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Design of a Haptic Feedback System for Flight Envelope Protection

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Current Airbus aircraft use a fly-by-wire control device: a passive spring-damper system which generates, without any force feedback, an electrical signal to the flight control computer. Additionally, a hard flight envelope protection system is used which can limit the inputs of the pilot when approaching the edges of the flight envelope. To increase the situation awareness of the pilot, this research aims to provide intuitive information on the flight envelope through haptics, force feedback trough the control device, integrated in the existing Airbus control laws. The goal of this paper is to describe *when* and *how* haptics is used in this design. The pilot can get five cues of the flight envelope: when approaching the flight envelope a discrete force cue is given. Next, control inputs which move the aircraft closer to the flight envelope are indicated with an increased spring coefficient. Moving too close to the lower velocity limit activates a stick shaker: a vibration force on the stick. If a stick neutral position is not sufficient to return to the safe flight envelope, the stick is moved forward to the desired control input. Finally, following the automatic Airbus pitch up command during an overspeed condition, the stick is moved back to follow this command. This new system is expected to help identifying the situation and choosing a possible mitigation technique which is evaluated for two scenarios: when the aircraft is moving to the flight envelope, i.e. a windshear, or when the flight envelope moves towards the aircraft.

Acronyms

ADIRU	Air Data and Inertial Reference Unit
AL	Alternate Control Law
ELAC	Elevator & Aileron Computer
FAC	Flight Augmentation Computer
FCC	Flight Control Computer
FCOM	Flight Crew Operation Manual
FE	Flight Envelope
FEP	Flight Envelope Protection
FMGC	Flight Management Guidance Envelope Computer
LGCIU	Landing Gear Control Interface Unit
ND	Navigation Display
NL	Normal Control Law
PFD	Primary Flight Display
RA	Radio Altimeter
SEC	Spoilers Elevator Computer
SFCC	Slat Flap Control Computer
SFE	Safe Flight Envelope
THR	Throttle
TOGA	Take Off/Go Around

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Nomenclature

Greek Symbols
- α Angle of attack, rad
- δ Control device deflection, rad
- ρ Density, kgm^2
- γ Flight path angle, rad
- θ Pitch angle, rad
- ϕ Roll angle, rad
- β Side slip angle, rad

Roman Symbols
- a Acceleration, ms^{-2}
- D Drag, N
- F Force, N
- K Gain, -
- g Gravitational acceleration, ms^{-2}
- L Lift, N
- C_L Lift coefficient, -
- n Load factor, g
- m Mass, kg
- q Pitch rate ($\dot{\theta}$), $rads^{-1}$
- k Spring, $Nrad^{-1}$
- S Surface, m^2
- T Thrust, N
- t Time, s
- V Velocity, ms^{-1}
- W Weight, N

Subscripts
- a Aerodynamic reference frame
- b Body reference frame
- br Breakout
- E Vehicle-carried normal Earth reference frame
- max Maximal value
- np Neutral point
- nom Nominal value
- prot Protected region value
- safe Safe value

I. Introduction

If you glance in the cockpit when entering a typical passenger flight you can, without much effort, see the main source of information to the pilots: visual displays. Ranging from the Primary Flight Display (PFD) for the most important aircraft states, to the Navigation Display (ND) for a planar overview of the situation, the cockpit presents a high visual information density for the pilots. Besides the visual inputs, auditory signals are used for urgent messages such as too high velocities, or throttle back commands on landing. Combining both givens, it can be concluded that the information flow in the cockpit is mostly visual and auditory.

Aside from these senses, the human operator is able to perceive information in one more way: via tactile senses. Using the control device, the tactile sense used to provide another source of information on aerodynamic forces through the cabling of the control device, for example buffeting close to a stall, actuator saturation through hard stops of the controls, or other control related issues. With the introduction of fly-by-wire, the forces on the control surfaces and the control devices were decoupled, hence this source of information is not available to the pilots anymore.

