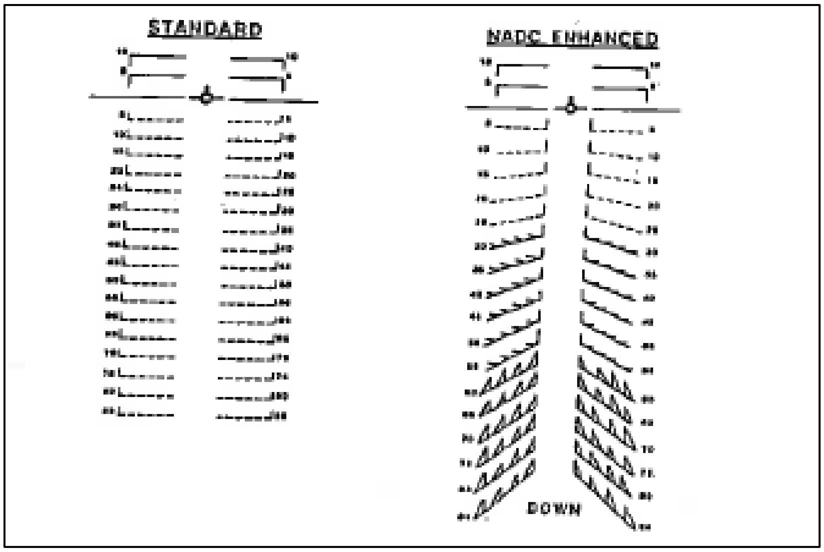

Figure 7: Pitch ladders

Self, Bruen, Feldt, Perry, and Ercoline investigated an articulated pitch ladder concept that they called a moving horizon (MH) in their research in 2002 [26]. Arc Segmented Reference Symbology and Moving Plane (MP) concepts were also investigated and will be discussed in Section 3.1.1.5 and 3.1.1.7 below. Pilots performed an UAR task and were assessed on time to initial roll input, time to recover to straight and level, and number of roll reversals. The MH used in this research involved rotating the pitch ladder to indicate bank angle and solid or dashed lines to indicate pitch angle. Angled dashed lines indicated a nose low situation and pointed the pilot to the artificial horizon. Figure 8 shows a nose high, banked left MH on the left and a nose low, and banked left on the right [26]. The results showed that with proper training the MH display was successful and reliable; however, the symbology movement sometimes confused pilots, which elicited incorrect control inputs.

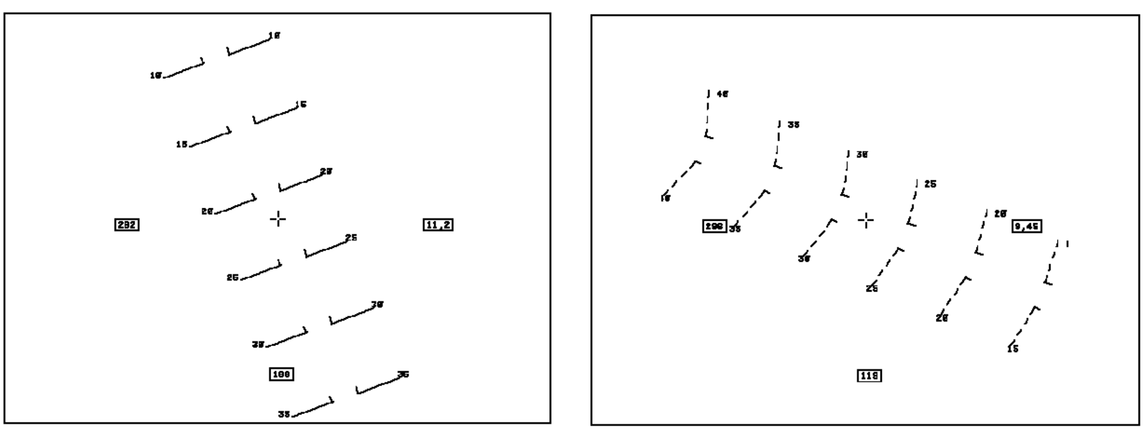

Figure 8: Moving horizon concept

3.1.1.2 Compression

Compression of the pitch ladder has been investigated as an aid for upset recovery. Compression provides more symbolic pitch information within a given display area. Zuschlag pointed out potential issues and research concerns of the HUD (which is typically a conformal or uncompressed 1:1 display) that he believed should be addressed. He pointed out that the compression of the pitch scale in the range of 1.5:1 to 2:1 may improve UAR when compared to the conformal HUD. Tapering the length of the pitch bars as well as articulation varying with the orientation are two additional ways that HUD pitch ladders may be altered to improve distinction between pitch angles above and below the horizon [27].

Newman, in 1988, investigated pitch scale compression between 1:1, 2:1 and 6:1 (See Section 3.1.1.1 for the experimental methodology). Full-time and automatic pitch scales were also investigated [21]. The automatic scale displayed the baseline 1:1 compression during normal flight, with compressed scales during UAs. For this experiment, UAs were defined as plus or minus 30 degrees of pitch and plus or minus 60 degrees of bank. Control position, airspeed, heading, pitch and roll attitude, and subjective measures were recorded. Subjective questionnaires asked pilots to rate each symbology for ease of maintaining orientation, ease of recovery, and symbology appropriateness. Pilots reported that they preferred the UA compressed scale design over the baseline. Results showed that the 2:1 pitch scale compression, either full-time or automatic, provided for quicker reaction times. Subjective ratings also showed a clear preference for the 2:1 pitch scale compression. Subjects reported a slight preference for the automatic pitch scales compression change in comparison to the full-time. As a result, the automatic, 2:1 pitch scale was recommended. Newman concluded that compressed pitch scales may be useful during non-ground-referenced flight operations, however, it is probably not practical during ground-referenced operations as compressed pitch scales require attention to the difference in angle between the waterline and velocity vector [21].

Hall, Stephen, and Penwill investigated the concept of a compressed pitch ladder for UA maneuvers in 1989 [28]. Their pitch ladder had a standard 1:1 scale when the aircraft was within plus or minus five degrees of pitch. Outside of this range, the ladder increased from the 1:1 scale at five degrees to the 4.4:1 scale at the extremities (not pictured). Hall, Stephen, and Penwill also investigated the ideal pitch ladder design. Although no details on the approach of the study were reported, results of the study showed that solid and dashed bars were found to be the most distinguishable. Their research indicated that a compressed pitch ladder may be helpful under high pitch angles. An extended, bold horizon line was suggested for use in combination with a standard 1:1 pitch scale. The study indicated subjects preferred the horizon-pointing legs to ground pointing legs on the pitch scale for recovery from UAs. After numerous flight and simulation trials, Hall, Stephens, and Penwill recommended the 4.4:1 pitch scale with tapered pitch bars [28]. This HUD format was developed in a flight simulator and validated in flight. Details of the methodology and results of these tests were not discussed.

3.1.1.3 Pitch Ladder Enhancements

HUDs are effective at displaying flight information during normal attitudes; however, they are less effective during detection and recovery of UAs [27]. In addition to pitch ladder compression research, efforts have been made to improve distinguishability of above and below the horizon, graphical indications of pitch extremities, and identification of the direction towards the horizon. To make these improvements, researchers have explored length, gap width, weight, color, use of dashed lines, position of vertical rung marks, position of value labels, and symbology for indicating extremities on the pitch ladder (e.g., zenith and nadir symbology).

Taylor conducted a series of four experiments to provide further guidance on the design and standardization of HUD pitch ladders [18]. These experiments investigated pitch scale numerals, pitch bars, local and global characteristics, and roll and horizon interpretation. A key element of Taylor's work involved asymmetry cueing, such as differences between nose-low and nose-high attitudes and upright and inverted flight, suggesting that asymmetry creates a means of better recognition and possibly, guidance back to the horizon/level attitude.

The first experiment investigated the impact of pitch scale numbers and varied the location of the numbers and use of negative signs [18]. Twenty-four non-aircrew subjects performed a recovery task using six HUD formats. To test the impact of negative pitch signs, three of the HUD formats had negative pitch scale numerals, while the other three displayed absolute values on the positive and negative sides of the scale. To test the impact of location, two formats aligned pitch numerals on both extremities of the pitch bars, two aligned the numerals to the right extremities of the pitch bars, and two aligned the numerals to the right and above the pitch bars. This experiment found the addition of negative signs reduced response times. Pitch angle numerals located to the right and above the pitch bars were the most effective for the recovery task.

The second experiment investigated pitch ladder design [18]. Thirty-six aircrew subjects were presented with a series of seven HUD pitch ladder concepts. The seven concepts explored various combinations of three key pitch ladder characteristics. The seven concepts were derived from concepts found useful in Experiment 1, including formats with tails on both the positive and negative pitch bars, formats with a solid and dashed lines for positive and negative pitch lines, respectively, and pitch numerals to the right and above the pitch bars. The timing and direction of initial control movements were investigated. The pitch bars with solid and dashed bars for positive and negative pitch angles provided the most effective indication of roll orientation.

The third experiment looked specifically at the design of symbols attached to pitch bars [18]. Twenty-four non-aircrew subjects were presented with 15 different HUD formats. Subjects were asked to identify the orientation based on the HUD format presented by pressing a button indicated "upright" or "inverted". The four basic HUD formats characteristics were vertical asymmetry, lateral asymmetry, symbol color, and symbol shape. Circles and triangles were used to distinguish between upright and inverted conditions. Blue and green were used for sky and ground symbology, respectively. All possible combinations of the four basic formats provided for 15 different HUD formats. Response time and keying errors were examined. Results showed that lateral asymmetry provided significantly faster response times than vertical asymmetry. Lateral asymmetry provided performance improvement when used with shape and color.

The fourth of the experiments investigated the utilization of pitch bars for roll and horizon interpretation [18]. These articulated pitch bars and the results of this experiment were discussed in section 3.1.1.1.

As a result of these four experiments, Taylor [18] suggested the following four characterizations for standardization of HUD pitch scales:

1. Continuous positive pitch bars and broken negative pitch bars

2. Numerals on one side of the pitch scale, above or below but not aligned with the pitch bar extremities

3. Negative signs for negative pitch scale numerals

4. Horizon-pointing tails and horizon-sloping pitch bars

In 1989, Taylor [29] continued to propose improvements to the HUD pitch attitude symbology that were optimized for UARs (Figure 9). These improvements incorporated research findings on pitch line coding, pitch scale numerals, horizon-sloping pitch lines, pitch-bar angle tags, horizon lines, and aircraft reference symbology. These symbology enhancements were aimed at improving identification and recovery from UAs. He suggested the use of dashed lines for negative pitch angles and solid lines for positive pitch provides a textural distinction between the two. Pitch scale numerals provided global cues for orientation, however, only the absolute value was used. Taylor stated that sloping pitch lines may provide a chevron-like coding as a pitch angle cue. Pitch-bar tags offered orientation towards the horizon, providing redundant horizon information which resulted in quicker recovery responses. The suggested horizon line was thickened and extended farther out on the display than the other pitch lines. The aircraft reference symbol included a tail-fin indication to enable pilots to more easily identify a roll inversion.

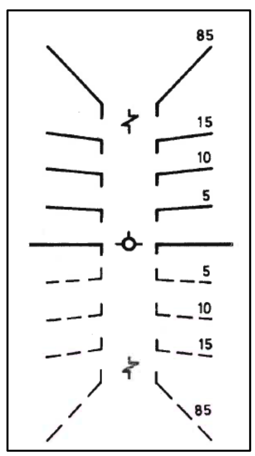

Figure 9 : HUD Pitch Attitude Format Improvements

Taylor noted the importance of a display providing clear and understandable awareness of internal and external influences to the aircraft. Display symbology and other means of providing attitude awareness to the pilot should be judged by the extent to which they facilitate the understanding of the aircraft's attitude and situation awareness at any given time. Taylor believed that pictorial displays were the future as they offered a direct link between representation, perception, and cognition [29].

Newman also investigated pitch ladder enhancements [21]. In this experiment, six operational pilots performed UARs in a fixed-base flight simulator using the HUD for flight information. A variety of symbology were evaluated, including: effect of pitch scale compression, effect of pitch ladder cues, type of bank information, velocity vector versus pitch cues, and form of data presentation. Only those applicable to attitude recognition and upset recovery will be discussed herein. Subjects performed a series of UARs with the various symbology conditions. Control position, airspeed, heading, pitch and roll attitude, and subjective measures were recorded. Subjective questionnaires asked pilots to rate each symbology for ease of maintaining orientation, ease of recovery, and symbology appropriateness. Based on these results, Newman expressed four design criteria for selecting display symbology for UAs, which included: effectiveness in assisting recovery from UAs, effectiveness in maintaining orientation, minimal interference with other operations, and minimal changes to existing equipment required. Symbology used to aid in identification and recovery from UAs should minimize the likelihood of entering an UA, and aid in recovery from such an occurrence [21].

Roust [22] also discussed enhancements to the pitch ladder in her survey research conducted in 1989. Pilots responded to two surveys regarding enhancements to pitch ladders and other pitch ladder characteristics. The first survey found that pilots preferred tails on the outer edge of the pitch ladder pointing toward the horizon with numerals on the outer ends. The majority of pilots agreed that color indications for below the horizon symbology would be helpful during UA. Pilots indicated that a command word during UA would be helpful. The words “CLIMB” rather than “NOSE UP” and “DIVE” rather than “NOSE DOWN” were preferred. It was concluded that the velocity vector should be retained during UA as it provides a strong visual cue. Pilots suggested further experimental study to investigate these suggestions.

3.1.1.4 Horizon Symbology

The presence of a horizon line (i.e., the zero pitch attitude reference line) provides a clear and distinct reference for level flight conditions. The design of this reference can provide attitude recognition and an implicit means of recovery guidance information, especially if it is always present on a primary flight reference display.

Resing, Zenyuh, and Barthelemy incorporated a horizon indicator into the HUD symbology for investigation in their experiment [20]. Experiment methodology is described in Section 3.1.1.1. Two different horizon indicator concepts were investigated. The first consisted of a single thicker and wider pitch line that appeared nearest the horizon when the true horizon was not visible [18]. The second concept incorporated a caged horizon indicator (see figure 5 above). This concept depicted a ghost horizon line with a single pitch bar displayed on the same side of the ghost horizon line as the true horizon. A ghost horizon is a dashed line with triangles pointing upward toward the sky and extended across the entire field of view of the HUD. A ghost horizon indicates the direction of the actual horizon when the actual horizon is not visible within the HUD field of view. Pilots commented that a constant horizon line was an excellent aid during upset recovery [18]. Neither horizon concept was found to be quantitatively superior.

