Indonesian Journal of Aerospace Vol. 22 No. 2 Desember 2024 : pp 119 – 134 (Sarah et al.)
DOI: 10.59981/ijoa.2024.4671
https://ejournal.brin.go.id/ijoa/

Review: Flight Envelope Monitoring and Protection as One of the Flight Safety System

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Received: 05-04-2024. Accepted: 05-07-2024. Publishied: 20-05-2025

Abstract

The development of civil aircraft technology, especially commercial aircraft, is now very advanced and complex. This development is intended to assist the pilots to control aircraft in various flight conditions with the main goal to achieved is flight safety. This literature review will discuss research on the flight warning system, which will support the flight envelope protection system development study, which has been conducted over the past few years. The review includes an analysis of existing literature, case studies of aviation accidents, and the evaluation of flight envelope protection systems in current aircraft models. This review shows that the development of technologies and systems can make a significant contribution to flight safety and pilot situational awareness of flight envelope boundaries, so the possibility of aircraft accidents due to loss of control can be reduced.

Keywords: *loss of control; flight envelope protection; flight warning system.*

1. Introduction

As shown in Figure 1-1, aircraft accidents happens due to several factors, one of the most common cause is Loss of Control (LOC) (Belcastro & Foster, 2010). This occur because the pilot gives control commands that force the aircraft to exceed its structural and aerodynamic operating limits. LOC is an accident in which the flight crew is unable to maintain control of the aircraft in flight, resulting in an irreversible deviation from the intended flight path (Association, 2022). Although the LOC category represents only 7% (39) of all accidents over the last 10 years (2013-2022), it resulted in the highest percentage of fatal accidents at 49% (35) and fatalities at 57% (1,290), as shown in Figure 1-2. LOC prevention cannot be addressed with a single system or equipment. Therefore, LOC is considered worthy of more attention (Association, 2022).

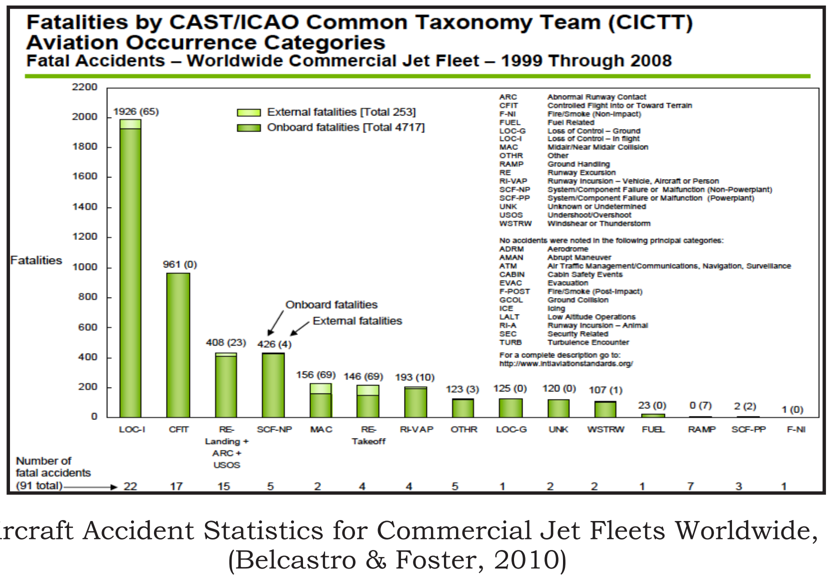

Figure 1-1: Aircraft Accident Statistics for Commercial Jet Fleets Worldwide, 1999-2008. (Belcastro & Foster, 2010)

e-ISSN 3032-0895 (online)
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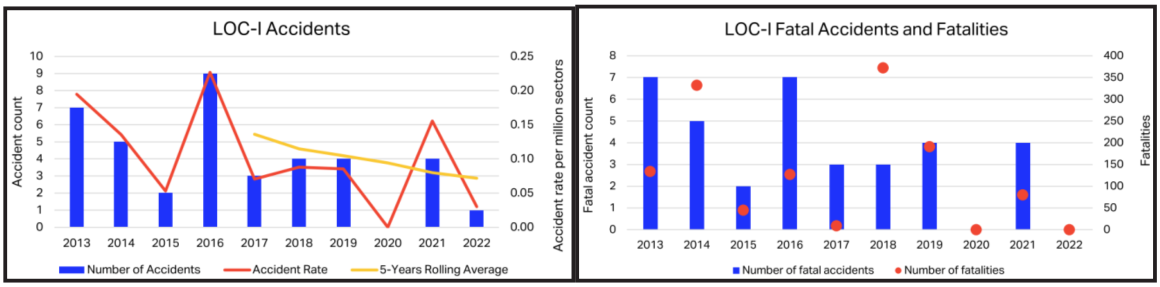
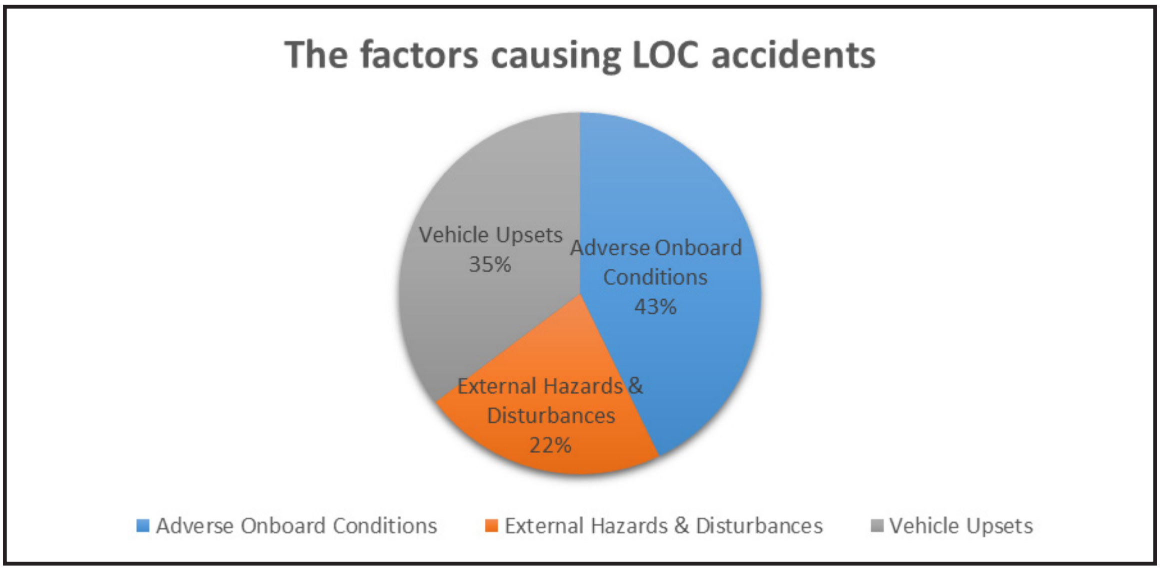