Together with the advances in control devices, automation in cockpits is rising resulting in a more supervisory role instead of low-level manual control. Nevertheless, the pilot are still required to manually control the aircraft in landing or takeoff, or during emergency scenarios. An example of the latter could be a computer or sensor malfunction. If the pilots in that moment are startled by unexpected high-altitude dynamics, a dangerous situation can occur. An example of such an occurrence is Air France flight 447, where the crew lost the overview of the situation, albeit the information present from the visual and aural displays.[1] Since the aircraft did not have the usual protections, they manually pitched to an unusual high attitude and thereby stalled the aircraft. The fly-by-wire control device, an Airbus A330 side stick, did not provide the pilots with direct feedback on their control actions or the aerodynamic stall buffets and therefore did not help the pilots in identifying the situation as a stall. As this example shows, when manual control is needed, the lack of tactile information through the control devise might contribute to a reduced situation awareness.

A reason that haptic feedback was not fully integrated after the introduction of fly-by-wire system, is the device required to implement the forces. This used to be an issue because of the size, power and stability requirements. Nevertheless, nowadays low-weight reliable force feedback for control devices offer the possibility to re-introduce haptic feedback in the fly-by-wire control systems.[2] These new devices can be used to bridge the gap of the fly-by-wire systems: provide haptic feedback to increase the situation awareness of the pilots.

Some aircraft do include an augmentation force on the control device, which can be provided on both control devices linked to the surfaces, or fly-by-wire control systems. An example of this is the Q-feel force, which changes the stiffness of the controls with changing dynamic pressure/velocity in Boeing type aircraft.[3] Another example is a stick shaker or pusher, which warns the pilot of the proximity to the extreme states.[4] The control device can also be loaded with two springs to create a change in spring coefficient for large control deflections as in Airbus aircraft.

With the use of fly-by-wire, the forces on the control device are fully decoupled from the control surface deflections. This means that the augmentation as well, is not limited to the direct relation of control device and surface deflection, and much more options for haptic feedback are available. In the operational field, an example are the Boeing 777 controls. They have an increased (artificial) force when rolling beyond the safe roll limit, irrespective of the control surfaces.[5] The research field also shows a large interest for haptic, just one example is Stepanyan et al. They showed a study in which a predictive controllability limit which was shown to the pilot both visually and hapticaly.[6] Nevertheless, the latter study was continuously changing the neutral position of the control device and hence changing the reference point for an input. This change of reference might be an issue when going through certification and could present an unclear reference point to the pilot.

With the new haptic control devices, a new setup should be possible which gives more information on the limits of the aircraft during manual control, while still fitting in existing control architectures of modern fly-by-wire aircrafts. An initial study already showed a potential benefit of such haptic feedback system of which the current state is a follow on.[7] This paper elaborates on a new iteration and gives a more thorough description on the *how* and *when* of the haptics, as well as the expected practical implications.

Section II will first elaborate on a basic set of flying variables and the control laws present in a fly-by-wire Airbus aircraft. Next, this information is used to design the haptic display in Section III. Two scenarios show the expected operational impact in Section IV. Finally the conclusion and outlook are given in Section V.

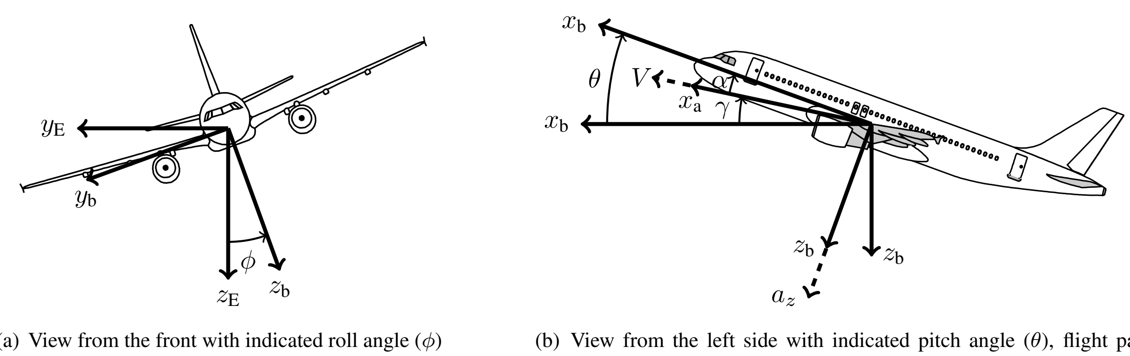
II. Flight dynamics and control laws

This section elaborates on the background used for the design of the haptic display. Subsection II.A covers the most basic variables for flight dynamics, readers with an aerospace background might want to skip this part. More important is the recap of the Airbus control law structure in Subsection II.B, as this determines the design in the following sections.