Ward and Hassoun also integrated horizon lines into their investigation of articulated pitch bars [23]. Pilot participants performed UARs using horizon line concepts with two different lengths. These two horizon line concepts include the F-16 Block 40 horizon line which extends from the airspeed tape to the altitude tape and an extended horizon line that extends the width of the HUD (Figure 10). Reaction time, recovery time, and altitude gain/loss was recorded. No statistically significant differences were found between the concepts. Subjective ratings from the pilots revealed that eleven of the twelve pilot participants preferred the extended horizon line [23].

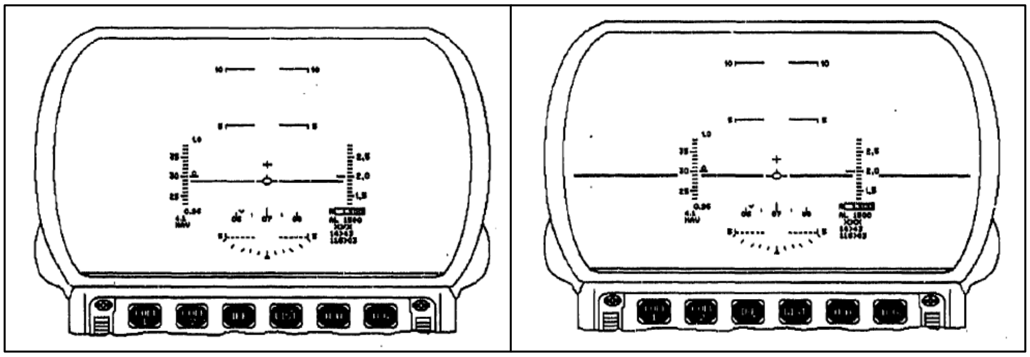

Figure 10: Horizon line concepts: F16 Block 40 horizon line (left) and extended horizon line (right)

Weinstein, Ercoline, and Bitton in 1992 continued research of the ghost horizon concept in a fixed-base simulator [30]. Subject pilots with and without HUD experienced performed an UAR task to investigate the use of a ghost horizon with three different tapered pitch ladder configurations. The six pitch ladder configurations used in this experiment incorporated a ghost horizon and various configurations of tapered pitch bars (Figure 10). The pitch bars were spaced with decreasing distance between lines with increasing pitch angles for tapered conditions. Accuracy of initial stick inputs, reaction time to the initial stick input, and total recovery time were recorded. Tapering of the pitch ladder did not have a significant effect on pilot performance or preference. Seven subjects preferred the ghost horizon, while five subjects did not. Ercoline and Bitton suggested that the mixed preferences of the ghost horizon may have been a result of the triangles attached to the ghost horizon. The triangles are sky pointers, while the ticks on the pitch ladder point toward the horizon. Subjects suggested the removal of these triangles may eliminate confusion. Overall, the use of a ghost horizon increased accuracy of initial response and may be useful for UAR [30].

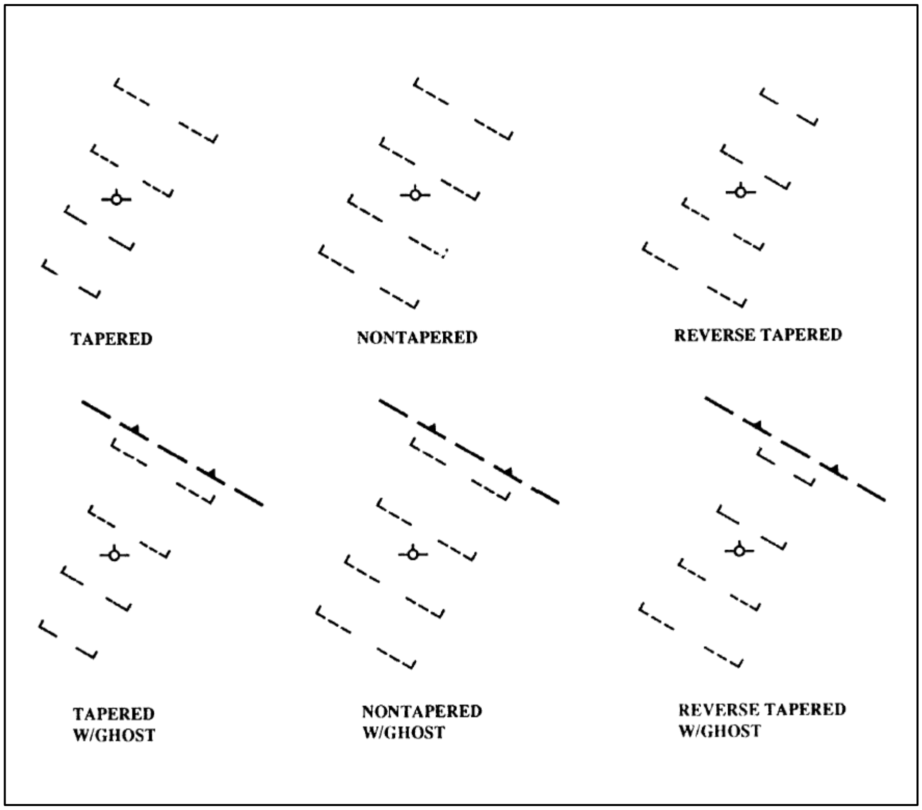

Figure 11 : Tapered Pitch Ladder and Ghost Horizon Concepts

3.1.1.5 PFD Colorization: SV vs. Blue-over-Brown

Beringer, Ball, and Brennan investigated the use of terrain-depicted backgrounds versus a uniformly blue sky over brown ground for performing recoveries from unusual attitudes [31]. In this experiment, 40 general aviation pilots flew upset recovery scenarios using one of three PFD concepts, with or without guidance. The three PFD concepts included a typical electronic attitude direction indicator (EADI), full-color terrain-depicting PFD, and a supplemental brown-terrain condition. Guidance came in the form of pitch or roll arrows and a zero pitch line. Pilots were placed into an upset, then told to recover to zero-pitch, zero-bank attitude. Concepts with a terrain-depicting background showed a tendency toward quicker recovery times. As the results did not show a significant improvement in recovery time, it was concluded that adding a terrain depicting background to the PFD is no worse than the baseline EADI, but may potentially provide for improved recovery times [31].

3.1.1.6 Arc Segmented Reference Symbology

The German Air Force developed an arc-segmented attitude reference (ASAR) symbology (Figure 11), more commonly known as “the orange peel” [32]. The symbology consists of a moving arc that wraps around the flight path marker, with a level attitude indicated by a semi-circle. The goal of the symbology is to help pilots maintain awareness of pitch, bank, and flight path angle, with explicit and obvious full-time reference to the direction of the horizon and the extent of the attitude in either a nose-high/nose-low attitude direction. As the aircraft rolls the arc rotates about the fixed-flight ownship symbol. As the climb increases, the angle area of the arc begins to narrow in proportion to the climb-dive angle. The arc will disappear completely at 90 degrees nose up and form a complete circle at 90 degrees nose down. While much research has been done on the use of ASAR, the results of these experiments are inconclusive.

In 1995, DeVilbiss and Sipes conducted two experiments investigating the use of the ASAR symbology [32]. Pilots experienced a simulated flight scenario that began with the aircraft already in an UA. The pilots had to quickly identify and recover from the upset. The study concluded that some spatial orientation information is valuable. Specifically, some spatial orientation information visible during off-axis viewing can improve the pilot's awareness of spatial orientation information. Pilot preference of the "orange peel" (figure 12) was not reported [32].

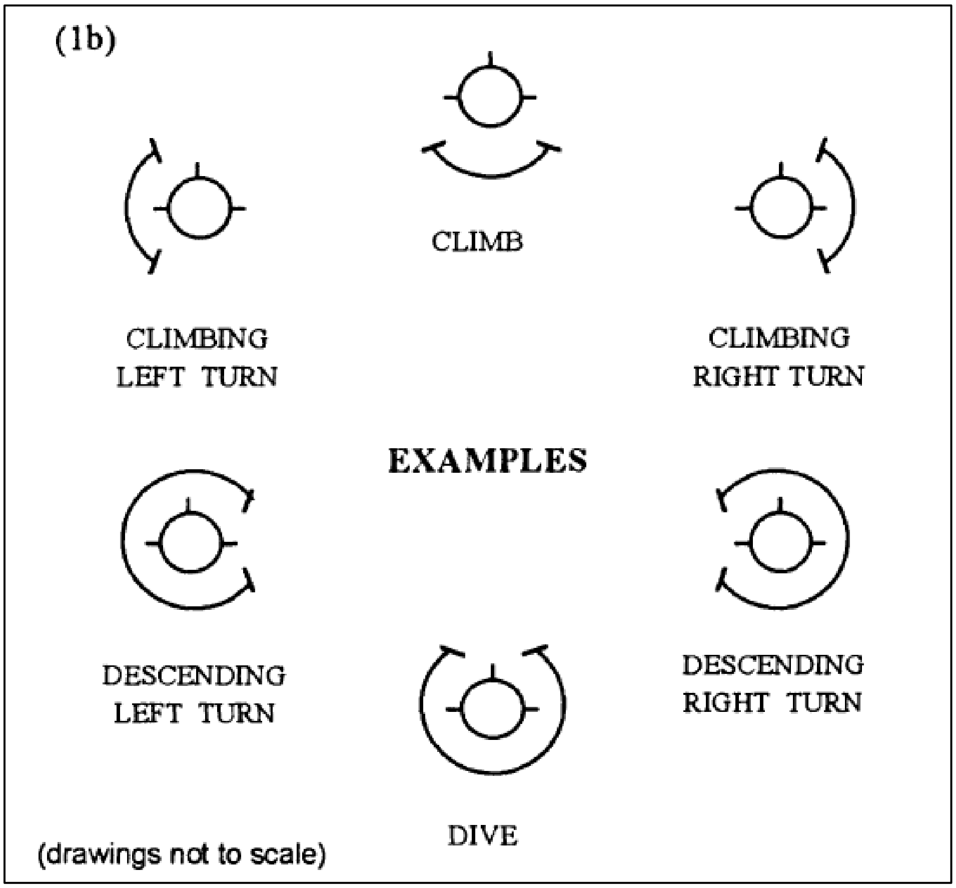

Figure 12: Arc segmented attitude reference

In 2002, Jenkins, Thurling, Havig, and Geiselman incorporated ASAR as part of non-distributed flight reference (NDFR) symbology used in a helmet-mounted display [33]. The NDFR symbology used in this research was in the form of an ASAR in addition to a digital airspeed, heading, and attitude indicator (Figure 13). This symbology was presented slightly below the center of the pilot's field of view for UARs. Ground and flight test research with five student test pilots was conducted to investigate the use of the NDFR for UAR. The United States Air Force NF-16D Variable Stability In-flight Simulator Test Aircraft was used for the flight test. The NDFR symbology was compared to a Mil-Std-1787B HUD symbology. The HUD symbology included a pitch ladder and flight path marker, an airspeed indicator, an altimeter, and heading tape. For a display and symbology to be helpful to a pilot during upset recovery, it must aid recovery and not make it more difficult. Thus, it must be at least as good as current display technology for UAR. For each UAR, speed and accuracy of pilots' first significant control inputs were recorded. Results showed that the NDFR improved the time taken before the first correct input. Subjective feedback revealed that the ASAR used as part of the NDFR allowed for easy recognition of approximate pitch and bank angles. The compactness reduced workload and crosscheck during recovery. However, precise pitch or bank angles were difficult to determine using the NDFR because of the lack of level flight reference. Pilots suggested the addition of trend information and a more defined level flight reference [33].

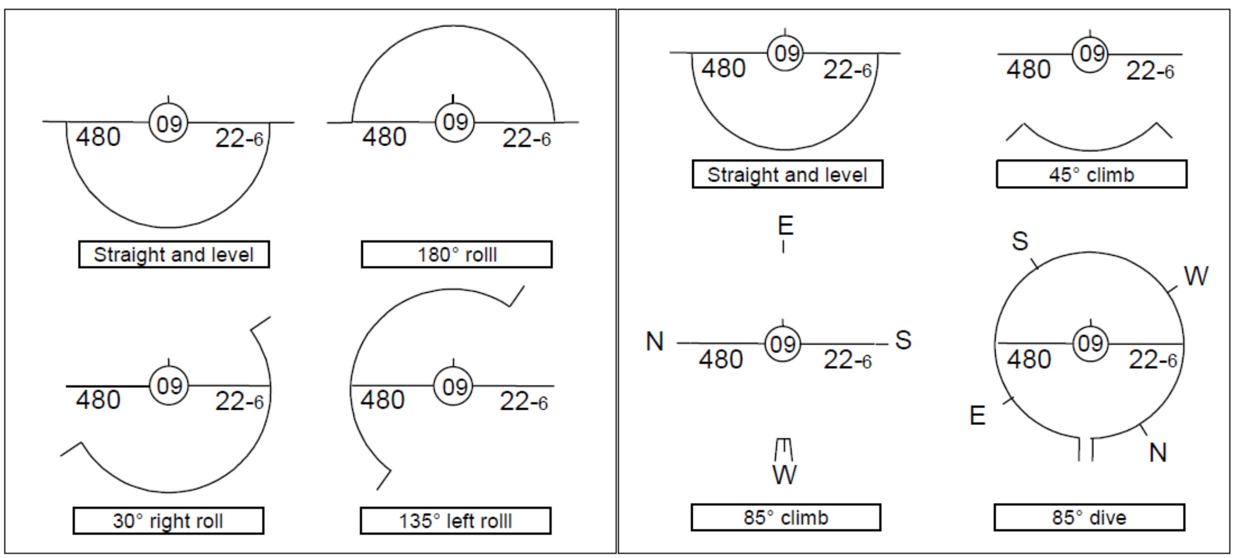

Figure 13: ASAR examples as part of NDFR

Self, Breun, Feldt, Perry, and Ercoline investigated the use of moving horizon (MH), moving plane (MP), and ASAR concepts in 2002 [26]. Fourth year United States Air Force Academy cadets performed daytime and nighttime scenarios as well as UARs in a nighttime scene. The MH display used in this study provided angled dashed lines in nose low attitudes to point the pilot back to the artificial horizon. The MP display used a blinking, dashed line that appeared at the top of the screen to lead the pilot back to straight and level flight. (The MP will be discussed in section 3.1.1.7. The MH concept was discussed in section 3.1.1.1.) The third display, the ASAR display, is an inside-out concept that integrated both roll and pitch information into a single display (Figure 14). The left image of Figure 13 indicates a nose high, banked left attitude, while the right image indicates an inverted flight with left bank, nose low attitude.