Figure 1-2: LOC accident in 2013-2022. (Association, 2022)

Compared to other accident event categories, LOCs are more difficult to predict and prevent, as they are highly complex events: usually resulting from a variety of causal and contributing factors. The analysis of causal factors of LOC accidents has become an extensive ongoing research topic in recent years (Jacobson, 2010). A study was conducted on LOC accidents between 1979 and 2009 (30 years) (Belcastro & Foster, 2010). On the causal factors of LOC accidents which were grouped into three categories: poor in-flight conditions, vehicle distractions, and external hazards and distractions. Figure 1-3 shows that, out of 126 accidents, 119 were due to adverse onboard conditions, 98 were due to vehicle upset, and 61 were due to external hazards and disturbance. Some LOC accidents were preceded by a poor in-flight condition and subsequently led to aircraft disruptions, which accounted for the largest proportion (Belcastro et al., 2016). A more detailed description of the three categories of LOC accident causal factors can be seen in Figure 1-3.



- vehicle impairment (including inappropriate vehicle configuration, contaminated airfoil, and improper vehicle loading)
- system faults, failures, and errors (resulting from design flaws, software errors, or improper maintenance actions)
- vehicle damage to airframe and engines (resulting from fatigue cracks, foreign objects, overstress during upsets or upset recovery, etc.)
- inappropriate crew response (including pilot-induced oscillations, spatial disorientation, mode confusion, ineffective recoveries, crew impairment, and failures to take appropriate actions)

- poor visibility
- wake vortices
- wind shear, turbulence, and thunderstorms
- snow and icing conditions
- abrupt maneuvers for obstacle avoidance or collisions

- abnormal attitude
- abnormal airspeed
- abnormal flight trajectory
- stall

Figure 1-3: The factors causing LOC accidents.

The Air France 447 crash (BEA, 2012) is a case where a lack of awareness on automation modes that led the aircraft to revert to its less stringent protection system due to a sensor failure. Surprised by the aircraft's altitude dynamics and confused by the active flight envelope protection mode, the pilots misjudged that they were in a high-speed condition. The pilot then pulled back on the side stick, not realizing that this put the aircraft into a stall condition that was only communicated to the pilot via an aural warning. Such aural warnings should have been supplemented with additional information to the crew that would have allowed them to get out of the misunderstanding of a dangerous situation (FAA Human Factors Division, 2004). In the case of Air Asia 8501 (KNKT, 2015), there was a rudder limiter malfunction and the pilot took actions that resulted in the protection mode revert to a simpler mode and rendering the autopilot inoperative. It took nine seconds for the pilot to take corrective action, by which time the aircraft had reached a roll angle of 54°. This caused the aircraft to stall, and subsequently crashed. Causing the loss of all crew and passengers. If the information about the approach to safe limits had been given earlier to the pilots, an accident like this could have been avoided. Both aircraft, which are Airbus A330 and A320, have computerized systems that provide flight envelope protection, and passive control devices (*Airbus A320 Flight Crew Operating Manual (FCOM)*, n.d.; *Airbus A330 Flight Crew Operating Manual (FCOM)*, n.d.).

There are a number of solutions that can help prevent aircraft LOC. One is to provide continuous education and training for pilots, especially in recognizing and handling emergency situations such as stalls or other LOC situations (ten Velde et al., 2015). This training also includes simulator exercises that introduce pilots to challenging situations. Pilots often miss or ignore available indications that could warn them of an impending disturbance or LOC event. Ultimately, failure to recognize these LOC sign or warning leads to unintentional or in some cases even deliberate pilot distractions. Current training methodologies and regulatory requirements have had little success in reducing this most frequent category of fatal aviation accidents. A focus on effective distraction prevention, recognition and recovery training is needed to reduce the risk of LOC accidents. Pilot training programs must also ensure that pilots have sufficient knowledge of aircraft systems and environments to recognize when they are exposed to elevated LOC risks and respond effectively to those threats.

LOC accidents can be significantly reduced by existing technologies on newer generation aircraft, such as flight envelope protection systems equipped fly-by-wire technology (*A Statistical Analysis of Commercial Aviation Accidents 1958-2016*, 2016). Most large commercial aircraft and high-performance military aircraft use fly-by-wire systems to improve their controllability, comfort and safety. Fly-by-wire is a flight control system that uses a computer to process flight control inputs made by the pilot or autopilot, and sends corresponding electrical signals to the flight control surface actuators (Traverse & Lacaze, 2004). This arrangement replaces the mechanical linkage, which means that there is no physical connection between the control surface and the control device. The pilot's input to the control device is read by the flight control computer that determines how to actuate the control surface to achieve what the pilot wants. Flight envelope protection techniques are used with flight control systems that utilize fly-by-wire techniques (Shin et al., 2011). The flight envelope protection system prevents these aircraft from exceeding structural/aerodynamic limits and controls the control surfaces (Shin et al., 2011). Fly-by-wire control has been in use for nearly 25 years, in combination with flight envelope function have significantly improved flight safety (Niedermeier & Lambregts, 2012).

Flight envelope monitoring and protection system are essential for several reasons beyond preventing loss of control. Flight envelope protection help maintain the structural integrity of the aircraft by preventing it from exceeding critical limits such as maximum load factors and speed. This reduces fatigue damage to the airframe and ensures long-term structural reliability (EASA, 2020). They also manage adverse weather conditions, ensuring stability and safety during turbulence or wind shear (ICAO, 2014). Additionally, these systems optimize aircraft performance by maintaining efficient operational parameters, supporting regulatory compliance, integrating with automated systems for seamless operations, and aiding in emergency management scenarios to stabilize aircraft and guide pilots effectively (FAA, 2018; ICAO, 2014). These functionalities collectively enhance safety, efficiency, and regulatory adherence in aviation operations. This literature review will discuss research on the flight warning system, which will support the flight envelope protection system development study, which has been conducted over the past few years.