II.A. Flight Dynamics

This subsection explains a basic set of flight dynamics variables which are essential to understand the aircraft control laws and the application of the haptics. Note that this is a very brief summary, a full discussion on flight dynamics can be found in literature.[8]

For the lateral variables, the most important variable is depicted in Subfigure 1(a) as the roll angle (ϕ) which, for small pitch angles (θ), indicates how much the aircraft is tilted with respect to the horizontal plane.



(a) View from the front with indicated roll angle (ϕ)

(b) View from the left side with indicated pitch angle (θ), flight path angle (γ), angle of attack (α) and vertical acceleration (a_z)

Figure 1. The A320 model used in the research with most important angles indicated

When discussing longitudinal variables, the relevant angles are shown in Subfigure 1(b). The pitch angle (θ) depicts the angle of the nose of the airplane relative to the horizon. Next the flight path angle (γ) gives the elevation of the true velocity vector (V, which is relative to the air) with respect to the horizon, hence this angle indicates whether the aircraft is climbing ($\gamma > 0$) or descending ($\gamma < 0$). For the wings to generate lift, they need a flow of air under an angle of the body relative to the local velocity called the angle of attack (α). Finally the accelerations are expressed in the body reference frame, from which the most important, the vertical acceleration (a_z) is commonly expressed in load factor ($n = \frac{a_z}{g}$) and also shown in Subfigure 1(b).

From the longitudinal variables, especially the latter angle, angle of attack, is most important for the aircraft performance, as too large values can cause separation of the air from the wings: a loss of lift or stall. If this occurs the amount of lift generated by the wings diminishes and the aircraft is not able to fly anymore as it is being dragged down by the weight. This event has to be avoided in all situations, therefore pilots are trained to pay attention to the aircraft angle of attack.

Limits of the aircraft concerning longitudinal variables are commonly expressed in the Flight Envelope (FE), which shows a relation between aircraft velocity (V) and load factor (n) as depicted by the solid black line in Figure 2. The upper velocity limit (right-hand vertical line) is due to the maximum velocity created by aerodynamic and vibration limits, while extreme load factor values are determined by static structural limits. Lower velocity limits follow a quadratic relation with velocity due to the lift equation shown in Equation 1, where ρ is the density of the air, S is the lifting surface of the wing, and C_L is the lift coefficient:

$$L = \frac{1}{2}\rho V^2 S C_L \tag{1}$$

The latter coefficient (C_L) depends on the wing shape and on the angle of attack: the higher α, the higher the lift coefficient. As before, up to a maximum value where this coefficient suddenly drops and a stall occurs.

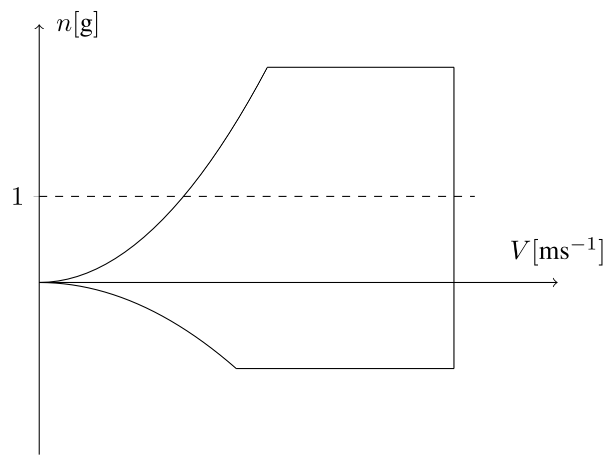


Figure 2. Flight Envelope, allowable velocity (V) versus load factor (n)

II.B. Airbus Control Laws

To better understand when the haptic feedback is applied, it is important to understand how the pilot controls the aircraft. As this research focuses on an Airbus A320, the main control device used is discussed: the side stick. All information in the following is retrieved from the A320 Flight Crew Operation Manual (FCOM).[9]

The side stick is a passively loaded, fly-by-wire, control device hence the feel is provided by springs and dampers, and it is not coupled to the actual control surfaces (ailerons, elevator), yet it produces an electrical signal to the Flight Control Computers (FCCs). The latter are responsible for converting the side stick deflections to required control input and combining them with the autopilot control commands to control surface deflections. As such, the FCCs can override what the pilot inputs and provide an extra layer of safety against aircraft states outside the allowed FE region. This procedure is called Flight Envelope Protection (FEP) and is applied for both lateral and longitudinal inputs as elaborated in the following.