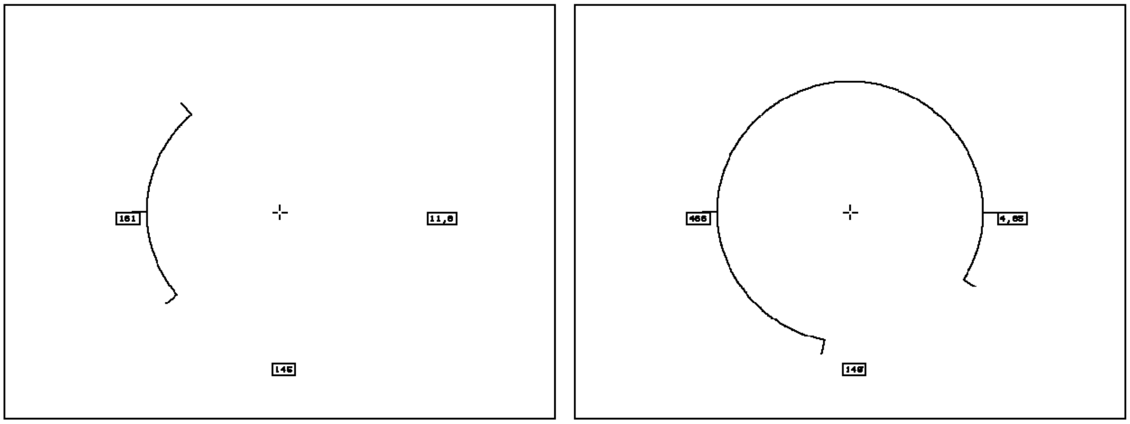

Figure 14: ASAR display

Pilots performed UAR with recorded metrics of time to initial roll input, time to recover to straight and level, and number of roll reversals. Pilots performed better, with faster stick inputs in both roll and pitch, when using the ASAR in comparison to the MH and MP. It provided the smallest root-mean squared error in pitch, although subjective ratings suggested that the ASAR was not preferred by subjects. The authors reported that the poor subjective ratings were due to unfamiliarity with the ASAR concept [26].

Wickens, Self, Andre, Reynolds, and Small also investigated the use of the ASAR symbology in 2007 [34]. This experiment utilized both novice and experienced pilot subjects. The novice group was comprised of students from the United States Air Force Academy. The experienced group consisted of cadets who were soaring instructors, aviation instructors, or held a private pilot license with more than 100 hours of flight experience. Subjects performed UARs using a series of display formats that alternated the use of the ASAR and an attitude indicator icon. Quantitative performance data and qualitative subjective ratings were collected. Participants were asked to rate each display format on a five-point scale according to ease of use, intuitiveness, and if it effectively helped them perform the task. Display preference was also recorded. The ASAR alone was found to be the least preferred display format. It was concluded that the ASAR display may be helpful during off-axis viewing, but not for standard forward-looking HUD symbology [34]. The results of the attitude indicator icon are presented in section 3.1.1.8 below.

Jenkins in 2008 continued his investigation of the ASAR concept [35]. Jenkins' objective was to determine if pilot performance during UAR, vertical banked S-turns, and vertical dive S-turns, and precision Instrument Landing System approaches when using the ASAR as compared to the climb-dive ladder [35]. Ground and flight tests were used to evaluate the three symbology sets. A vision restriction device was used to eliminate the use of the real horizon as an attitude reference during the scenarios. Pilots performed upset recoveries using three different HUD concepts: the ASAR HUD, dual-articulated (DA) HUD, and the standard MIL-STD-1787C HUD (see figure 15).

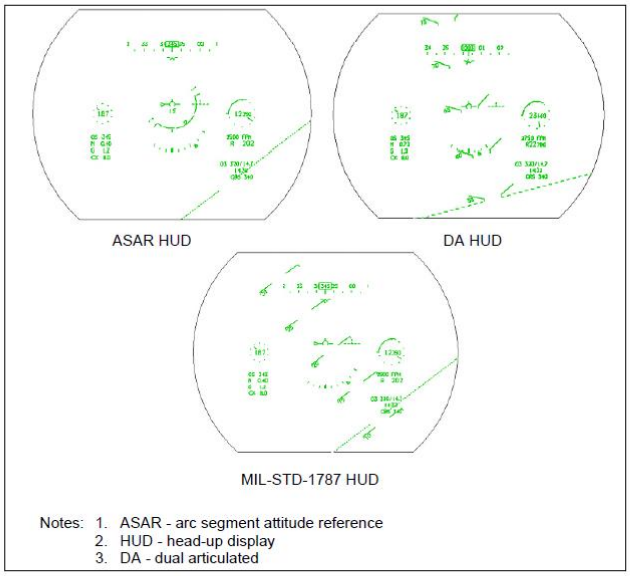

Figure 15: HUD symbology

Statistical significance was found between the reaction times of pilots when using the ASAR HUD rather than that MIL-STD-1787C HUD. The ASAR HUD provided for significantly faster reaction times. No significant differences were found in reaction time when comparing the ASAR HUD and the DA HUD. Pilots reported that all three display concepts were satisfactory and acceptable for performing UARs. The ASAR HUD concept was most preferred by pilots for the completion of UARs [35].

3.1.1.7 Moving Plane

In addition to their research on ASAR and MH, Self, Breun, Feldt, Perry, and Ercoline also investigated the Moving Plane (MP) concept [26]. This concept is a hybrid display with a pitch ladder and airplane symbology indicating the pitch angle and bank angle of the aircraft. Figure 16 shows the MP display when flying nose high, banked right (left), and flying inverted banked right (right). Self and his colleagues mentioned the intuitiveness of the MP concept, in comparison to inside-out displays. Pilots performed initial roll inputs more quickly using the MP display, rather than the MH display while recovering from UAs [26].

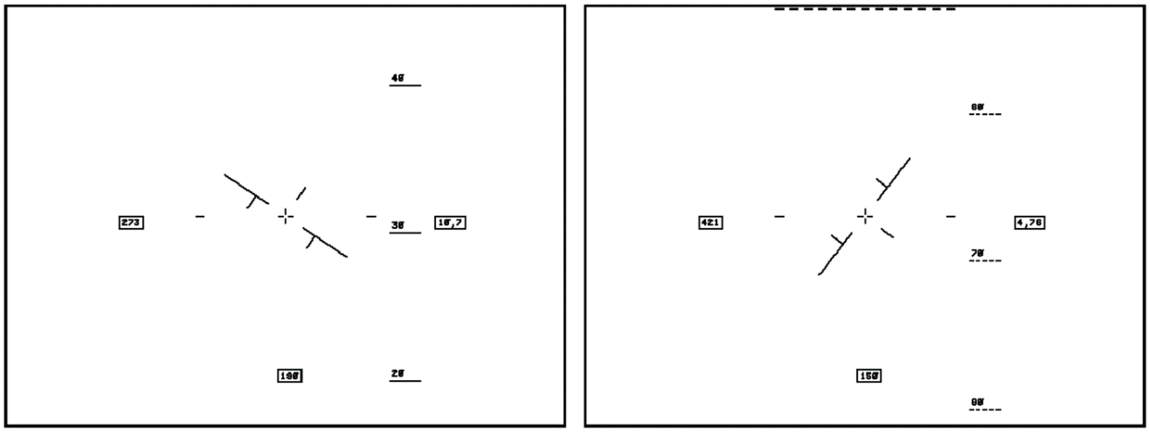

Figure 16: Moving airplane concept

3.1.1.8 Attitude Indicator Icon

Wickens, Self, Andre, Reynolds, and Small also investigated the use of an attitude indicator icon in their 2007 experiment [34]. The attitude indicator icon was presented in the form of a diamond, representing pitch and roll (figure 17). The icon was distorted in shape such that the more acute corner points in the direction in which a correction is required to restore a level attitude as seen in figure 17(b and c). In the case that a correction is required in both bank and pitch angle, the vertical and horizontal corners would be extended and more acute as seen in figure 17(d). The perceived benefits of the attitude indicator icon included the use of a single geometric object as a more conspicuous and perceivable icon. The two dimensional icon permitted the required actions to be more easily understood if a correction in both axes is required. Results of the experiment showed that the icon helped in identification of an upset and reduced the number of roll reversal errors. Pilots were also asked if the icon helped them to effectively accomplish the recovery task. Pilots reported that the command icon was extremely useful for attitude recovery. Wickens and colleagues emphasized the need for the icon to be distinguishable from other symbology. [34].

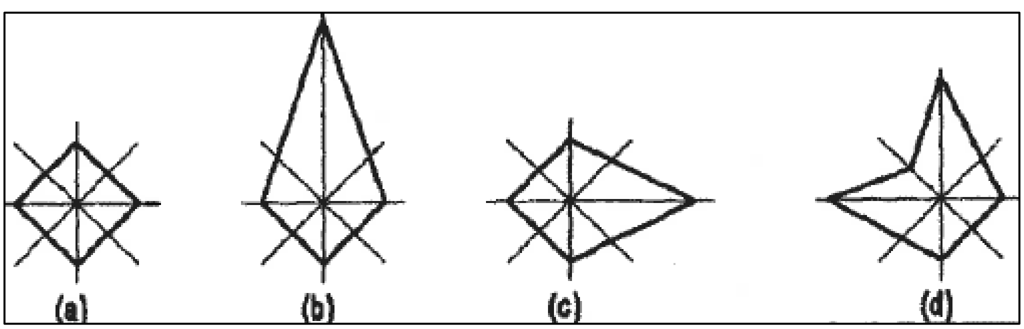

Figure 17: Attitude indicator icon

3.1.2 Enhanced Attitude Displays

Other concepts for attitude awareness have been explored which expand upon or enhance the extent of the visual stimuli typically provided by an ADI. In particular, these display concepts attempt to activate the human's ambient vision as a means to create visual dominance [36]. These concepts investigate displays of aircraft attitude different from typical symbology displays.

3.1.2.1 Peripheral Vision Horizon Displays

The concept of a Peripheral Vision Horizon Display (PVHD) has been around for many years. Originally developed by Malcom in 1983, the display projected a beam of light across the instrument panel that rotated and raised/lowered with the aircraft's bank and pitch attitude. Benefits of this system include that no major hardware changes to current flight instruments are required and pilot workload is not increased [37].

In 1983, Malcolm discussed the need for a PVHD, also known as a Malcolm Horizon (MaH) [38]. He proposed the incorporation of a projector into the flight deck that would display a bar of light across the instrument panel (not pictured). Motors would control the projector and adjust the illuminated horizon bar based on the pitch angle and bank angle of the aircraft. Malcolm stated that this PVHD would allow for enhanced spatial orientation without interruption to normal scan patterns. A pilot would see the bar of light in his peripheral and perceive it as the true horizon outside the plane. Although no specific details were provided, Malcolm described many laboratory and flight tests of this concept. The prototype was flown in a wide variety of aircraft including a DC-8, Cobra Helicopter, and Boeing 747. Forty to fifty pilots participated in these trials and reported that the artificial illuminated horizon reduced the likelihood of disorientation. Malcolm stated that it reduced pilot workload during typical high workload phases of flight. However, specific details of this research were not explained [38].

Gillingham [39] conducted work with the MaH in 1983. For his research, a laser PVHD was installed in a flight simulator. Seven military and seven civilian instrument-rated pilots participated in the study. Subjects flew simulated approaches into Kelly Air Force Base with conventional instruments with and without the MaH. Pitch attitude, roll attitude, turn rate, airspeed, vertical velocity, heading, altitude, course deviation and pilot comments were recorded. Results showed that control of pitch attitude and vertical velocity were consistently better with the MaH than without. Pilots commented that the MaH provided intuitive pitch deviation and bank information. Suggested improvements to the MaH included the addition of a heading reference and a sky pointer [39].

In 2003, Comstock, Jones, and Pope [40] also investigated the use of a MaH in their research using a part-task simulator. Their version of the MaH, a red laser line presented to the left and right of the attitude display, was paired with a fixed reference line that represented the central horizon plane of the airplane. This reference line was expected to provide a point of reference with which to align the MaH for level attitude. It was hypothesized that the addition of an extended horizon line to the attitude display would lead to better performance and the reference line would increase pilot awareness of bank deviations. Twelve volunteers at NASA Langley Research Center participated in the study. Five subjects had pilot-in-command experience on General Aviation aircraft, five reported ground school experience, and two non-pilots reported no formal flight experience or training. Root mean squared error of pitch and bank from the horizon line was used as the measure of performance. Subjective measures were also recorded in the form of the NASA Task Load Index (TLX) and open-ended questionnaires. Results showed an improvement in performance with the addition of the MaH. There was no significant difference in NASA TLX workload ratings by display or extended horizon line conditions. There was no significant difference in performance with or without the reference line. The lack of improvement with the reference line may have been a result of the similarity in colors of the MaH and the reference line [40].

Poonawalla and Braasch [41] of Ohio University also discussed a PVHD in their work in 2007. They suggested that providing adequate information to the pilot for sound decision-making can minimize disorientation. Their version of the PVHD incorporated a synthetic vision display and a strip of light-emitting diode (LED) lights mounted on the side of the windshield. The strip of lights displayed bank angles up to 28 degrees. They hypothesized that the use of this system would help minimize spatial disorientation and aid pilots in UAR. A flight test was conducted to evaluate this hypothesis. Results showed that the PVHD provided at least equivalent situational awareness to traditional instrument systems. However, the display of LED lights provided insufficient bank angle information; indeed, the lights displayed minimal bank angle information when compared to the 60 degree bank angle displayed by current systems. It was concluded that there was not enough evidence to state that the PVHD performed better than traditional systems [41].

In addition to the work of the authors above, new technologies and implementations of the PVHD are emerging today. The Green Orientation Light or "GO Light" is a cockpit lighting system providing a field of light across the cockpit giving pilots a constant point of reference to the horizon and airplane attitude within their peripheral vision [42].