2. Methodology

2.1. Related Works

There are two functions of a flight envelope protection system. First is the function to monitor and maintain the aircraft within its flight envelope. For example, maximum angle of attack protection to prevent the aircraft from stalling (Briere & Traverse, 1993). This protection prevents the pilot from over piloting the aircraft by limiting commands to the control surface, in particular, during avoidance maneuvers, such as during obstacle avoidance (near miss) and wind shear at low altitude. Pilots who must avoid other aircraft, can concentrate on the flying the aircraft without worrying about structural limits or the possibility of a stall. The second function is to inform the pilot of the safe boundary of the aircraft (e.g. minimum speed) through human and machine interaction such as haptics feedback and visual displays. These safeguards directly provide safety-related information to pilots so that they can make unscheduled control adjustment without violating the envelope boundaries. Protection is often achieved by combining visual aids, haptic feedback on the control inceptor, and/or with soft or hard limits used in the flight control system.

Currently, fly-by-wire systems with flight envelopes protection on board modern aircraft, protects the aircraft within the constraints of load factor, airspeed, and angle of attack to prevent stall (Briere & Traverse, 1993). This protection is designed to be either hard envelope protection (used by Airbus aircraft) or soft envelope protection (used by Boeing aircraft), depending on the policies of the pilot authority (Lambregts, 2013). In a hard envelope protection scheme, control inputs are generated by comparing critical inputs and pilot inputs. If the aircraft approaches the limit of the flight envelope, the fight control computer (FCC) that would recognizes the flight envelope is about to be exceeded and adjust the control input directly. Figure 2-1 shows the structure of a hard envelope protection system where the command limiter directly adjusts the pilot control input.

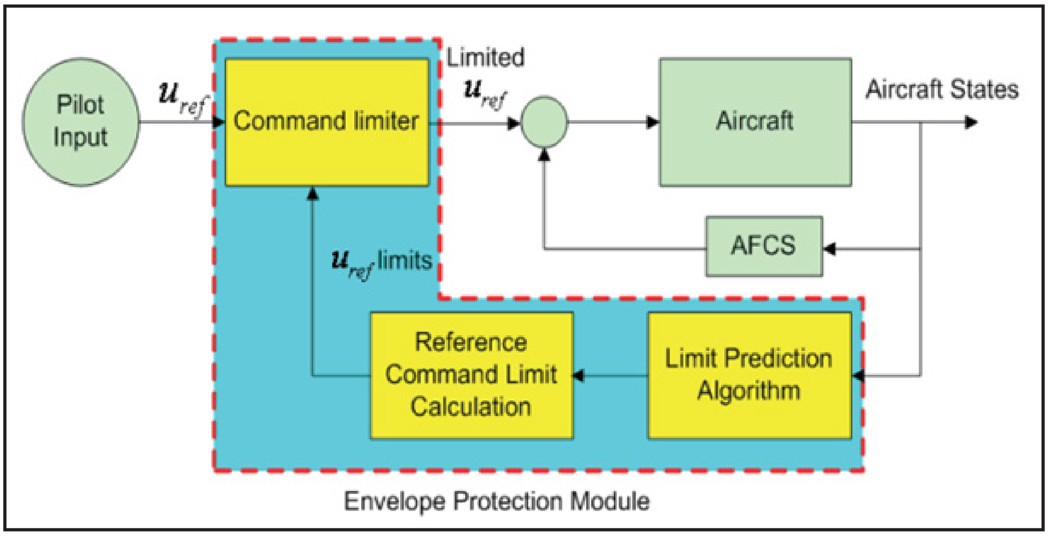


Figure 2-1. Structure of hard envelope protection (Shin et al., 2011)

The argument for hard envelope protection is clear. Maneuver that exceeds these boundaries could lead to unsafe situations that can potentially cause structural damage to the aircraft, and can ultimately lead to an irreversible loss of control. On the other hand, extreme maneuvers are sometimes necessary as a last resort, where the other alternative is the certainty of an accident. For example, in the case of the China Airlines B747 in 1985, the pilot was required to apply excessive force on the horizontal tail surface to recover from a rolling and near-vertical dive (NTSB, 1986). This recovery would not have been possible with a hard envelope protection system.

Boeing integrates soft envelope protection in their fly-by-wire flight control systems, which issues warnings and suggestions when approaching operational limits by increasing control stick resistance and providing auditory and visual alerts. This system allows pilot to override the protection and exceed limits if necessary. The benefits of soft envelope protection include alerting pilots to potential risks, but it also has drawbacks. While pilot receive visual, audible, and stick force signals to indicate approaching limits, they retain the ability to control the aircraft beyond these limits, potentially leading to dangerous situations if not managed carefully (Ellerbroek et al., 2016). Therefore, pilot must fully understand their aircraft's limitations and rely on experience, especially in non-standard situations. NASA research indicates that pilots often overreact to auditory or visual warnings, providing excessive control inputs that can destabilize the aircraft. Conversely, active stick force cues enable quicker recognition of flight conditions. Figure 2.2 illustrates a soft envelope protection scheme where the active stick force cue component is integrated into the envelope protection module instead of the command limiter (Rogers, 1999).

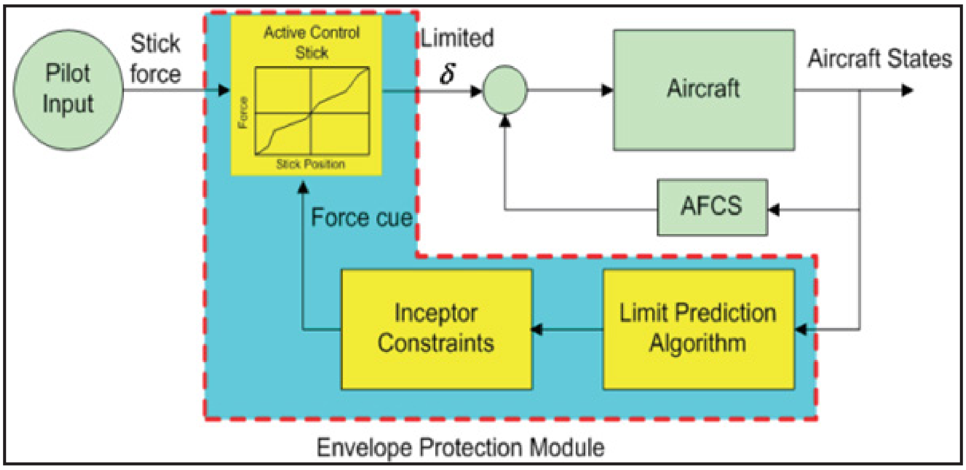


Figure 2-2. Structure of soft envelope protection (Shin et al., 2011)