The FCCs consist out of seven computers with three functions:

- 2 Elevator & Aileron Computers (ELACs): normal elevator and stabilizer control, constant aileron control
- 3 Spoilers Elevator Computers (SECs): spoilers control, standby elevator and stabilizer control
- 2 Flight Augmentation Computers (FACs): electrical rudder control

These computers are provided with information on the states by the following sources/sensors:

- Air Data and Inertial Reference Unit (ADIRU)
- Slat Flap Control Computer (SFCC)
- Accelerometers
- Landing Gear Control Interface Unit (LGCIU)
- Radio Altimeter (RA)
- Flight Management Guidance Envelope Computer (FMGC)

Within the Airbus philosophy and based on internal sensor validity checks, five different control laws are possible:

1. Normal Control Law
2. Alternate Control Law with reduced protections
3. Alternate Control Law without reduced protections
4. Direct law
5. Mechanical backup

This paper will not discuss in detail when each of the control laws is active, this can be further checked in the FCOM, yet a general guideline together with the control laws are discussed in the following. Note that we discuss the control laws from most till least assistance for the pilot, and that the direct law and mechanical backup are kept for completeness but not used in the following sections.

1. Normal Control Law

If all systems are functioning nominal, the FCCs operate in Normal Control Law (NL) and follow the default control behavior of the Airbus design philosophy. For both longitudinal and lateral pilot commands, the signal is interpreted as the reference signal for the autopilot as discussed in the following. Additionally, the FEP uses the following protections, also explained below:

- Bank angle limitation
- Load factor limitation
- Pitch attitude protection
- High-angle-of-attack proteciton
- High-speed protection

LATERAL CONTROL The FCC interprets lateral control inputs as commands to change the roll angle. From zero to 33° of roll, the side stick lateral deflection is a roll rate command, whereas the roll from 33° up to 67° is position control. If the roll is more than 33°, positive roll stability is present such that the aircraft rolls back to 33°. Therefore, if the pilot wants to execute a steep turn, constant input is required. To assist the pilot during normal turns, for roll angles up to 33°, an automatic pitch command is added such that the pilot does not need to maintain back pressure on the stick to compensate for the required increase in lift.

Finally, the FCC limits the maximum achievable roll at 67° which is the first hard envelope limit implemented by the FCC. A visual summary of the lateral controls law can be found in Figure 3.[9]

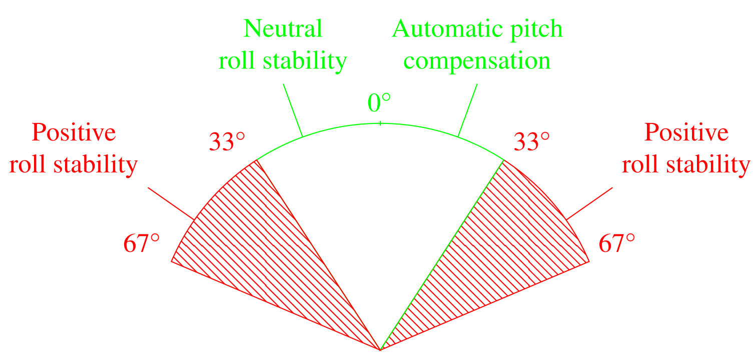


Figure 3. Lateral control in NL, based on A320 FCOM[9]

LONGITUDINAL CONTROL For longitudinal control, Airbus uses the C^* approach which is a combination of both pitch rate (q) and load factor (n).[9–12] It results in a rate control task for longitudinal control, such that in a low speed regime up to approximately 240 knots, the pilot controls pitch rate, and in high speed regions the main control variable is load factor[12]

On top of the C^* control law, protections are present on the pitch angle, angle of attack, and load factor. The limit on the pitch angle is without any buffer zone: when approaching the limit, the FCC gradually reduces the pitch rate until the maximum pitch angle is reached and no further control can be achieved. For the other two limits, angle of attack and load factor, there is a zone from a protected value up to the maximum value where the C^* control law is altered to provide position control from the control device deflection proportional to the variable approaching the limit.