3.1.2.2 Background Attitude Indicators

Similar to the PVHD described above, researchers have investigated the use of a Background Attitude Indicator (BAI) for attitude awareness. The BAI concept is directly analogous to the Malcolm horizon but the implementation is within the display itself. The extent of the BAI is therefore confined to the extent of the displays/instrument panel, around the periphery of the instrument displays. The BAI is, however, theoretically easier to implement than the PVHD.

Dawson and Spengler first developed a BAI in 1988 where they drew an electronic boarder on a display surface for attitude indication. The border area provided a white horizon line with blue sky, brown ground. Pilot participants evaluated the BAI and concluded that roll deviations were easily detected, however, pitch deviations were not easily recognizable. This was because at high pitch attitudes and low pitch attitudes, pilots saw solid blue or solid brown respectively with no altitude cues for correcting to straight and level flight.

Liggett, Reising, and Hartsock [43] made improvements to this concept, adding a ghost horizon, attitude information, and aircraft wings. A series of three studies was conducted in order to evaluate the improved concept.

The first study investigated the best way to present attitude information to assist in recovering from unusual attitudes. Color shading, color patterns, and pitch lines with numbers were investigated. Color shading provided gradual shading from light blue to dark blue for positive pitch and light brown to dark brown for negative pitch. As pitch increased or decreased away from the 0 degree line, the darker the color would become. The color patterns involved vertical wedges, with the thinnest portion of the wedge being closest to the horizon and the widest portion of the wedge being at the 90 degree pitch up and 90 degree pitch down attitudes. Pitch lines with numbers were add at 10 degree increments [43].

Sixteen military pilots performed unusual attitude recoveries in a single seat fighter cockpit simulator. 8 combinations of features were tested:

1. The common features (ghost horizon, attitude information, aircraft wings)
2. The common features with color shading
3. The common features with color patterns
4. The common features and pitch lines with numbers
5. The common features with color shading and color patterns.
6. The common features with color shading and pitch lines with numbers
7. The common features with color patterns and pitch lines with numbers
8. The common features with color shading, color patterns, and pitch line with numbers

Initial input time and total recovery time was recorded for all scenarios. Although statistical analysis found that performance was best when color shading and color patterns were used in combination, differences were not operationally significant. Pilots commented that the shading and wedge-shaped patters provided for immediate indication of the attitude of the aircraft.

The second study compared the BAI with color shading with the baseline BAI and the Dawson-Spengler BAI [43]. The same subjects, procedures, and metrics from Study 1 were used. The BAI from Study 1 allowed for significantly faster reaction times than the EAI. The BAI from Study 1 also provided for quicker initial inputs than the Dawson-Spengler BAI.

The third of the three studies investigated the use of a BAI across three horizontally adjacent head-down displays [43]. Five BAI formats were investigated, including redundant BAI cues, continuous BAI cues, and features recommended by participants of Study 1 and Study 2. Once again, the same subjects, procedures, and metrics from Studies 1 and 2 were used. Redundant BAI cues provided a repeat of the BAI behind each of the three displays, while the continuous BAI cues provided one continuous BAI across the three displays. Results showed no significant difference between the formats, however, pilots preferred the continuous format. Pilots commented that this format provided for excellent peripheral bank cues.

From these studies, it was concluded that the use of a BAI may be beneficial for presenting attitude information and may enable pilots to recover from unusual attitudes. The importance of visual cues that help the pilots to detect motion and more quickly recover from unusual attitudes was emphasized [43].

Although these studies found that a BAI may be beneficial, further research is still needed. The reference point of the BAI is still an area to be investigated especially for side-by-side, two seat installations. Bailey, Ellis, and Stephens [44] point out that, to date, an inside-out design spanning the entire cockpit may not aid in eliminating attitude interpretation problems. To answer this questions, researchers at NASA Langley Research Center have developed a BAI (Figure 18). In Figure 18, the reference point of the BAI is the left-hand PFD which creates a confound for the right-hand PFD. Alternative references need to be explored. In addition, the level of sufficient detail of the synthetic scene and appropriate field of regard for the visual area necessary to provide pilots all the information necessary to maintain correction orientation is yet to be determined.

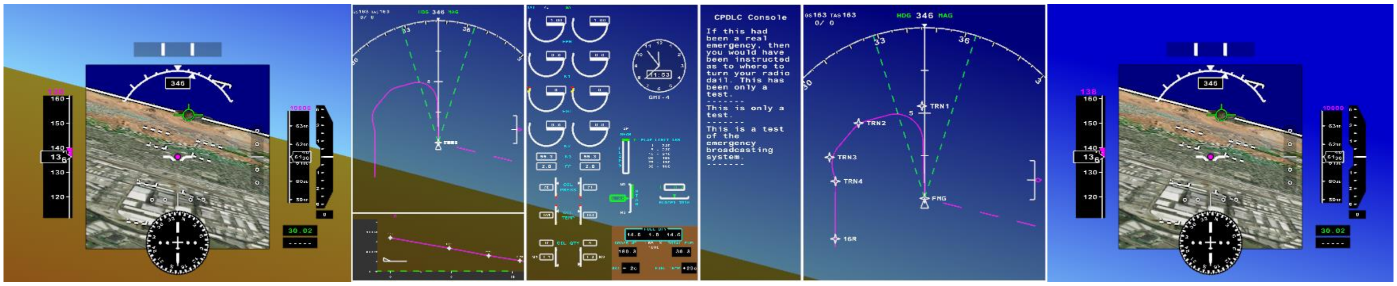

Figure 18: NASA LaRC BAI Experimental Concept

3.1.3 Pitch Chevron

In addition to the importance of understanding the orientation of the horizon line (zero pitch attitude reference), extreme attitude conditions and nose-up/nose-low orientation can be perceptually powerful and support control guidance.

The work of Taylor indicated that the nadir and zenith symbols provided perceptually powerful indicators for nose-up/nose-low orientation [29].

Similarly, many PFDs now include chevron symbology to indicate approaching upset attitudes in commercial aircraft operations. For instance, Chelton Flight Systems [45] provided a pitch chevron on the PFD (Figure 19). This version of the pitch chevron is displayed when pitch exceeds plus or minus 25 degrees.

FedEx has included a pitch chevron as a part of their UA HUD symbology [47]. The pitch chevron is an upward or downward pointing “V” icon that is attached to the pitch ladder (Figure 20). The chevron points in the direction of level flight. The points of the chevron are located at 25 degrees pitched up and 12.5 degrees pitched down to aid in recovery from nose high and nose low UA conditions.

Figure 19: Pitch Chevron Example

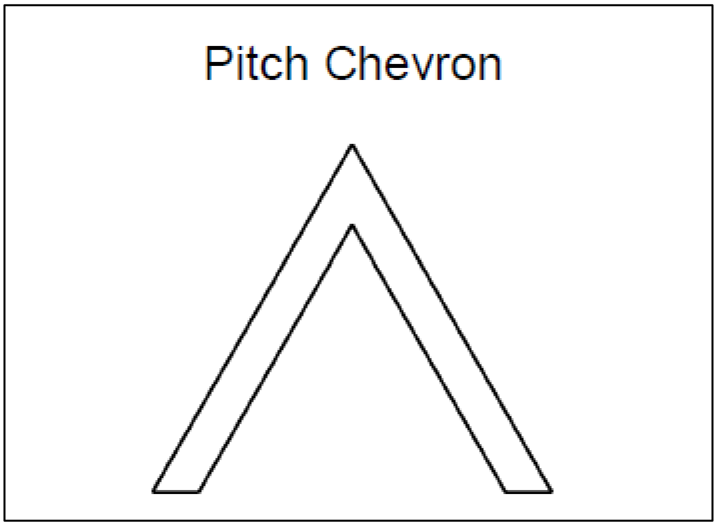

Figure 20: FedEx Pitch Chevron

3.1.4 Aircraft State Awareness Symbology

Aircraft attitude is a necessary, but perhaps not sufficient, element by which to maintain an understanding of an aircraft energy state and to effect correct UA awareness and recovery. The flight crew's awareness of the aircraft angle-of-attack, trim, and thrust conditions are also of critical importance.

The following outlines various displays of these critical aircraft state parameters which significantly influence aircraft state awareness.

3.1.4.1 Angle-of-Attack Indicators

Angle-of-attack (AOA) indicators are one kind of technology that has been proposed to aid pilots in the ability to avoid, detect, and recover from UAs. (See Le Vie, 2015 for an intensive review of the use of AOA indicators [46]). Research for AOA indicators has been ongoing since the 1950's. Providing pilots with an AOA indicator allows for easy detection and recognition of approach-to-stall and stall attitudes. A gauge and digital readout provide the pilot with the actual angle of the wing and trend information including an indication of the stall warning activation and ideal approach AOA.

The attitude awareness benefit of displaying AOA in the cockpit has prompted many aircraft manufacturers to offer AOA indicators as an option on their aircrafts. AOA indicators may be visible both from the left and right pilot seats, and may be displayed either in an analog or digital format. Some manufacturers display the AOA indicator in the corner of the Primary Flight Display (PFD) or HUD in the form of a gauge and digital readout, such as seen in the Boeing fleet (Figure 21). Color is sometimes used when displaying AOA to indicate approach-to-stall or stall angle.

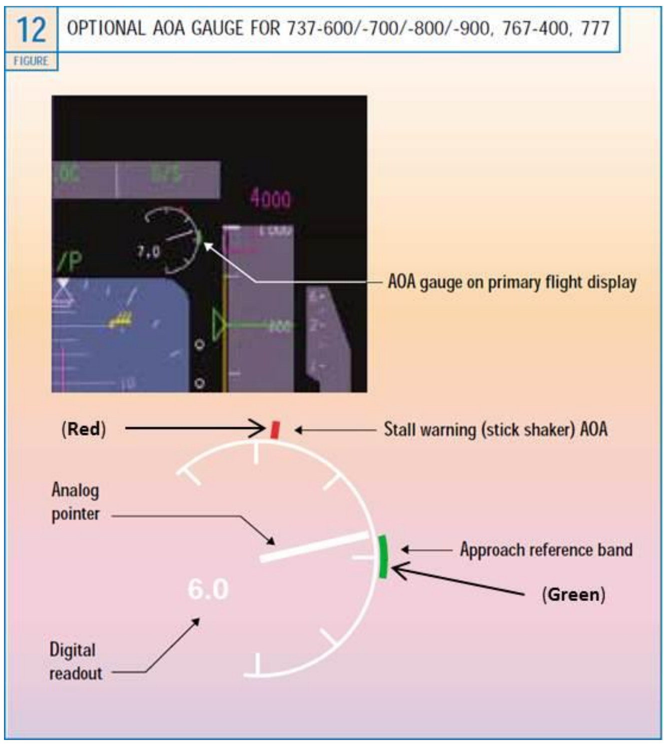

Figure 21: Boeing AOA indicator

AOA indicators vary from aircraft to aircraft, with some aircraft not displaying an AOA indicator at all. Although aircraft manufacturers provide options for AOA indicators, research supporting the use of these indicators during pitch axis upsets was not found. AOA research from the 1950s to the 1980s suggests the need for further research on these indicators and UAR.

3.1.4.2 Pitch Limit Indicator

FedEx, Boeing, and Airbus have incorporated an AOA Limit Indicator, also known as a pitch limit indicator (PLI), as part of the HUD symbology for their fleet of aircraft (Figure 22). The FedEx symbology shows the AOA limits of the airplane and appears when the AOA is within 3 degrees of stick shaker activation. The AOA Limit Indicator moves closer to the flight path marker as the AOA increases. Stick shaker activation is reached when the AOA Limit Indicator lines up on the wings of the flight path marker [47].

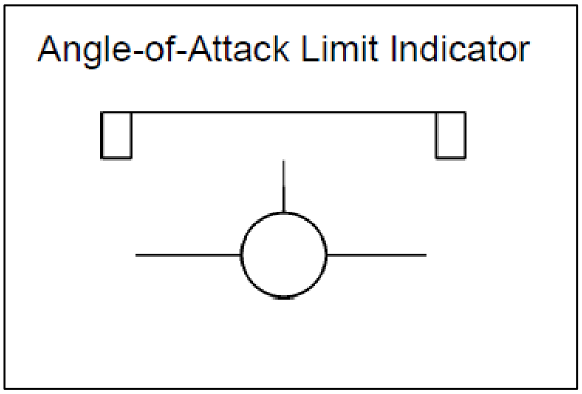

Figure 22 : FedEx AOA Limit Indictator

The Gulfstream cockpit also incorporates a PLI (Figure 23). This version of the PLI – analogous to Boeing and Airbus pitch limit indicators - consists of two horizontal lines with three angled “cat whiskers” attached to either end. Similar to the FedEx AOA Limit Indicator, this symbology moves vertically down the pitch tape as the AOA approaches stick shaker activation [48].

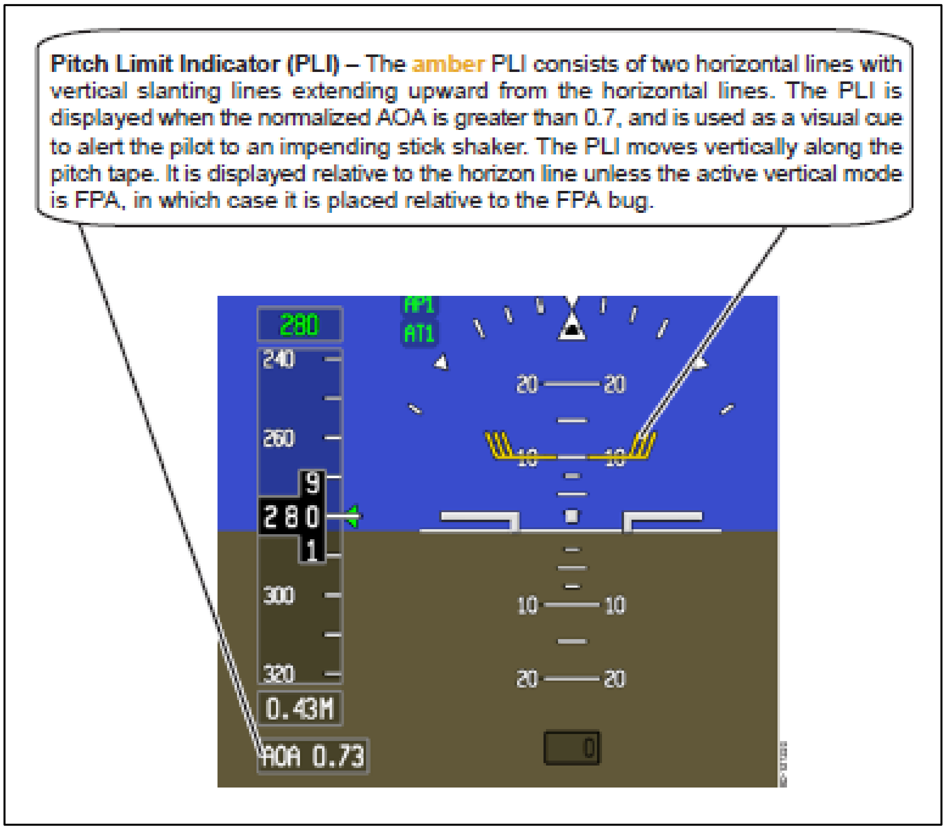

Figure 23: Pitch Limit Indicator

3.1.4.3 Airspeed/Attitude Scales

The aircraft’s energy state is obviously a direct function of the aircraft’s altitude and airspeed. Intuitive understanding of these parameters by the flight crew is critical.