Both envelope protection systems are capable of reducing pilot workload and improving flight safety, although which is better is still debated. By 2016 aircraft equipped with flight envelope protection had increased to 48%, which will likely contribute to a significant reduction in accident rates (*A Statistical Analysis of Commercial Aviation Accidents 1958-2016*, 2016). However, due to the persistence of LOCs occurrence despite the flight envelope protection introduction, research to improve and augment aircraft flight control systems is still ongoing.

2.2. Problem Definition

By systematically examining a wide range of academic articles, the study aimed to identify key concepts, identify trends, and address gaps within the current body of literature related to the research topic. This approach able facilitated an understanding of the subject matter and also allowed for the incorporation of diverse perspectives and expert opinions. In general, fly-by-wire aircraft such as Airbus A320 have various flight envelope protections, which protect the aircraft from entering certain critical situations when normal law is active. Normal law is the primary mode of operation in modern fly-by-wire systems (Airbus, 2008). It provides a high level of automation and protection to the pilot. In normal law, the flight control system automatically limits the performance of the aircraft within safe operating parameters. Table 2-1 shows the protection when normal law is active. Alternate law is activated when there is a failure or loss of certain flight control system components (Airbus, 2008). In this mode, some of the protections and automatic features of the normal law may be lost or degraded. The flight control system relies more on direct pilot input and provides a lower protection envelope. Alternate law allows the aircraft to remain controllable and flyable despite a system failure.

Table 2-1. Flight envelope protection on fly by wire aircraft and an example of an accident if the aircraft flew without the protection.

<table>
<tr><td rowspan="2">1</td><td>High angle-of-attack protection</td><td>protects against the risk of aerodynamic stalling, including in gust situations, as well as during dynamic maneuvers or in high wind conditions</td></tr>
<tr><td colspan="2">


Figure 2-3. Aeroflot Flight 593 aircraft debris. (S.Megill, 2014)

A case in point is the crash of Aeroflot Flight 593 in 1994. Aeroflot Flight 593, an Airbus A310, was traveling from Moscow, Russia, to Hong Kong with a stop in Novosibirsk. During the flight, the captain gave the aircraft's stick to his 15-year-old son and 12-year-old daughter, who were visiting the cockpit. While the captain's son was at the controls, the aircraft experienced a rapid increase in AOA and reached stall speed. The autopilot shut down due to a signal from the manual controls. The crew was unable to overcome the stall, and the aircraft crashed into a forest in Krasnaya Polyana, Russia. (S.Megill, 2014)

Another case is the Lion Air Flight 610 accident, a Boeing 737 MAX 8 aircraft, was a domestic flight that crashed on October 29, 2018, resulting in the loss of all 189 passengers and crew. The AOA sensor misread the data and caused the Maneuvering Characteristics Augmentation System (MCAS) system to think that the aircraft had stalled (lost lift). In response, MCAS automatically pushed the nose down to prevent a non-existent stall. The pilot attempted to overcome the nose down, but the MCAS system repeatedly pushed for the nose down. These troubleshooting attempts eventually failed, and the aircraft crashed into the Java Sea. (NTSC, 2018)
</td></tr>
</table>

<table>
<tr><td rowspan="2">2</td><td>Speed protection</td><td>protect against overspeed to avoid structural problems due to high aerodynamic loads, and underspeed to avoid stalls</td></tr>
<tr><td colspan="2">


Figure 2-4. Airplane debris found at sea. (National Transportation Safety Committee, 2007)

One example of a plane crash due to too low speed is the crash of Adam Air Flight 574 in 2007. The plane, a Boeing 737-400, lost control while flying over Indonesian waters and crashed into the Java Sea. One contributing factor was a possible stall (loss of lift) due to too low speed. During the flight, the aircraft received a signal from an incorrect sensor regarding speed, which resulted in the flight management system equating the speed to zero. This causes the aircraft to move at a very low speed and tend to lose lift, making it difficult to control. This then leads to a loss of control of the aircraft and an eventual crash. (National Transportation Safety Committee, 2007)
</td></tr>
<tr><td rowspan="2">3</td><td>Pitch attitude protection</td><td>protect against excessively steep climbs or descents by limiting the pitch angle between minimum and maximum values</td></tr>
<tr><td colspan="2">


Figure 2-5. Debris of SilkAir flight MI185 recovered from the river. (National Transportation Safety Committee, 1997)

A Boeing 737-300 aircraft operated by SilkAir, flight number MI185, crashed near Palembang, Indonesia, during a flight from Jakarta to Singapore. The aircraft suddenly lost control in level flight and crashed into the Musi River. The investigation concluded that the primary cause of the crash was most likely due to the aircraft experiencing a rapid pitch-down due to a fault in the flight system or a deliberate act of one of the crew members. The crash killed all 104 people on board. (National Transportation Safety Committee, 1997)
</td></tr>
</table>

<table>
<tr><td rowspan="2">4</td><td>Bank angle protection</td><td>protect against excessive lean, steep turns, and the risk of inversion by limiting bank angle and roll rate to maximum values</td></tr>
<tr><td colspan="2">
Figure 2-6: Location of the crash of Garuda Indonesia flight GA152. (National Transportation Safety Committee of Indonesia, 1997)

An Airbus A300B4-220 aircraft operated by Garuda Indonesia, flight number GA152, crashed at Polonia International Airport, Medan, Indonesia. The accident occurred during the aircraft's approach to land on runway 05. Investigations found that the aircraft was unstable and entered into an extreme bank angle after the crew tried to correct the aircraft for descending too fast. The plane then hit the ground and burst into flames, killing all 234 people on board. (National Transportation Safety Committee of Indonesia, 1997)</td></tr>
<tr><td rowspan="2">5</td><td>Load factor protection</td><td>protect against structural damage by keeping aircraft vertical speed within safe limits</td></tr>
<tr><td colspan="2">
Figure 2-7. Piper PA-25-235 light aircraft crashes during gender reveal party. (*Accident Piper PA-25-235 Pawnee XB-ABM*, 2023)

A Piper PA-25-235 Pawnee crashed after the left-hand wing failed after an emergency hopper release of (pink dyed) water or powder during a gender reveal party. The pilot perished. (*Accident Piper PA-25-235 Pawnee XB-ABM*, 2023)</td></tr>
</table>

2.3. Method

Research methodology that is utilized in this study involved an extensive exploration of existing technology, knowledge and scholarly contributions through a thorough review of reputable journals. The objective was to systematically gather and synthesize relevant information, theories, and empirical studies to establish a solid foundation for the study. Literature reviews are essential to research and place findings in the context of broader academic discussions. By drawing on the insights and findings from established journals, this paper contributes to the existing knowledge base and strengthens the robustness and credibility of the research.