For all three limits, the maximum value, and if applicable the size of the position control zone, depends on flight conditions and the state of the aircraft itself. Nevertheless, generally the limit of the pitch angle is between $-15°$ and $30°$, load factor is between $-1g$ and $2.5g$ with a zone of $0.5g$, and angle of attack lower as $12°$ with a zone of $2°$.

To prevent structural damage when controlling the aircraft at high speeds, a high-speed protection is also present. This protection triggers at the maximum operational velocity, or above depending on the configuration, and inputs a permanent nose-up command while reducing the nose-down stick authority to reduce the airspeed below the maximum, effectively creating an artificial high-speed stability. Note that the nose-up command cannot be overridden by the input of the pilot, even with full forward deflection. In order to avoid abnormal attitudes during this situation, the positive roll stability shown in Figure 3 roll the aircraft back to $0°$ and the maximum bank angle is limited to $40°$. These additional limitations are present until the velocity drops below the maximum velocity.

Figure 2 showed the nominal flight envelope. Here, we discussed the angle of attack (related to velocity through Equation 1), load factor and high velocity protections present in the A320 control laws. These protections can be visualized on the flight envelope as shown in Figure 4, where every state where no protection is active is defined as belonging to the Safe Flight Envelope (SFE). As can be seen on the figure, the protected zones provide a buffer for the pilot when approaching the limits.

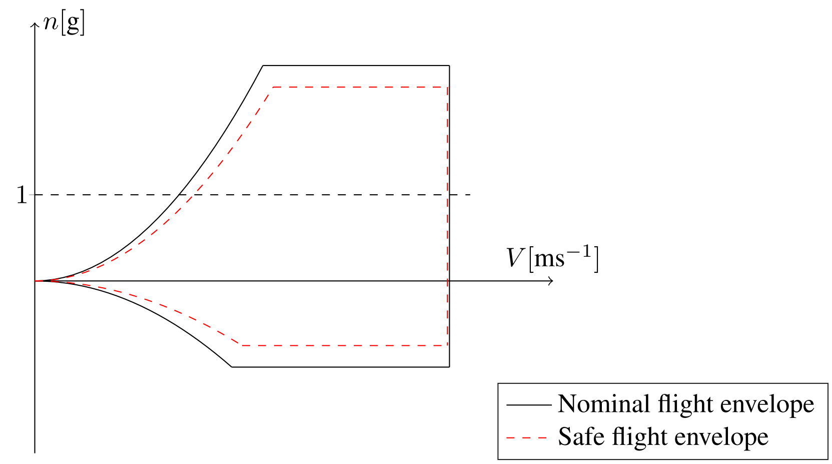


Figure 4. Flight Envelope with A320 longitudinal Flight Envelope Protection limits indicated

2. *Alternate Control Law with reduced protections*

In case of sensor or computer failures, the FCC reverts back to control laws which provide less support for the pilot. The first of these degraded control laws is the Alternate Control Law (AL), with reduced protections, which triggers when a dual failure of the computers are present.

LATERAL CONTROL Lateral control is now a direct stick-to-control-surface-position relationship. Hence the positive roll stability and the bank angle protection are lost. Furthermore, the autopilot disconnects at $45°$, requiring the pilot to take over control.

LONGITUDINAL CONTROL The control law for longitudinal control is not changed. The major change to NL with respect to safety is the loss of the angle of attack protection.

As mentioned before, the angle of attack is one of the prime factors for generating lift over the wings. Making this angle too large, and a stall occurs which can result in a crash. Although pilots are trained to avoid this event in all circumstances, because of reliance on the NL, a possibility exists for pilot to cross the maximum value in extreme workload conditions. This event should taken into consideration in the design of our new haptic system.

To assist the pilot in this control law, a region with low speed stability is introduced: 5 to 10 knots, dependent on the configuration, above the stall warning speed a nose-down signal is introduced. Additionally, the high-speed stability from the NL remains, yet the pilot is now able to overrule the imposed nose-up command.

3. *Alternate Control Law without reduced protections*

In some cases, for example when all three air data reference units fail, the control laws revert to even less protections. Both lateral and longitudinal control laws remain equal to AL with the protections, yet now the low- and high-speed stabilities are lost. The load factor limitation does remain available for the pilot.