Newman in 1988 was also interested in variations in airspeed and altitude scales on the HUD [21]. He compared six scales: baseline digital, analog, digital surrounded by analog minute hands, enhanced minute hands, analog to digital during UAs, and automatic deletion during UAs. Recorded metrics included control position, airspeed, heading, pitch and roll attitude, and subjective measures. Subjective questionnaires asked pilots to rate each symbology for ease of maintaining orientation, ease of recovery, and symbology appropriateness. The use of digital scales was supported both by faster reaction times and positive pilot preferences [21].

The Airspeed Trend Vector (Figure 24) is in use across state-of-the-art PFDs to also aid in speed control and understanding aircraft energy state [47]. This indicator displays an upward or downward pointing arrow attached to the airspeed odometer point. An upward arrow indicates acceleration, while a downward arrow indicates deceleration.

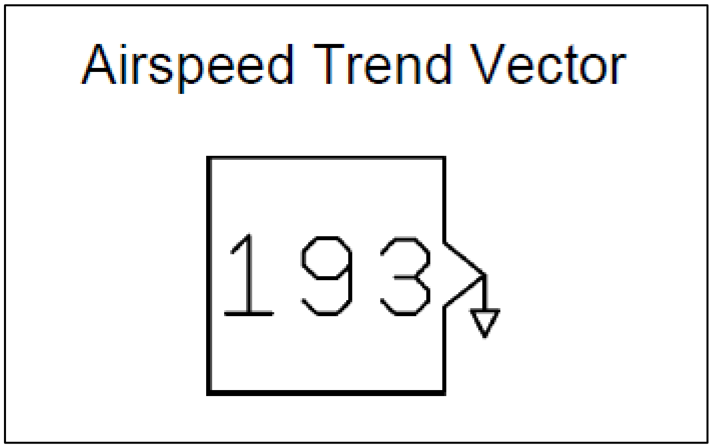

Figure 24: Airspeed Trend Vector

This trend information is also complemented with the ‘barber poles’ which indicate low speed and over-speed conditions to the flight crew as well as flap limit speeds.

3.1.4.4 G-Meter

The load-factor during an upset or recovery certainly affects the energy state of the aircraft. Ward and Moreau discussed the use of g-meters in their work to develop training maneuvers and programs that would aid FedEx in more complete training of their pilots in upset recovery techniques [6]. FedEx found that because of a lack of g-cues, pilots often tend to over-correct and over-control recovery efforts during full-flight simulation training. FedEx found the g-meter used during training could effectively serve as a form of pitch guidance for upset recovery.

The FedEx g-meter depicts the g-load of the airplane with a large-font, digital read out located below the airplane attitude reference on the HUD (Figure 25). The training maneuvers, including UARs and upset event recoveries, were tested on twenty FedEx line pilots in a full-flight simulator and in aircraft with a g-meter installed. The installation of the g-meter aided pilots in making smaller inputs throughout upset recovery maneuvers during simulator training. Without the g-meter, pilots tended to make inappropriately larger control inputs in an effort to expedite the recovery. Pilot awareness, performance, and ability to recover were recorded. The test showed that pilot inputs were more immediate and precise as a result of the g-meter. G readouts reduced control input magnitudes while allowing for timelier control inputs.

Further research found that the addition of the g-meter improved pilot performance during upset recoveries in an airplane as well. Pilot inputs without the g-meter were typically too slow and too small – resulting in slower recoveries and more low speed or overspeed excursions. With the g-meter, the control inputs were more immediate and precise. G readouts improved control input magnitudes while allowing for timelier control inputs [6].

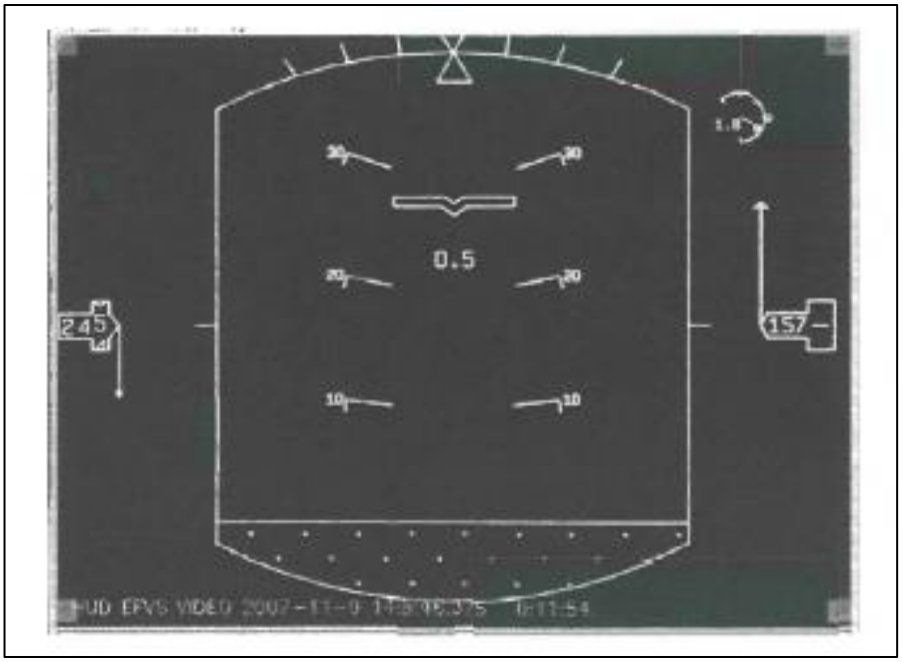

Figure 25: FedEx G-Meter

3.1.4.5 Thrust Indications

AC 120-111 points out that clear understanding of energy state is critical to the pilots' understanding of how to recover an aircraft from an unusual attitude. The result of thrust application can obviously be derived from the airspeed indications on the primary flight instrumentation; in contrast, a direct thrust indication on the primary flight instrumentation is one aspect of energy state that may enhance the pilot's understanding [5].

A Flight Path Acceleration Cue (FPAC) and Airspeed Trend Vector displayed on the HUD aids in thrust indication for pilots. The FPAC (Figure 26) is a right-pointing empty arrowhead, or caret, displayed to the left of the flight path vector. When the FPAC is above the flight path vector, the aircraft is accelerating. When the FPAC is below the flight path vector, the aircraft is decelerating. Although not directly a throttle or thrust indicator or command symbol, the FPAC was designed to aid pilots in speed control and understanding aircraft energy state [47]. The symbology movement is directly influenced by the throttle / thrust level.

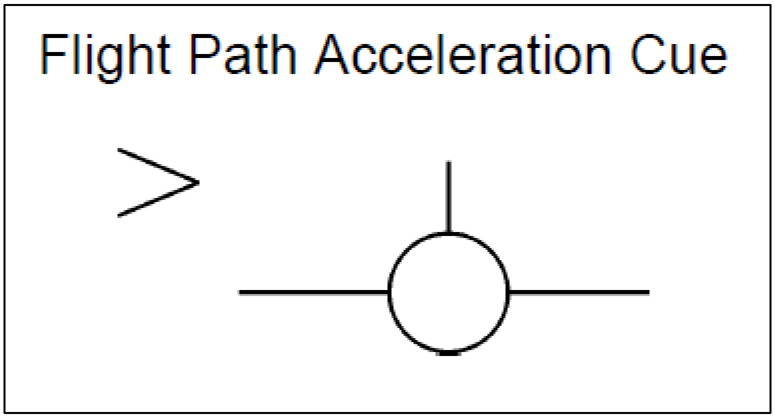

Figure 26: Flight Path Acceleration Cue

Wyatt of Honeywell International Incorporated patented an aircraft display with potential thrust indicator in 2002 [49]. Wyatt's system displays potential thrust to the left of the pitch ladder and horizon line. Although no publicly available research was found supporting this system, in this patent, Wyatt stated that the potential thrust indicator could allow pilots a means of setting engine power to a desired level to achieve a desired flight path and acceleration. The potential thrust indicator is comprised of throttle indicators (Referenced in Figure 27, as 180 and 190) and a maximum thrust limit indicator (Referenced in Figure 27, as 170) [49].

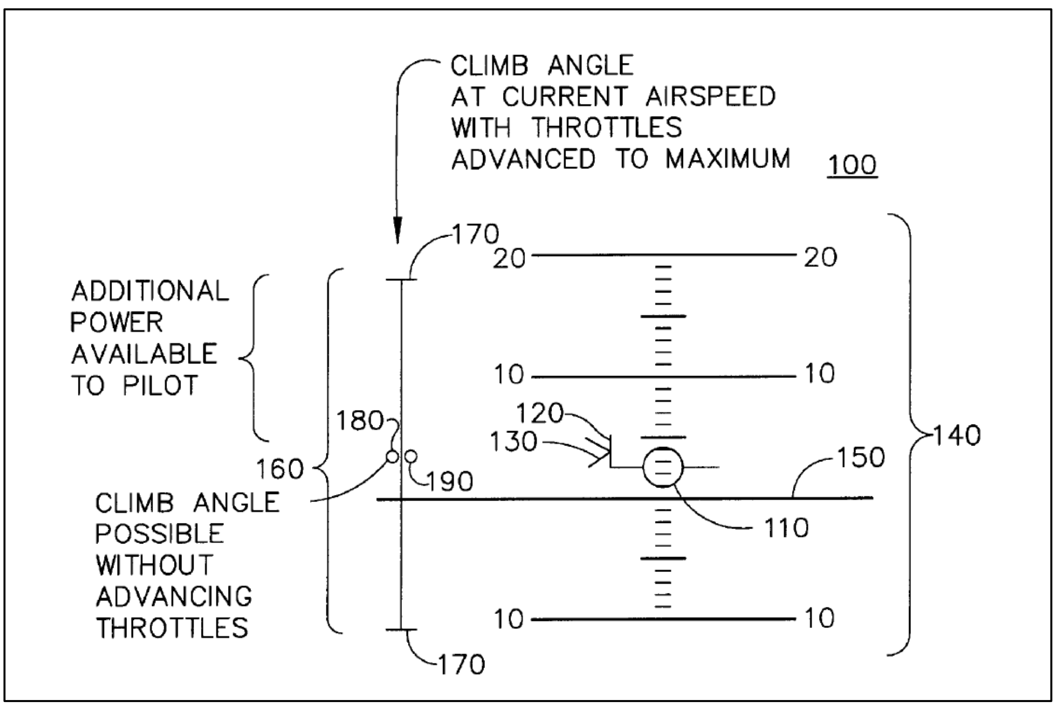

Figure 27 : Thrust Indicator

This symbology provides information about the limitations of the engines and an indication of engine failure. When an engine has failed, an "x" is displayed as the given engines thrust indicator (Referenced in Figure 28, as 190). In this patent, Wyatt explained that providing this information to the pilot may increase understanding of the aircraft's climb capabilities given that an engine has failed. This system aims to provide pilots with the information necessary to set appropriate climb or descent angles of the aircraft. No publically available research was found to support the use of this system [49].

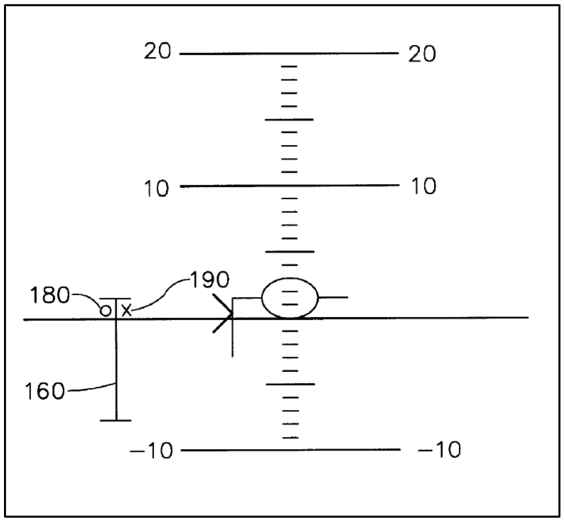

Figure 28 : Engine Failure Indication on Thrust Indicator

As found on current aircraft, the Engine Indication and Crew Alerting System (EICAS) provides pilots with thrust indications and knowledge of engine status [50]. These data are not shown on the primary flight instrumentation, but the EICAS displays do provide a wealth of critical engine data on temperature, fuel flow, fuel quantity, and engine vibrations. The EICAS also includes a

Figure 29: Boeing 757 EICAS

Caution Alerting System (Figure 29). Aircraft system data is displayed graphically on the EICAS. This system improves reliability and simplifies the flight deck, while reducing crew workload by employing easily interpreted graphical images. The EICAS continually monitors aircraft state data for unusual conditions and notifies the pilots when these conditions occur [50].

3.1.4.6 Stabilizer

Schwartz of Bodenseewerk Gergtetchnik, a German defense and technology company proposed pitch trim indicator in the early 1970's [51]. Schwartz patented a directional and pitch trim indicator in 1970. The indicator was in the form of a square set of four lights as seen in Figure 30. The indicator lit up vertically for directional mistrimming and horizontally for pitch mistrimming on the respective side of the mistrimming. In the case of a simultaneous pitch and directional mistrimming, three lamps lit up. The indicator aimed to provide the pilot with an indicator of a mistrimming at a simple glance. An option for blinking lights was provided to make the signal difficult to overlook [51]. No research was found to support the use of this system.