3. Result and Analysis

The function of the flight warning system is to provide warnings to the flight crew to increase their situation awareness and provide appropriate indications of the actions required to avoid impending danger (Committee, 2018). In general, there are 3 types of warnings used on aircraft, which are vibratory, visual, and aural. To increase pilot awareness of these protection systems, force feedback on the control device is used, which is haptic (Van Baelen et al., 2020). Haptic feedback is seen as a way to flexibly share information and control between human operators and automation at a physical level (Abbink et al., 2012). In the field of haptic research, there are two main categories identified: touch (stimulation of the skin) and kinaesthetic thesis (stimulation of receptors in muscles, joints, and tendons) (Hutchison & Mitchell, 2010), as shown in Figure 3-1.

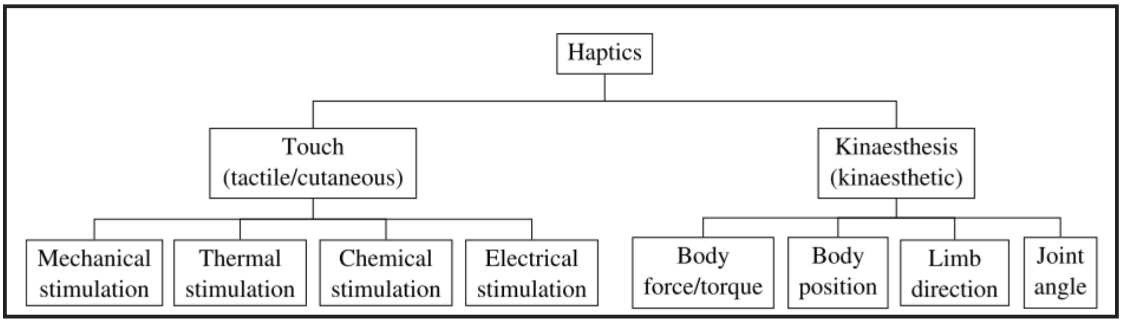


Figure 3-1. Components of haptic (Van Baelen et al., 2020)

Paper (Ellerbroek et al., 2016) discusses the design and evaluation of a haptic feedback system to communicate the intent of the flight envelope protection system. This concept uses stiffness and vibration feedback to communicate the proximity of the aircraft status to the flight envelope boundaries. In addition, the envelope protection system can jointly perform corrective actions by shifting the control in case of severe excursion from the envelope boundaries. Evaluation experiments showed improved pilot performance in wind shear and icing scenarios with haptic feedback. This concept uses stiffness and vibration feedback to communicate the proximity of the aircraft status to the flight envelope boundaries. Experimental results show improved pilot performance with the use of haptic feedback, suggesting that this system can assist pilots in managing extreme situations or envelope excursions more effectively. Pilot responded positively to the system, particularly in relation to the effectiveness of the combination of stiffness and vibration feedback in providing information. This paper contributes to the understanding of how haptic feedback can improve pilot understanding and performance of the flight envelope protection system, with a focus on the combination of stiffness and vibration feedback.

The research of (Van Baelen et al., 2020) discusses the design of a haptic feedback system to increase pilot awareness of flight envelope protection systems. This research aims to increase pilot awareness of flight envelope protection systems through the use of force feedback on control devices, which is haptics. The haptic feedback system provides five different cues to the pilot, including discrete force feedback when approaching the limit, increased spring coefficient, stick shaker, automatic stick movement for inputs in low-velocity conditions, and adherence to Airbus overspeed commands. Each cue is designed to provide pilots with information about their proximity to the aircraft limits and necessary control actions. The research anticipates that the haptic feedback system will help pilots accurately assess situations and make informed control decisions, especially in scenarios near the flight envelope limits such as wind shear and icing. This paper provides insight into how haptic feedback can be used to increase pilot awareness of the flight envelope protection system and facilitate appropriate control decision-making in critical situations. Evaluation of experimental results is expected to provide further insight into the effectiveness of this system. This emphasizes the importance of practical testing and validation of the proposed system. The focus on scenarios close to the flight envelope limits, like wind shear and icing events, highlights the system's specific applicability in critical situations, where pilot awareness and precise control actions are crucial for safety.

In addition to haptic feedback, pilots also require information in the form of a visual interface that displays or visual warnings to assist them in keeping the aircraft within safe operational limits. Modern cockpits provide a wealth of information to pilots, primarily utilizing visual and auditory communication channels (Van Baelen et al., 2020). An example of a visual display is the Primary Flight Display (PFD) for the most critical aircraft status, and navigation displays for an overview of the environment from top to bottom in a planar manner. The PFD typically presents information such as speed, altitude, heading, angle of attack, and other crucial data necessary for the pilot to control the aircraft. Auditory signals are often used to convey important messages, such as warning the pilot of excessive speed and providing altitude readings along with commands to reduce speed during landing (Harris, 2004).