4. *Direct law*

When all three inertial reference units fail, the RAs fail when the landing gear is down, or when flaps are selected while the LGCIUs disagree, the control law is reverted even more to direct law. In this law, side stick inputs are relative to control surface deflections.

LATERAL CONTROL Although direct stick-to-roll is low-level control, the FCC still aids the pilot inputting the right magnitude of inputs by scaling the control gains based on the configuration. Yaw damping and turn coordination are lost in this case, as is the maximum roll angle.

LONGITUDINAL CONTROL Stick-to-pitch direct control is aided by scaling the control gains with the center of gravity of the aircraft. In this control law, no protections are active and the pilot can therefore move the aircraft outside the flight envelope as commanded.

5. *Mechanical backup*

When a complete loss of electrical power is detected, the side stick is unusable due to the transducers used in the design. Therefore a mechanical backup is available which is a very basic and crude control.

LATERAL CONTROL Lateral control is achieved solely by operating the rudder pedals, without any direct roll control. Rolling is achieved due to the coupling of yaw and roll, as this is a slow response, Airbus does advice to gently do an input and wait for the response. Care should be taken to not exaggerate the input as to not over control the aircraft.

LONGITUDINAL CONTROL The mechanical backup for the pitch control is by manually trimming the horizontal stabilizer. Again, this provides a slow control method and should be executed with caution.

III. Haptic Display Design

This section describes the haptic display that is used to show the FE boundaries to the pilot. First the definition of haptic feedback for this research is shown, followed by the goal of the support system. Next the information used to elaborate on *how* and *when* haptic feedback is provided in the current design.

The haptic feedback for this research is defined by changing the haptic profile which is the relation between the deflection of the control device (δ) and the amount of force required (F). A typical profile is a piece-wise linear relation as shown in Figure 5. δ_{np} is the position of the control device when no force is applied, hence the neutral point, and δ_{br} is the position of the break point. Additionally k_{br} is the spring coefficient within the break point ($\delta_{\text{np}} - \delta_{\text{br}} < \delta < \delta_{\text{np}} + \delta_{\text{br}}$). Finally k^+ and k^- are the spring coefficients for, respectively, positive and negative control device deflections.

By changing the haptic profile, the feel on the controls presented to the human operator can be altered. A literature overview for automotive haptics gives two ways in which it can be applied: using a forcing function (vibrations) or a change in the neutral position (perceived as a guidance force).[13] In the aerospace field, literature indicates that haptics can be applied as well using a forcing function,[14] as a change in neutral position[6] and additionally using a change in slope of the haptic profile (stiffness change).[15] Summarizing, in this research haptics is achieved using three different cues, which are elaborated below:

- Change in position of the neutral point (δ_{np})

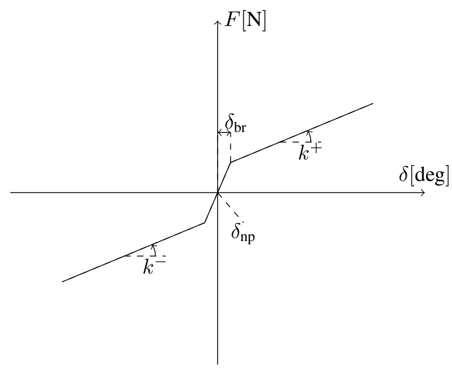


Figure 5. The nominal control device profile: required force exerted (F) versus deflection (δ)

- Addition of forcing function on the control device
- Change in spring coefficient for positive and/or negative positions (k^+ and/or k^-)

As mentioned, the FE given in Figure 6 shows the allowed load factor and velocity combinations in which the aircraft can be operated by a solid line. Although all of the FE is achievable, it is not feasible for continuous safe flight, especially near the edges. Therefore the boundary region is indicated by a dashed line as explained before, with the inside called the SFE: it indicates the states with sufficient margin to the limits for safe flight.

Subsection II.B showed how the locations outside the SFE have a change in control law (for example changing from $C^*$to α-position control when approach the maximum angle of attack). As such the control law provides some information on the proximity to the boundaries of the FE, nevertheless it still has to be inferred from the aircraft reaction.