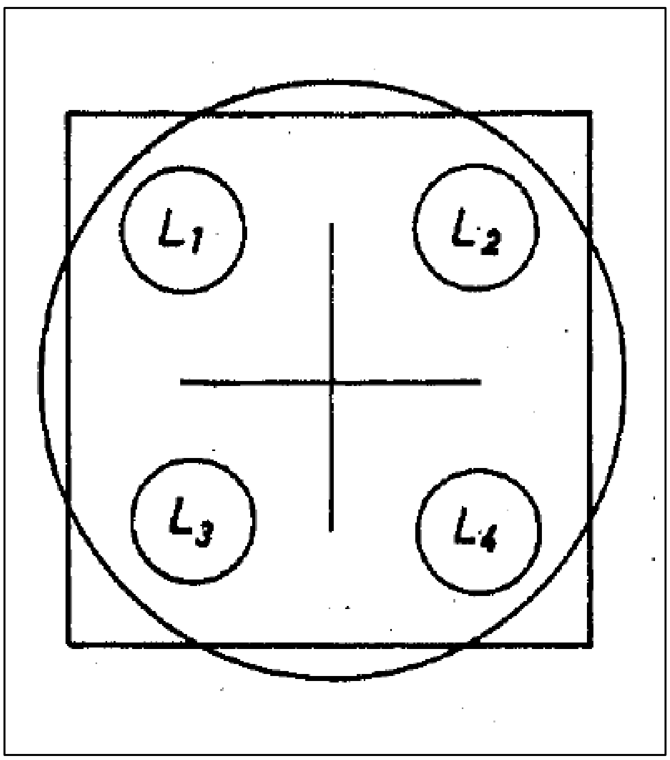

Figure 30: Pitch trim indicator

Niedermeir and Lambregts noted that it is crucial for pilots to be aware of the horizontal stabilizer position for flight safety. They point out that it is of high importance to find adequate means for alerting the pilots to current stabilizer position and the need for manual trimming [52]. AC 120-111 supports the notion that understanding energy state is key in UAR. Knowledge of stabilizer position will enhance the pilots' knowledge of the airplane's energy state.

Both Airbus and Boeing have stabilizer trim functions that automatically offload the elevator [52]. Airbus and Boeing vary in the way that the crew is informed of the horizontal stabilizer position. On the Airbus, the position is displayed below the PFD and is also available on the flight controls page of the Electronic Centralized Aircraft Monitor. In the case of a loss of automatic stabilizer trim function, an alert informing the crew to "USE MAN PITCH TRIM" is indicated on the PFD. Similarly, on the Boeing 777, the horizontal stabilizer position is indicated by the Stabilizer Position Indicator located to the left of the Alternate Pitch Trim Levers on the center pedestal. The horizontal stabilizer position is also indicated on the flight control synoptic page of the multifunction display [52].

3.2 Upset and UA Alerting

Attitude symbologies and upset/UA recognition symbology are designed to create immediately discernable attitude recognition. If this symbology does not provide sufficient awareness to the pilot to prevent approaching an UA or an upset condition, a caution may be used to alert the pilot of approach conditions. The FAA defines a caution as "a condition that requires immediate flight crew awareness and subsequent flight crew response" [14]. A caution alert should provide awareness and encourage flight crew response prior to the onset of a time-critical warning. Cautions are to be displayed in an amber or yellow color [13].

The literature review uncovered research investigating aural alerts, visual alerts via changes in symbology which trigger the equivalent of an alerting mechanism, and both.

Also, several of the symbology concepts provide arrows or symbology indicating to the pilot the direction of the nearest horizon or a level flight attitude. Although one might be tempted to consider this information as "pitch control guidance", this information is really situation information since it does not direct the pilot in the manipulation of the control inceptors to follow a course of action.

3.2.1 Aural Alerts

Rockwell Collins investigated the use of audio cues for conveying aircraft attitude in one simulation experiment and two flight tests [53]. For the purpose of the simulation experiment and first flight test, an audio system that simulated the wind noise a pilot would hear when flying a glider was used. Loudness and frequency varied with speed to alert the pilot of his attitude. High frequencies denoted high speeds, while low frequencies denoted low speeds. Louder noise in the pilot's left ear indicated a left bank, whereas a louder noise in the pilot's right ear indicated a right bank. The pilot would hear no noise given that he was level, and on-speed. From results of the simulation and initial flight test, the system was not found to be successful as pilots indicated they often ignored the audio cues when other cues were available.

For the final flight test, alerts were modified to provide verbal alerts in the form of status and command information to aid recovery from UAs. The alerts were designed to help pilots identify the onset of an UA when set flight parameters were exceeded. Results showed that this type of system was helpful for UAs along a single axis, however, did not offer benefits for recovery from UAs along multiple axe [53].

Conner, Feyereisen, Morgan, and Bateman also investigated the use of aural alerts in conjunction with attitude recovery arrows (discussed in Section 4.3.1). These alerts cautioned pilots to "pitch up," "pitch down," "roll left," or "roll right". However, pilot preferences and statistical results were not reported for the aural alerts [54].

3.2.2 Symbology Changes

Some researchers have studied the addition or deletion of certain pieces of symbology during UAs to alert the pilot of an UA. The deletion of symbology works to alert the pilot and declutter the display for easier recovery. The addition of symbology elements works to alert pilots to an UA state.

Newman investigated the deletion of the velocity vector during UAs as a part of his velocity vector and pitch cue research in 1988 [21]. The concepts tested included a baseline waterline and velocity vector, a velocity vector only, a waterline only, and automatic deletion of the velocity vector at high AOA. Automatic deletion of the velocity vector provided quickest reaction times and fewest number of incorrect responses for an UA. Subjective preferences also supported the use of the automatic deletion of the velocity vector [21].

The addition of symbology to the HUD may also alert pilots of an UA. Much of the alerting symbology and command guidance outlined appears on the HUD once certain parameters are surpassed.

The pitch chevron, discussed in Section 3.1.3, appeared at unusual pitch attitudes of 25 degrees pitched up and 12.5 degrees pitched down [47]. Researchers have discussed symbology additions for UAs, however, the exact parameters under which the symbology would appear were not outlined.

The Rockwell Collins HGS HUD, as installed aboard the FedEx 757-200 airplanes (as well as others), incorporates an UA display that automatically appears when the aircraft enters one of the following conditions:

- Greater than 29 degrees pitch-up attitude
- Less than -12.5 degrees pitch-down attitude
- A roll angle of greater than +55 degrees

The change in symbology under these conditions alerts the pilots of an UA. This display works to enhance pilot awareness and recognition of UAs and aids pilots during recovery procedures. The display includes a large circle that replaces standard symbology with UA symbology in a manner that is similar to an attitude indicator (figure 31). The display contains a horizon line, ground lines, roll scale, and pitch scale. The horizon line indicates the zero degree pitch line and is parallel to the horizon. The ground lines extend from the horizon line at an angle to give the perspective view of the ground. These ground lines represent the brown area on a typical attitude indicator. The pitch scale ranges from 90 degrees pitched up to 90 degrees pitched down with a zenith symbol and nadir symbol displayed at the outer limits respectively [47].

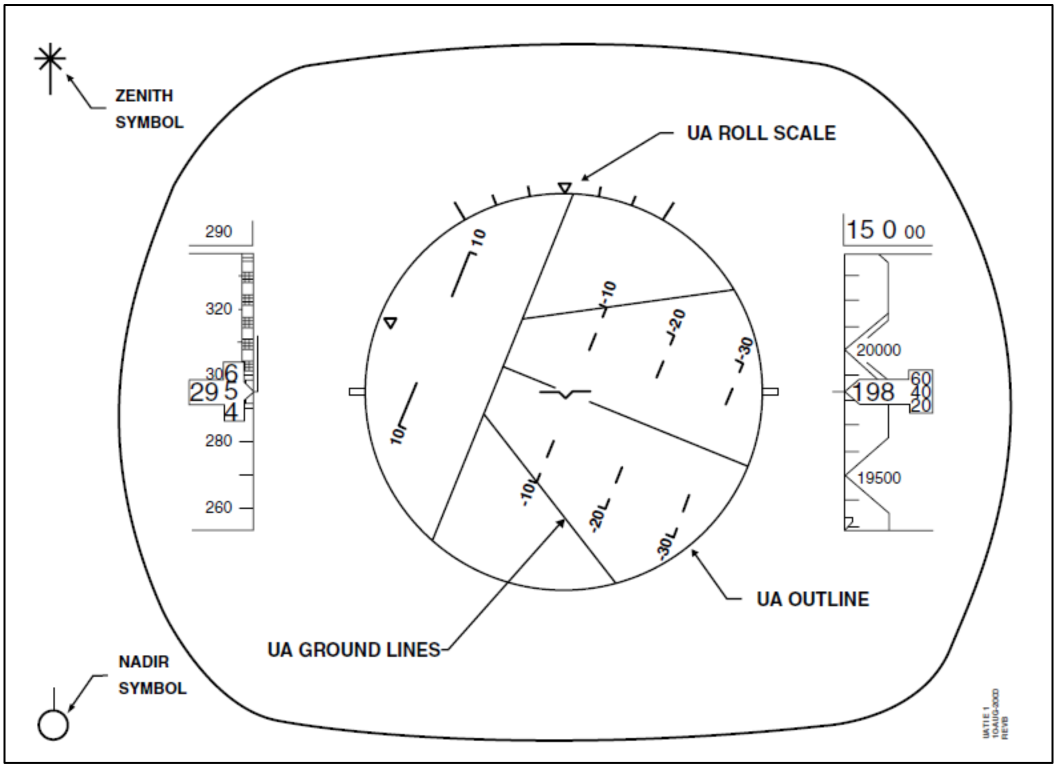

Figure 31: Unusual attitude display

3.2.3 Attitude Recovery Arrows

Researchers have investigated the use of arrows on the PFD or HUD for alerting and situation guidance to inform pilots the correct direction to roll or pitch to recover from an UA.

Gershzon examined the use of roll arrows for UAR in 2001 [55]. The roll arrow concept in this experiment was large, red, and attached to the PFD bank angle pointer (Figure 32). The roll arrow indicated the shortest direction to roll to achieve wings level attitude. Gershzon found that performance was significantly better with the roll arrow than without. Reduced hesitation, roll reversal, and confusion were also reported when the roll arrow was used. Pilots subjectively reported that the arrow was helpful in providing a roll solution [55].

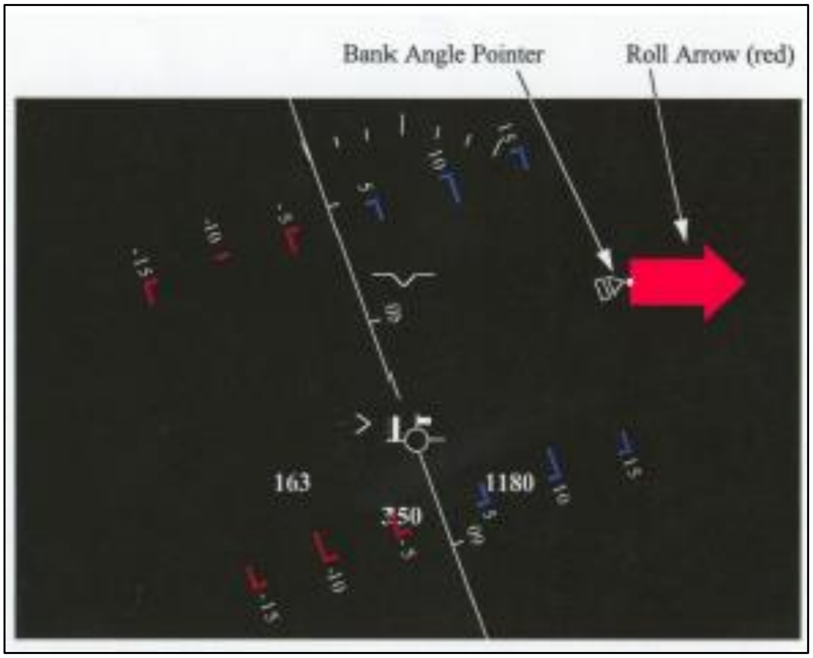

Figure 32: Roll arrow

Beringer, Ball, and Brennan found different results when incorporating a roll arrow into symbology in their 2005 experiment [31]. In this experiment, 40 general aviation pilots flew upset recovery scenarios using one of three PFD concepts, with or without guidance. The three PFD concepts included a typical electronic attitude direction indicator, full-color terrain-depicting PFD, and a supplemental brown-terrain condition. Guidance came in the form of pitch or roll arrows and a zero pitch line (Figure 33). Pilots were placed into an upset, then told to recover to zero-pitch, zero-bank attitude. Pilots indicated that they focused on the zero pitch line that was depicted on the displays as it was easily distinguished from other symbology no matter the terrain concept. The white zero pitch line was haloed in black to enhance the contrast of the symbology. Pilots reported the zero-pitch line to be helpful in recovery and that they preferred terrain depicted displays. Despite positive pilot responses, a decrease in total recovery time was not found. The frequency of reversals was too low to draw any conclusions [31].