The application of vibrotactile (vibratory tactile) displays in aeronautics has received much attention. Vibratory tactile refers to a type of haptic feedback that uses vibrations or oscillations to convey information through touch (Ellerbroek et al., 2016). These tactile displays have been reported to be effective in improving flight attitude awareness for pilots and disengaging other sensory channels (Ouyang et al., 2017). As in (Salzer & Oron-Gilad, 2015) which evaluates the vibrotactile-based collision avoidance warning component placed on pilot's thigh in a tactical collision avoidance system (TCAS). The system aims to improve flight safety by enhancing helicopter pilots' situational awareness and reducing the probability of collisions. The on-thigh vibrotactile component was added to increase the assertiveness of the TCAS warning. Experimental results showed that the addition of tactile signals on the thighs improved pilots' response accuracy and shortened the response time to collision avoidance warnings. The tactile components did not interfere with pilots' ability to control flight, suggesting that the use of these tactile modules can be integrated without compromising flight control. Although the tactile module improved responses, participants' recall of identified landmarks decreased. This could have implications in further design related to the balance between rapid response to alerts and retention of information regarding the mission. This paper discusses the design implications of the findings, highlighting the importance of considering side effects such as memory reduction in the development of collision avoidance warning systems. This paper also provides insights into the use of vibrotactile components on thighs in the context of collision avoidance systems, with an emphasis on improving helicopter pilots' situational response and awareness.

In (Schmidt-Skipiol & Hecker, 2015), the paper acknowledges the continuous evolution of aircraft cockpits into complex environments with highly automated systems. It highlights the issue of human-machine interface (HMI) on modern sidestick-controlled aircraft using fly-by-wire technology. This research introduces tactile feedback to enhance situational awareness of the flight envelope. It combines flight envelope protection with tactile feedback using an active sidestick. To evaluate this concept in an experimental simulator study, a test environment simulating key aspects of the concept has been developed. The testing environment replicates key aspects of the proposed system, and pilots with varying flying experience are used to evaluate the impact on specific flight parameters. The analysis of the results indicates that the developed tactile feedback concept can potentially assist pilots in adhering to envelope limits, particularly in terms of maintaining specified values for speed, bank angle, and angle of attack. Despite positive indications, further research and development is still needed. Figure 3-2 shows the working mode on the sidestick.

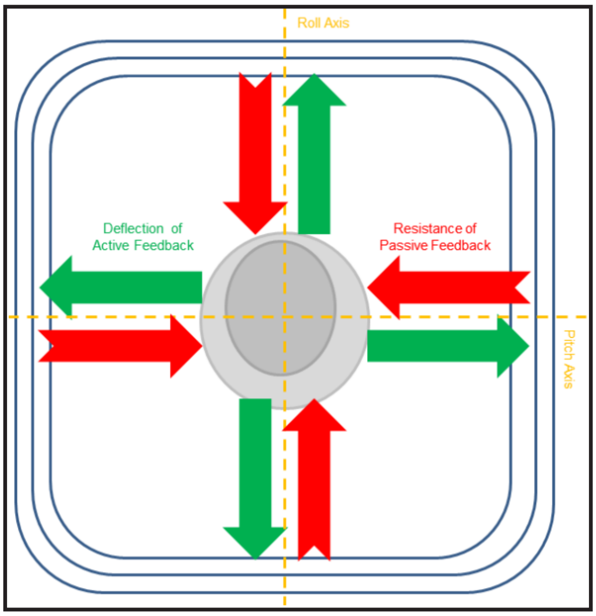


Figure 3-2. Action of active and passive tactile feedback modes (viewed on the sidestick from above) (Schmidt-Skipiol & Hecker, 2015)

The paper (Van Baelen et al., 2021) addresses the challenges associated with flight envelope protection systems in modern aircraft, emphasizing the potential for automation to cause mode confusion for pilots, even with visual or auditory feedback. This research identified that overriding pilot inputs by the flight envelope protection system can cause mode confusion, especially when visual or auditory feedback is provided to the pilot. The study assesses three haptic feedback designs for communicating flight envelope protection. Each design incorporates different elements, including force feedback, vibro-tactile alerts, and asymmetric vibrations. The first design, combining force feedback and vibro-tactile alerts, shows promising results, although the outcomes are inconclusive. This implies that further research or refinements may be needed to draw definitive conclusions about its effectiveness. The second design, using asymmetric vibrations for directional alerting cues, initially does not improve performance but exhibits an enhanced learning rate over time. This suggests the potential for improved effectiveness with continued use and training. The third design, employing force feedback to physically guide the pilot away from envelope limits, demonstrates immediate safety improvements but raises concerns about pilot dependence. Performance degradation occurs when the force feedback is removed, highlighting a need for careful consideration of potential drawbacks. Based on the findings, the paper recommends using asymmetric vibrations during training, leveraging active control interfaces for force feedback during operation, and exploring a combination of both approaches to optimize their advantages, particularly in single-pilot operations. This provides practical insights for integrating haptic feedback into flight envelope protection systems.

The paper (Ackerman et al., 2015) introduced an interface display system designed to enhance pilot situational awareness related to the flight envelope protection system developed for medium-sized transport aircraft. The focus is on developing a display that complements existing cockpit displays and provides additional information related to both aircraft state and control automation. The new display is designed to work in tandem with existing cockpit displays, indicating its complementary role in providing supplemental information rather than replacing current displays. This approach recognizes the importance of integrating new information seamlessly into the pilot's overall display. The new display is designed to work in conjunction with existing cockpit displays. This approach recognizes the importance of seamlessly integrating the augmented information into the pilot's overall cockpit view without causing cognitive overload. The paper outlines a forthcoming evaluation test plan, emphasizing the intention to validate the developed interface. Figure 3-3 shows a primary flight display consisting of flight instrumentation on a black background. The evaluation will focus on assessing the relevance of the displayed information and the adequacy of the display layout, ensuring that the augmented information effectively contributes to pilot situational awareness. The research addresses the practical application of the developed display in a real-world setting. By planning an evaluation test, the authors aim to demonstrate the effectiveness of the interface in improving pilot situational awareness and ensuring its practical relevance in operational scenarios.