For the current research, the goal is to use the haptic cues shown above to provide clear information on the proximity of the current state to the FE, hence increasing the situation awareness of the pilots. Additionally, a possible mitigation strategy can be suggested to the pilot by indicating undesired actions. Since this design focuses on communicating the FE boundaries to the human operator, only longitudinal haptic feedback is considered, lateral haptic feedback can be added in a next iteration.

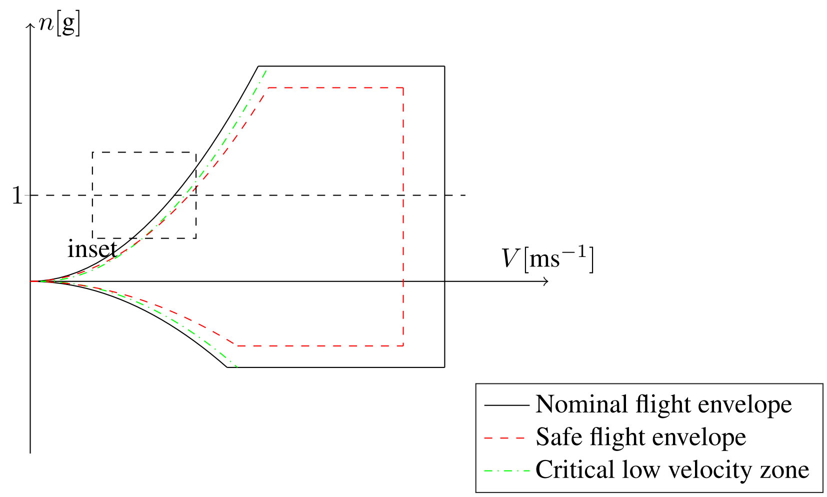


Figure 6. Flight envelope, velocity (V) versus load factor (n)

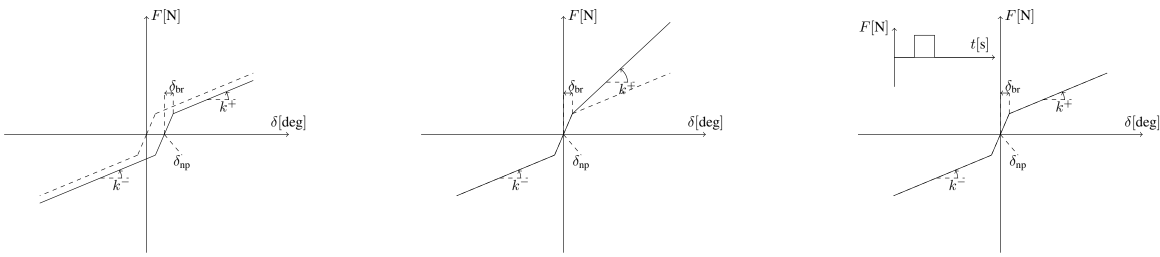
Note that the FE used for the design of the haptic display presented in Figure 6, has two differences with respect to the FE for Airbus control laws shown in Figure 4:

- Decreased upper limit for the velocity of the SFE to provide a buffer of 20 knots
- Added critical low velocity zone elaborated with the forcing functions

In normal operations, the aircraft is operated within the SFE in the Normal Control Law. If abnormal situations do occur, as discussed in Subsection II.B, the aircraft can revert to an Alternate Control Law in which less protections are active and the pilot has more control to move outside the FE. In the current stage, the haptic display is designed such that in both cases, NL and AL, the behavior is identical. The full haptic display is still applied in AL since the intensities of the cues are chosen such that a pilot can still overrule all haptic signals and therefore has the final control of the side stick. Hence in both conditions, if the aircraft is maneuvered outside the SFE the haptic cues discussed below, based on the literature search, are designed such that it should help the pilot identifying the situation and choosing a possible mitigation technique.

III.A. Neutral point shift

The position of the neutral point is altered by changing the value of δ_{np}. If applied, the information provided by the haptic display is directly proportional to a required control command hence the pilot can just follow the position. If the pilot does not agree, he/she can choose to override the cue by actively counteracting the cue by using co-contraction of the muscles.[16] Nevertheless, the shift in neutral position gives a clear message to the pilot on what he/she should do. The effect of this change in neutral position on the profile can be seen in Subfigure 7(a) by the shift of the entire graph to the right.