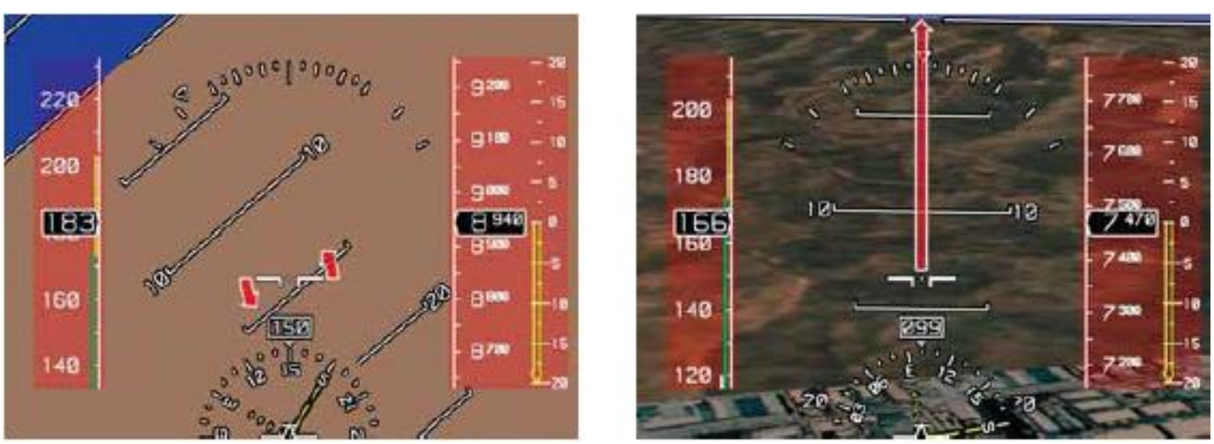

Figure 33: Roll and pitch arrow

Conner, Feyereisen, Morgan, and Bateman also investigated the use of arrows in upset prevention and recovery in 2012 [54]. This work investigated roll and pitch arrows to be integrated into the flight deck to reduce the likelihood of an upset, while also helping pilots recover from an upset event. The examined concepts included attitude arrows, synthetic vision displays, flap settings, and low airspeed conditions. Attitude arrows indicated to the pilot the need to roll or pitch to correct the attitude of the airplane to prevent an upset event or to recover from one. For this concept, arrows were attached to the wing symbology on the PFD (Figure 34). A roll arrow arc indicated which direction the pilot should roll the airplane to correct a bank angle. Two pitch arrows were attached to each wing, extending up or down in the case of a low or high pitch angle, respectively. The color of the arrows was altered depending on the severity of the pitch or bank angle. Cautionary arrows were yellow, while warning arrows were red. Aural alerts accompanied the arrows. Aural alerts cautioned pilots to “pitch up,” “pitch down,” “roll left,” or “roll right.” These concepts are believed to aid in recovery; however, statistical results and pilot preference were not reported [54].

Figure 34: Roll arrow for upset recovery

3.3 Pitch Control Guidance for Recovery

In the instance that advisory and cautionary alerting does not prevent the pilot from entering an UA, an approach-to-stall, or stall, warnings and command guidance may be appropriate to notify and aid the pilot in recovery.

CFR 25.1322 defines a warning as “a condition that requires immediate flight crew awareness and immediate flight crew response” [14]. AC 25.1322-1 emphasizes the need to be consistent in the display of warnings [13]. Red is used consistently to indicate a warning. Warning alerts are displayed when immediate action is necessary. Pilot awareness must be gained and immediate action taken in order to recover from the UA and/or an eminent stall. The warning symbology discussed below are displayed to aid the pilot during recovery.

Control guidance is defined as information provided to pilots to direct their manipulation of the controls to follow a course of action and, in the case of guidance for upsets, return the vehicle to normal flight conditions.

3.3.1 Pitch Command Cue

The NLR - Netherlands Aerospace Centre - conducted an exploratory study investigating different display techniques to improve a pilot's awareness of the AOA and margin to stall [56]. They also stressed the importance of improving recognition of approach to stall and stall warnings.

Fifteen airline pilots participated in an experiment to investigate if and how AOA awareness should be presented to pilots. Three different angle-of-attack indicators were investigated: a separate AOA indicator, a fast-slow indicator, and a pitch cue command (Figure 35). The three scenarios flown included an upset recovery, unusual airspeed at high altitude, and a stall on final approach in landing configuration. These scenarios were flown with and without enhancements to the baseline PFD. Enhancements to the PFD included a separate AOA indicator displayed in the upper right corner, a pitch command cue, and fast-slow indicator replacing the normal speed tape. During an upset, the less time spent under stall conditions and avoidance of a secondary stall during the recovery would indicate a "better" display. Objective and subjective measures were taken. Performance metrics included the duration of the stall, the stall margin, the secondary stall margin, and altitude loss were collected. Perceived workload and acceptability also helped to identify the superior display.

At high altitudes, when pilots were presented with an icing situation, fewer pilots progressed into a stall as a result of the icing when using the pitch command cue. At low altitudes, the pitch command cue helped to reduce the loss of altitude during recovery. Subjective ratings were also positive when using the pitch command cue. Pilots reported reduced workload and increased performance when using the pitch command cue [56].

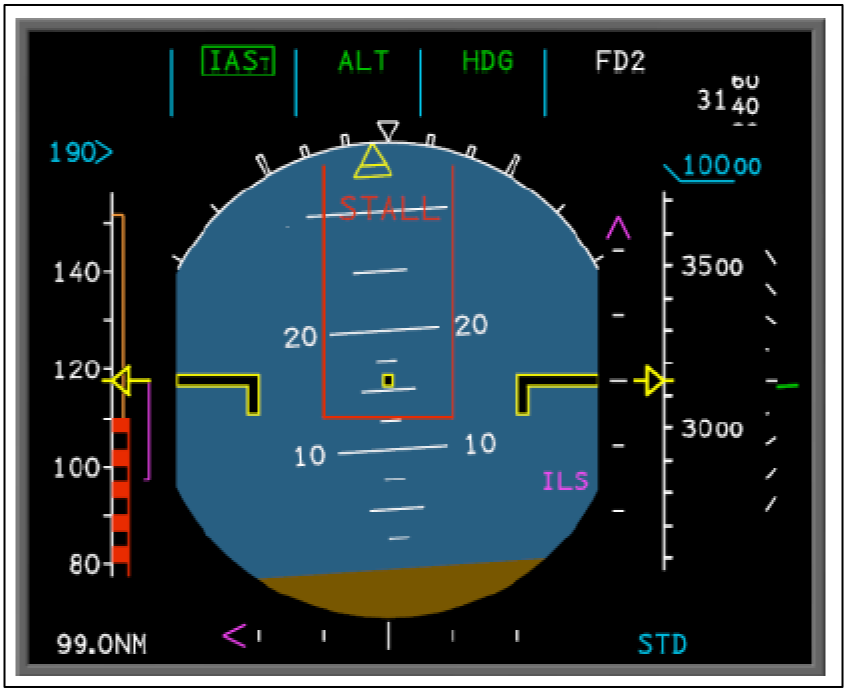

Figure 35: Pitch Command Cue

3.3.2 Augie Arrow

The Augie Arrow, also known as the Augie Vector, was designed to provide pilots guidance for recovery. The proposed Augie Arrow was an emergency-use arrow set that provided the pilot with guidance to recover quickly from an upset. The Augie Arrow indicates the shortest way to roll, then pitch, to achieve wings level. As the aircraft rolled, the length of the curve of arrows shortened [57].

Newman in 1988 investigated the Augie Arrow as a part of his research of bank indices [21]. A baseline, no-bank index was compared to a ground pointer limited to 30 degrees, a sky pointer, a sky pointer enhanced when bank exceeded 60 degrees, an Augie Arrow, and a ground pointer combined with an Augie Arrow on the velocity vector. Subjects preferred the Augie Arrow on the velocity vector, especially when combined with another bank index. Control position, airspeed, heading, pitch and roll attitude, and subjective measures were recorded. Subjective questionnaires asked pilots to rate each symbology for ease of maintaining orientation, ease of recovery, and symbology appropriateness. Subjective and objective data support the use of the Augie Arrow. Newman stated that the preference for the Augie Arrow may be attributed to the display of the arrow in the center of the field of view of the pilots [21].

Roust [22] briefly discussed pilot opinion of the Augie Arrow in her survey research in 1989. After surveying F/A-18 pilots at Lemoore Naval Air Station in California, it was concluded that the standard velocity vector, with and without the Augie Arrow, was good for UAR. Pilots stated that the Augie Arrow should be sky pointing [22].

In 1992, Weintraub and Ensing proposed a version of the Augie Arrow. Figure 36 provides an example where the Augie Vector instructed the pilot to roll left and then pull up to recover from the UA [57]. When the aircraft had departed controlled flight, path guidance was no longer relevant, therefore, in an UA, the flight path marker disappeared and the command arrow was attached to the waterline symbology. Neither research nor results were provided.

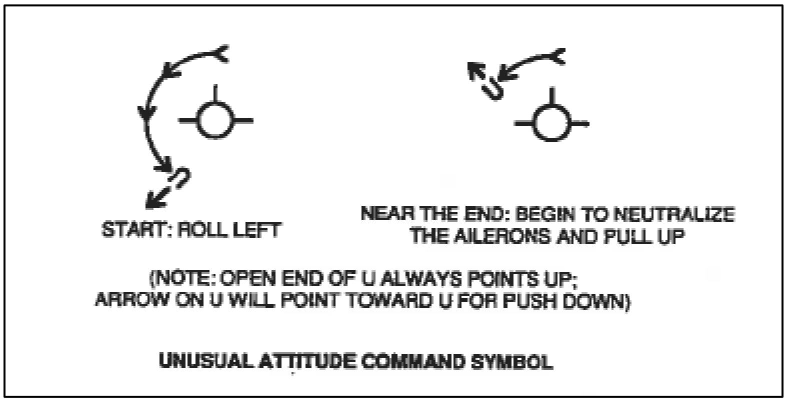

Figure 36: Augie Vector

Deaton, Barnes, Kern, and Wright also investigated the use of an Augie Arrow and analog dials as an aid for UAR in 1992 (not pictured) [58]. Twelve HUD experienced pilots performed UARs using one of four HUD formats. Four HUD formats were evaluated: the standard HUD, Augie Arrow, Analog Dials, and Augie Arrow with Analog Dials. For HUD formats with Augie Arrows, the arrow only appeared during UAs. Half of the subjects experienced an Augie Arrow that pointed to the nearest horizon, while the other half of the subjects experienced an Augie Arrow that pointed upwards. Results showed that subjects using the Augie Arrow had the quickest recovery, while the analog dial format provided the slowest recovery performance. Subjective measures reflected the results of the performance data. Fifty percent of pilots preferred the Augie Arrow HUD format for UARs. Thirty percent of the pilots preferred the standard HUD format, with the remaining 20 percent showed preference for the Augie Arrow with analog dials. No preference was reported for the Analog Dials display. During normal flight the standard HUD was preferred over the other three HUD formats. Time-to-recover was collected to test the effectiveness of the HUD formats. Subjective data in the form of questionnaires were also collected. From these results, it was concluded that the Augie Arrow was beneficial for UAR. The nearest horizon pointing Augie Arrow was the most effective version of the Augie Arrow, producing the most rapid recovery. Further research involving the implementation and use of the nearest horizon pointing Augie Arrow was suggested [58].

In 1993, Chardra addressed the problem of designing an attitude display for use when a pilot has lost attitude awareness [15]. She also investigated the use of an Augie Arrow as a means for attitude awareness. A limitation of the Augie Arrow is that it only provides roll guidance. Chardra argued that although complete recovery involves roll and pitch corrections, pilots are often trained to roll prior to recovering pitch. Chardra's research investigated the design of an Augie Vector through a series of five experiments that each incorporated the findings from the previous. Experiment one investigated symbol-meaning, symbol shape, flight path marker tail-fin orientation with the use of an Augie Vector. Experiment two investigated attitude displays, flight path marker shape, and instructions. Twelve subjects experienced either sky-pointing symbology or ground-pointing symbology. In experiment three, the same twelve subjects from the second experiment performed initial recovery responses incorporating an up task and down task with static or moving symbols using circle and arrow symbology shapes. Experiment Four investigated many of the same concepts as investigated in experiment three in an aviation context. This experiment investigated the impact of sky-pointing and ground-point symbology, circles versus arrows, moving versus static symbology position. These experiments found that roll magnitude and response direction were significant factors in performing recovery. The Augie display with a sky-pointing symbology provided for the fastest response time. The results from these four experiments drove the design of experiment five, the final experiment [15].

The final experiment integrated the work of the previous four experiments, while expanding to a more operationally relevant flight task. Previously, the experimental tasks simply involved initial inputs while experiment five required subjects to perform recovery task to completion. Specifically, subjects were instructed to roll to wings level, then pull to the horizon. Seventeen subjects, thirteen pilots and four college students, participated in experiment five. Subjects performed a static task similar to the tasks performed in the previous experiments, as well as a dynamic task that required full recovery from an unusual attitude. Subjects were provided with ownship, heading, bank angle, airspeed, and an attitude indicator in order perform the dynamic tasks. An Augie Arrow was displayed at all times during the static tasks. For the dynamic tasks, the Augie Arrow was only shown during the UA. The time to initiate response and recovery time were recorded for the dynamic tasks. The dynamic tasks started with the simulation in an UA and concluded when steady, wings level flight had been obtained for two seconds. This work looked into symbol shape, symbol position, pitch perturbation, and other factors for varying roll magnitudes and directions, as well as pitch magnitudes and direction. The arrow symbology and command symbology provided for faster response times during the static tasks. The results were not significant during dynamic tasks [15].

The results of these five experiments were used to make conclusions about best practices for developing attitude displays for UAR, specifically regarding the use of the Augie Arrow. Chardra stated that the Augie Arrow display should be a nearest-horizon pointing display with an ownship symbol that has an upward pointing feature and command symbology. Sky-pointing symbology allows pilots to choose the correct roll direction by aligning vertical feature of the ownship symbol with the Augie vector making recovery of a transport category aircraft easier per UAR training techniques. Chardra concluded that the Augie vector display is a promising aid for UAR; however, it is not ready to be incorporated into standard HUD symbology. Shape and orientation of the ownship symbol and the outside-in versus inside-out display for attitude awareness still require further research [15].

3.3.3 Pitch Trim/Thrust Command Guidance

The reviewed literature did not reveal any research on pitch trim and thrust command guidance with regard to warning and guiding the pilot in the event of an UA, approach to stall, or stall condition.

4 Conclusions & Recommendations

Literature from government agencies, industry, and academia was collected and reviewed to assess past research efforts for providing control guidance for pitch axis upsets, including stalls. This literature review focused on various guidance concepts researched to detect upsets and determine proper recovery response applicable to large commercial aircraft operations, including: a) primary pitch control only, b) primary pitch control and pitch trim; c) primary pitch control, pitch trim, and thrust; and, d) other control strategies, as applicable. This literature review identified several concepts for providing symbology and systems for recognition, alerting, and command pitch and roll guidance for recognition and recovery from UA.

Significant research has been conducted on the design of primary flight instrumentation symbology to create pilot awareness of an airplane attitude or awareness and recovery from an upset or unusual attitude conditions. These systems work to indicate, advise, or promote awareness for pilots that the aircraft was entering an unusual state, prior to a pitch axis upset. A wide variety of attitude symbology and systems have been investigated, including, but not limited to, articulated pitch ladders, pitch ladder enhancements, and horizon line concepts. From this work, continuous positive pitch bars and broken negative pitch bars, numerals on one side of the pitch scale, numerals located above or below but not aligned with the ends of the pitch bars, negative signs for pitch scale numerals, horizon-pointing tails, and horizon sloping pitch bars might be incorporated as standards for pitch ladder symbology [18]. It was also noted that the horizon line remaining on the display added an additional level of attitude awareness and was helpful during UAR [19].