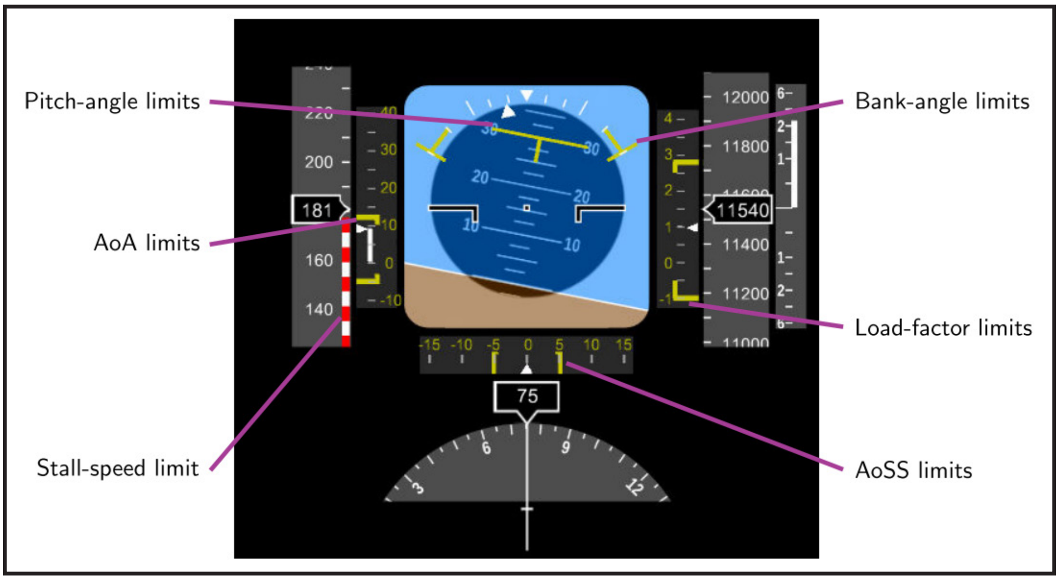


Figure 3-3. Primary flight display with the addition of flight envelope protection limits (Ackerman et al., 2015)

The paper (Khan et al., 2018) introduces the Flight Guardian system, an autonomous flight safety improvement tool designed to monitor aircraft cockpit instruments during in-flight emergencies. This research identifies that during in-flight emergencies, pilots' workload increases, and human errors often occur during these stressful periods, which can reduce flight safety. Research shows that many aircraft accidents can be attributed to ineffective cockpit instrument monitoring by pilots. The Flight Guardian system was developed to provide efficient flight deck awareness, improve flight safety, and assist pilots in abnormal situations, especially in older aircraft that are difficult to modify. The system was developed as a solution for older aircraft that are difficult or expensive to modify with modern digital avionics systems. One important feature of the Flight Guardian system is its non-physical connection to the aircraft. This design choice eliminates the impact on airworthiness and the need for re-certification, making it a cost-effective and feasible solution for older aircraft. The system integrates video analysis, knowledge representation, and machine belief representations to create a unique flight-deck warning system. This composite of techniques aims to provide a comprehensive and effective tool for monitoring cockpit instruments. The prototypes were tested in laboratory simulations and real flights with the guidance of expert pilots. The system performance was evaluated through statistical analysis of experimental results, proving the power of the methodology in generating automatic warnings in hazardous situations. The system has the potential to increase pilot awareness and provide automatic warnings in hazardous situations, which can contribute to flight safety, especially in older aircraft that have not adopted modern digital avionics systems. This paper presents an innovative solution in the form of Flight Guardian to improve flight safety and provide assistance to pilots during abnormal situations, focusing on effectively monitoring cockpit instruments. Evaluation of experimental results conducted in various environments reinforces the validity and effectiveness of this system.

4. Conclusions

Based on the analysis of the papers above, a general conclusions can be drawn regarding the use of technology and innovation in improving flight envelope protection and flight safety. Haptic feedback emerges as a promising tool to improve pilots' situational awareness of flight envelope boundaries and their ability to handle critical situations. This feedback, incorporating force, vibration, and tactile cues, provides intuitive information directly through control devices. Additionally, advancements in informative interface systems aim to enrich cockpit displays with real-time data, enhancing pilot understanding of flight conditions and emergency situations. Automated monitoring systems offer further safety enhancements by providing alerts and can potentially be retrofitted into older aircraft. Evaluation and testing in both simulated and real flight environments ensure the reliability and effectiveness of these systems. Overall, this paper review shows that the development of technologies and systems can make a significant contribution to flight safety and pilot situational awareness of flight envelope boundaries, so the possibility of aircraft accidents due to loss of control can be reduced.

Acknowledgements

The authors would like to thank Mr. Fadillah Hasim as the head of Research Center for Aeronautics Technology, BRIN for all support until this research's manuscript writing is done.

Contributorship Statement

All authors contributed equally to this work.

References

A Statistical Analysis of Commercial Aviation Accidents 1958-2016. (2016). https://flightsafety.org/wp-content/uploads/2017/07/Airbus-Commercial-Aviation-Accidents-1958-2016-14Jun17-1.pdf

Abbink, D. A., Mulder, M., & Boer, E. R. (2012). Haptic shared control: Smoothly shifting control authority? *Cognition, Technology and Work*, *14*(1), 19–28. https://doi.org/10.1007/s10111-011-0192-5

Accident Piper PA-25-235 Pawnee XB-ABM. (2023). https://aviation-safety.net/wikibase/345178

Ackerman, K. A., Seefeldt, B. D., Xargay, E., Talleur, D. A., Carbonari, R. S., Kirlik, A., Hovakimyan, N., Trujillo, A. C., & Belcastro, C. M. (2015). Flight envelope information-augmented display for enhanced pilot situation awareness. *AIAA Infotech at Aerospace*, 1–16. https://doi.org/10.2514/6.2015-1112

Airbus A320 Flight Crew Operating Manual (FCOM). (n.d.).

Airbus A330 Flight Crew Operating Manual (FCOM). (n.d.).

Airbus, S. A. S. (2008). *Airbus training-A320 flight crew operating manual: Flight controls*.

Association, I. A. T. (2022). *IATA Annual Safety Report-2022 Recommendations for Accident Prevention in Aviation 2 IATA Annual Safety Report-2022*. 11–44.

BEA. (2012). Final report on the accident on 1st June 2009 to the Airbus A330-203 registered F-GZCP operated by Air France flight AF 447 Rio de Janeiro – Paris (English courtesy translation). *Tech. Rep. No. June 2009*.

Belcastro, C. M., & Foster, J. V. (2010). Aircraft loss-of-control accident analysis. *AIAA Guidance, Navigation, and Control Conference*, 1–41. https://doi.org/10.2514/6.2010-8004

Belcastro, C. M., Newman, R. L., Crider, D. A., Klyde, D. H., Foster, J. V., & Groff, L. (2016). Aircraft loss of control: Problem analysis for the development and validation of technology solutions. *2016 AIAA Guidance, Navigation, and Control Conference*. https://doi.org/10.2514/6.2016-0092

Briere, D., & Traverse, P. (1993). Airbus A320/A330/340 electrical flight controls a family of fault-tolerant systems. *Digest of Papers - International Symposium on Fault-Tolerant Computing*, 616–623. https://doi.org/10.1109/ftcs.1993.627364

Committee, A. R. A. (2018). Task 4 – Warning Caution and Advisory Lights. *Federal Aviation Administration*, 3039–3039. https://doi.org/10.1007/978-1-4939-7131-2_101313

EASA. (2020). *Flight Envelope Protection - Certification Considerations*.

Ellerbroek, J., Martin, M. J. M. R., Lombaerts, T., van Paassen, M. M., & Mulder, M. (2016). Design and evaluation of a Flight Envelope Protection haptic feedback system. *IFAC-PapersOnLine*, *49*(19), 171–176. https://doi.org/10.1016/j.ifacol.2016.10.481

FAA. (2018). *Advisory Circular AC 120-109A - Stall Prevention and Recovery Training*.

FAA Human Factors Division. (2004). *Human Factors Considerations in the Design and Evaluation of Flight Deck Displays and Controls*.

Harris, D. (2004). *Human Factors for Civil Flight Deck Design*. Ashgate Publishing Ltd. https://doi.org/10.4324/9781315253039

Hutchison, D., & Mitchell, J. C. (2010). *Haptics: Generating and Perceiving Tangible Sensations*. *6192*(September). https://doi.org/10.1007/978-3-642-14075-4

ICAO. (2014). Manual on aeroplane upset and prevention recovery training. *ICAO Doc 10011 AN/506*.

Jacobson, S. R. (2010). Aircraft loss of control causal factors and mitigation challenges. In *AIAA Guidance, Navigation, and Control Conference*. https://doi.org/10.2514/6.2010-8007

Khan, W., Kingdom, U., Ansell, D., Kuru, K., Kingdom, U., Bilal, M., & Angeles, L. (2018). *Flight Guardian : Autonomous Flight Safety Improvement by Monitoring Aircraft Cockpit Instruments*. 1–14. https://doi.org/10.2514/1.I010570

KNKT. (2015). Aircraft accident investigation report, PT. Indonesia Air Asia, Airbus A320-216, PK-AXC. *Tech. Rep. No. December 2015*, *December 2014*.

Lambregts, A. A. (2013). Flight Envelope Protection for Automatic and Augmented Manual Control. *Proceedings of the EuroGNC 2013, 2nd CEAS Specialist Conference on Guidance, Navigation & Control*, 1364–1383.

National Transportation Safety Committee. (1997). Investigation of Aircraft Accident SilkAir Flight MI 185 Boeing B737-300, 9V-TRF Musi River, Palembang, Indonesia 19 December 1997 FINAL REPORT. *Aircraft Accident Report*, *DECEMBER 1997*.

National Transportation Safety Committee. (2007). *NTSC Aircraft Accident Investigation Report KNKT/07.06/07.02.35 NATIONAL*. *March*. http://knkt.dephub.go.id/knkt/ntsc_aviation/baru/Final report PK-GZC Release.pdf

National Transportation Safety Committee of Indonesia. (1997). Informe final investigación, 26 septiembre 1997, Garuda Indonesia, vuelo 152 (Accidente aéreo nº 49). *Asn*, *September 1997*. https://reports.aviation-safety.net/1997/19970926-0_A30B_PK-GAI.pdf

Niedermeier, D., & Lambregts, A. A. (2012). Fly-by-wire augmented manual control - basic design considerations. *28th Congress of the International Council of the Aeronautical Sciences 2012, ICAS 2012*, *4*, 3073–3086.

NTSB. (1986). *Aircraft accident report - China Airlines Flight 006*.

NTSC. (2018). *Preliminary Aircraft Accident Investigation Report, PT. Lion Mentari Airlines Boeing 737-8 (MAX); PK-LQP*. *8*(October), 1–68.

Ouyang, Q., Wu, J., & Wu, M. (2017). Vibrotactile display of flight attitude with combination of multiple coding parameters. *Applied Sciences (Switzerland)*, *7*(12). https://doi.org/10.3390/app7121291

Rogers, R. (1999). Pilot Authority and Aircraft Protections. *Air Line Pilots Association*, 1–53.

S.Megill. (2014). REPORT on the investigation into the crash of A310-308, registration F-OGQS, on 22 March 1994. *Antimicrobial Agents and Chemotherapy*, *58*(12), 7250–7257.

Salzer, Y., & Oron-Gilad, T. (2015). Evaluation of an “on-thigh” vibrotactile collision avoidance alerting component in a simulated flight mission. *IEEE Transactions on Human-Machine Systems*, *45*(2), 251–255. https://doi.org/10.1109/THMS.2014.2364721

Schmidt-Skipiol, F. J., & Hecker, P. (2015). *Tactile Feedback and Situation Awareness - Improving Adherence to an Envelope in Sidestick-Controlled Fly-by-Wire Aircrafts*. *October*. https://doi.org/10.2514/6.2015-2905

Shin, H. H., Lee, S. H., Kim, Y., Kim, E. T., & Sung, K. J. (2011). Design of a flight envelope protection system using a dynamic trim algorithm. *International Journal of Aeronautical and Space Sciences*, *12*(3), 241–251. https://doi.org/10.5139/IJASS.2011.12.3.241

ten Velde, T., Norden, C., & Bennetts, B. (2015). *Loss of Control In-Flight Accident Analysis Report 2010-2014*. https://www.iata.org/whatwedo/safety/Documents/LOC-I-1st-Ed-2015.pdf

Traverse, P., & Lacaze, I. (2004). *Airbus fly-by- wire: A total approach to dependability*. *January*. https://doi.org/10.1007/978-1-4020-8157-6

Van Baelen, D., Ellerbroek, J., van Paassen, M. M. R., & Mulder, M. (2020). Design of a haptic feedback system for flight envelope protection. *Journal of Guidance, Control, and Dynamics*, *43*(4), 700–714. https://doi.org/10.2514/1.G004596

Van Baelen, D., van Paassen, M. M., Ellerbroek, J., Abbink, D. A., & Mulder, M. (2021). Flying by Feeling: Communicating Flight Envelope Protection through Haptic Feedback. *International Journal of Human-Computer Interaction*, *37*(7), 655–665. https://doi.org/10.1080/10447318.2021.1890489