In the event that these awareness methods are insufficient, research has been conducted on the use of alerting through visual (i.e., symbology) or aural means. This alerting symbology would further alert the pilot to an unusual attitude and provide the pilot with awareness that action is urgent. The goal of the alerting symbology and systems would again be to aid the pilot in correcting aircraft attitude, before a pitch axis upset occurs. The addition or deletion of symbology has been suggested as a way to alert the pilot of these situations. The Rockwell Collins HGS HUD, in particular, incorporates an UA display that automatically appears when the aircraft falls into UA parameters and provides symbology for UAR [47].

Finally, warning symbology and systems providing command guidance to pilots would assist the pilot in recovery and alert of the need for immediate action. Research done in this area included guidance that would command a pilot on how to adjust the aerodynamic controls of the aircraft to recover from an upset. This research focused primarily on primary pitch control guidance (i.e., a guidance cue). The pitch command cue was found to decrease the number of stall events and was helpful in high and low altitude events [56]. As a result of Roust's research, in addition to providing additional visual cues to alert of an UA, pilots supported the use of the words CLIMB and DIVE as command guidance, the use of an Augie Arrow, and the inclusion of color to designate below-horizon angles [22].

Although much past research has been conducted in the area of providing attitude awareness and primary control guidance to the pilot, little if any research was found on creating pitch command guidance for stall recovery or in the use of stabilizer, thrust, or other devices and controls (e.g., flaps, gear, roll, and yaw) for upset recovery and stall. The past work was deficient in how best to display pitch, trim, and thrust; effectively use a balance of command guidance and attitude awareness symbology for UAR or avoidance; and when to display command guidance symbology.

It is recommended that further research be specifically conducted in the following areas:

- The reviewed literature primarily focused on pitch and roll guidance for recovery from UAs, but little on trim and thrust adjustments or other secondary controls to aid recovery. As a result, it is recommended that research be conducted on how to intuitively present trim and thrust indications on the flight deck during these time-critical conditions.
- The literature review showed a clear distinction between command guidance and attitude awareness symbology. Command guidance directs a pilot to perform a maneuver to avoid or recover from an UA. Attitude awareness symbology provides the pilot with attitude and situation awareness. Further research should be conducted to investigate how command guidance and attitude awareness symbology can effectively complement each other and be used to assist pilots in avoiding or recovering from UAs and/or approach-to-stall and stall. The potential for hazardously misleading information by using command guidance for highly dynamic, non-linear flight regimes, with numerous critical control effectors (e.g., pitch, trim, thrust) and extensive potential aircraft configuration and loading conditions must be considered in this work.
- Many different techniques for providing command guidance and attitude awareness symbology were discovered, however, there was no consensus regarding when to display this information. It is recommended that further research be conducted investigating triggers and when to display command guidance and attitude awareness symbology.

5 References

1. Boeing, "Statistical Summary of Commercial Jet Airplane Accidents World Wide 1959-2012", Boeing Commercial Airplanes, 2013.
2. Commercial Aviation Safety Team, "Safety Enhancement SE 207 ASA-Research-Attitude and Energy State Awareness Technologies", CAST SE Implementation Plan, 2013.
3. United States Air Force, "Instrument Flight Procedures", Manual 11-217, Volume 1, 2010.
4. Brooks, R., Edwards, J., Kochan, J., Ransubury, P., Stowell, R., "Maintaining Aircraft Control", Society of Aviation and Flight Educators, 2012.
5. Federal Aviation Administration, "Advisory Circular: Upset Prevention and Recovery Training", AC No: 120-111, 2015.
6. Ward, B., Moreau, B., "A Systematic Approach to Development of Full Flight Simulation Based Advanced Maneuver & Upset Recovery Training", FedEx Express.
7. Upset Recovery Team, "Airplane Upset Recovery Training Aid, Revision 2", Federal Aviation Administration & Airline Industry, 2008.
8. Federal Aviation Administration, "Pilot's Handbook of Aeronautical Knowledge", FAA-H-8083-258A, 2008.
9. Moreau, B., Priest, J., "Advanced Maneuvering and Upset Recoveries with Alternate Control Strategies", FedEx, Calspan, 2010.
10. Federal Aviation Administration, "Advisory Circular: Stall and Stick Pusher Training", AC No: 120-109, 2012.
11. Boeing, "Aerodynamic Principles of Large-Airplane Upsets", Aero Magazine, 2003.
12. Federal Aviation Administration, Code of Federal Regulation, Title 14 Part 25 Section 207, 2002.
13. Federal Aviation Administration, "Advisory Circular: Flight Crew Alerting", AC No: 25.1322-1, 2010.
14. Federal Aviation Administration, Code of Federal Regulation, Title 14 Part 25 Section 1322, 2010.
15. Chardra, D., "Design of Head-Up Display Symbology for Recovery from Unusual Attitudes", University of Michigan, 1993.
16. Department of Defense Interface Standard, "Aircraft Display Symbology", MIL-STD-1787C, 2001.
17. SAE Aerospace, "Bank and Pitch Instruments (Indicating Stabilized Type) (Gyroscopic Horizon, Attitude Gyro)", Aerospace Standard AS396B, SAE International Group.

18. Taylor, R.M., "Some Effects of Display Format Variables on Perception of Aircraft Spatial Orientation”, RAF Institute of Aviation Medicine, Farnborough, Hampshire, UK 1984.

19. Zenyuh, J., Reising, J., McClain, J., Barbato, D., Hartsock, D., "Advanced Head-Up Display (HUD) Symbology: Aiding Unusual Attitude Recovery", Human Factors Society 31st Annual Meeting, Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, 1987.

20. Reising, J., Zenyuh, J., Barthelemy, K., “Head-Up Display Symbology for Unusual Attitude Recovery”, Wright-Patterson AFB, Ohio, 1988.

21. Newman, R., "The HUD in Spatial Disorientation", 20th European Symposium, Society of Experimental Test Pilots, Linkoping, Sweden, 1988.

22. Roust, L., “Evaluation of Head-Up Display Formats for the F/A-18 Hornet”, Naval Postgraduate School, Monterey, California, 1989.

23. Ward, G.F., Hassoun, J., “The Effects of Head-Up Display (HUD) Pitch Ladder Articulation, Pitch Number Location, and Horizon Line Length on Unusual Attitude Recoveries for the F-16”, Wright-Patterson Air Force Base, Ohio, 1988.

24. Weinstein, L., Ercoline, W., "HUD Climb/Dive Ladder Configuration and Unusual Attitude Recovery", Human Factors Society 35th Annual Meeting, Krug Life Sciences, Brooks AFB, Texas, 1991.

25. Deaton, J. Barnes, M. Lindsey, N. and Green, J., “The Effects of Windscreen Bows and HUD Pitch Ladder on Pilot Performance during Simulated Flight”, Naval Air Development Center, Warminster, Pennsylvania, 1989.

26. Self, B., Breun, M., Fedlt, B., Perry, C., and Ercolin, W., “Assessment of Pilot Performance Using a Moving Horizon (Inside-Out), a Moving Aircraft (Outside-In), and an Arc Segmented Attitude Reference Display”, RTO HFM Symposium. La Coruna, Spain, 2002.

27. Zuschlag, M., "Issues and Research Concerning the Use of Head-Up Displays in Air Transports", Volpe NTSC, Cambridge, MA.

28. Hall, J.R., Stephens, C.M., Penwill, J.C., "A Review of the Design and Development of the RAE Fast-Jet Head-Up Display Format", Royal Aerospace Establishment, Bedford, United Kingdom, 1989.

29. Taylor, R.M., "Aircraft attitude awareness from visual displays", RAF Institute of Aviation Medicine, Farnborough, Hampshire, UK, 1989.

30. Weinstein, L., Ercoline, W., Bitton, D.F., "The Utility of a Ghost Horizon and Climb/Dive Ladder on Tapering on a Head-Up Display", Human Factors Society 36th Annual Meeting, Krug Life Sciences, Randolph AFB, Texas, 1992.

31. Beringer, D., Ball, J., and Brennan, K., “Comparison of a Typical Electronic Attitude-Direction Indicator with Terrain-Depicting Primary flight Displays for Performing Recoveries from Unknown Attitudes: Using Difference and Equivalence Test,”, Federal Aviation Administration, Washington, D.C, 2005.

32. Devilbiss, C., Sipes, W., “Effect of arc segmented attitude reference symbology on a helmet-mounted display during an unusual attitude recovery task”, SPIE Vol. 2465/ 255, 1995.

33. Jenkins, J., Thurling, A., Havig, P., Geiselman, E., “Flight test evaluation of non-distributed flight reference off-boresight helmet-mounted display symbology”, SPI Vol. 4711, 2002.

34. Wickens, C., Self, B., Andre, T., Reynolds, T., Small, R., “Unusual Attitude Recoveries With a Spatial Disorientation Icon”, The International Journal of Aviation Psychology, 17th ed, vol (2), pp 153–165, 2007.

35. Jenkins, J., “Arc Segment Attitude Reference (ASAR) Head-Up Display (HUD) Symbology as a Primary Flight Reference Test and Evaluation.”, Air Force Flight Test Center, Edwards Air Force Base, California, 2008.

36. Previc, F., Ercoline, W., “Spatial Disorientation in Aviation”, American Institute of Aeronautics and Astronautics, 2004.

37. Squair, M., “Malcom’s horizon and unusual attitude recovery”, Critical Uncertainties, 2015.

38. Malcolm, R., "Pilot Disorientation and the Use of a Peripheral Vision Display", The 1983 Annual Harry G. Armstrong Lecture, Aerospace Medical Association, Washington, D.C, 1984.

39. Gillingham, K., “Evaluation of the Malcom Horizon in a Moving-Base Flight Simulator”, USAF School of Aerospace Medicine, Brooks Air Force Base, Texas, 1983.

40. Comstock, J., Jones, L., Pope, A., “The Effectiveness of Various Attitude Indicator Display Sizes and Extended Horizon Lines on Attitude Maintenance in a Part-Task Simulation”, NASA Langley Research Center, Hampton, Virginia, 2003.

41. Poonawalla, B., Braasch, M., “Human Factors Studies Evaluating Synthetic and Peripheral Vision Displays in General Aviation”, Ohio University, Athens, Ohio, 2007.

42. General Aviation News Staff, “Pilot develops cockpit lighting system to prevent spatial disorientation”, General Aviation News, 2014.

43. Ligget, K., Reising, J, Harstock, D., “Development and Evaluation of a Background Attitude Indicator”, The International Journal of Aviation Psychology, v 9, pp 49-71.

44. Bailey, R., Ellis, K., Stephens, C., “Test and Evaluation Metrics for Crew Decision-Making and Aircraft Attitude and Energy State Awareness”, NASA Langley Research Center, Hampton, VA, 2013.

45. Chelton Flight Systems, “Synthetic Vision EFIS”, Flightlogic, Chelton Flight Systems.

46. Le Vie, L., “Review of Research on Angle-of-Attack Indicator Effectiveness”, NASA Langley Research Center, Hampton, VA, 2014.

47. Federal Express, “FAA Approved Airplane Flight Manual Supplement for Boeing 757-200 Series Airplane Revision 1”, FedEx Document ER 10-120, Memphis, Tennessee.

48. Honeywell, “Primus Epic PlaneView Pilot’s Manual for the G500/G550”, Honeywell International, Inc., Glendale, Arizona.

49. Wyatt, I., U.S. Patent No. 6,469,640 B2, United States Patent and Trademark Office, Scottsdale, Arizona, 2002.

50. Tooley, M., Wyatt, D., “Aircraft Digital Electronic and Computer Systems”, Elsevier. Burlington, Massachusetts, 2007.

51. Schwartz, K., Uberlingen, Germany, U.S Patent Application for “Directional and Pitch Trim Indicator For Automatic Pilots”, U.S. Patent No. 3,676,843, 1970.

52. Niedermeir, D., Lambregts, A, “Fly-By-Wire Augmented Manual Control – Basic Design Considerations”, Federal Aviation Administration, 2012.

53. Etherington, T., Schnell, T., “Spatial Orientation Enhancement System (SOES)”, Rockwell Collins, Air Force Research Labs, 2006.

54. Conner, K., Feyereisen, T., Morgan, J., and Bateman, D., “Cockpit Displays and Annunciations to Help Reduce the Loss of Control (LOC) or Lack of Control (LAC) Accident Risks”, AIAA Guidance, Navigation, and Control Conference, Minneapolis, Minnesota, 2012.

55. Gershzohn, G., “Unusual Attitude Recovery Using the Roll Arrow”, SAE World Aviation Congress, Seattle, Washington, 2001.

56. Fokkerweg, A., “Angle-of-Attack information in civil aircraft: A comparison of different display methods”, National Aerospace Laboratory NLR, Amsterdam, The Netherlands, 2013.

57. Weintraub, D., Ensing, M., "Human Factors in Head-Up Display Design: The Book of HUD", Crew System Ergonomics Information Analysis Center, University of Michigan, 1992.

58. Deaton, J. Barnes, M., Kern, J., Wright, D., "Enhanced HUD Symbology Associated with Recovery from Unusual Attitudes", Naval Development Center, VEDA, Inc, 1992.

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14. ABSTRACT
A literature review was conducted to identify past efforts in providing control guidance for aircraft upset recovery including stall recovery. Because guidance is integrally linked to the intended function of aircraft attitude awareness and upset recognition, it is difficult, if not impossible, to consider these issues separately. This literature review covered the aspects of instrumentation and display symbologies for attitude awareness, aircraft upset recognition, upset and stall alerting, and control guidance. Many different forms of symbology have been investigated including, but not limited to, pitch scale depictions, attitude indicator icons, horizon symbology, attitude recovery arrows, and pitch trim indicators. Past research on different visual and alerting strategies that provide advisories, cautions, and warnings to pilots before entering an unusual attitude (UA) are also discussed. Finally, the review of potential control guidance for recovery from upset or unusual attitudes, including approach-to-stall and stall conditions, are reviewed. Recommendations for future research are made.

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