(a) Positive shift in position of the neutral point

(b) Increased spring coefficient for positive deflections

(c) Added positive (push) pulse

Figure 7. Altered control device profiles

The effect of a change in neutral point is a required control input, in Airbus philosophy, a required load factor command. Therefore, for the cases discussed below, the goal is to find the required load factor change which can be translated to a required change in neutral point. If δ is the displacement of the stick, and zero stick deflection gives a command load factor of one, the required shift in neutral point can be determined using:

$$\Delta\delta_{\text{req}} = \frac{\delta_{\text{max}}}{n_{\text{max}} - 1}\Delta n \tag{2}$$

If the required change in neutral point calculated with Equation 2 would be implemented immediately, abrupt changes in the control feel can be observed. Hence the change in neutral point could be perceived more as an alert cue, whereas the idea is to form a guidance cue. Therefore the required change in neutral point ($\Delta\delta$) is ramped in linearly using Equation 3 where $\delta_{\text{np}}$is the current neutral position, $\delta_{\text{np}_{\text{prev}}}$ is the previous neutral position, dt is the time difference with the previous step, and the rate is given by $\dot{\delta}$. This is a recursive formula which can easily be implemented in a simulator.

$$\delta_{\text{np}} = \min\left(\Delta\delta_{\text{req}}, \delta_{\text{np}_{\text{prev}}} + \text{dt}\dot{\delta}\right) \tag{3}$$

In the current design, the neutral point shift is used for those cases in which a zero stick input is not sufficient to return to the SFE: in case of overspeed, and at g-loadings for low velocities.

1. Overspeed

When an overspeed occurs, the speed has to be reduced actively by the pilot by either reducing the throttle, or by pitching up such that kinetic energy is exchanged for potential energy. In the current state, the Airbus control law will implement a forced nose-up command (see Subsection II.B), which could be translated to a change in neutral point. Nevertheless, the actual implementation of this signal is not known for this research, hence a new signal has to be designed. The main reason for this cue is to inform the pilot that stick at zero input does not solve the FE violation, therefore action has to be taken. Note that this research has one change with respect to the A320 FEP: the nose-up command is implemented when crossing the high velocity boundary of the SFE as depicted in Figure 6.

For this research, the nose-up command, and therefore the magnitude of neutral point shift, is governed by the change in load factor required to bring the positive acceleration to zero. It is determined by starting from the longitudinal equation of motion,[8] here it is assumed that thrust is parallel to the body:

$$T\cos(\alpha) - D - W\sin(\gamma) = m\frac{dV}{dt} \tag{4}$$

From this equation, the flight path angle (γ) can be controlled directly by moving the side stick. Therefore, as before, the neutral point is shifted to obtain a flight path angle such that there is no positive acceleration (hence $\frac{dV}{dt} = 0$). Since the aircraft is accelerating, the left part of Equation 4 is not zero and can be rewritten to obtain a steady flight path angle:

$$\gamma_{\text{steady}} = \arcsin\left(\frac{T\cos(\alpha) - D}{W}\right) \tag{5}$$

The thrust and drag cannot be measured directly, yet the effects can be measured by the current acceleration. Note that the accelerations are measured in the body axis reference frame and therefore need to be rotated to the velocity reference frame:

$$T\cos(\alpha) - D = ma_{x_a} = m\left(\cos(\beta)\cos(\alpha)\, a_{x_b} + \sin(\beta)\, a_{y_a} + \cos(\beta)\sin(\alpha)\, a_{z_a}\right) \tag{6}$$

Combining Equation 5 with Equation 6 results in the required change in flight path angle for zero acceleration ($\gamma_{\text{steady}} - \gamma$), expressed in measured quantities.

As discussed above, the side stick gives load factor commands for high velocities and therefore a relation between change in flight path angle and load factor is required. Load factor is governed by the time derivative of the flight path angle, therefore a tuning factor ($K_{\text{overspeed}}$) is chosen which gives the time it takes to recover to zero acceleration:

$$n = \frac{V\tan(\dot{\gamma})}{g} = \frac{V\tan\left(\frac{\gamma_{\text{steady}} - \gamma}{K_{\text{overspeed}}}\right)}{g} \tag{7}$$

Finally the required change in load factor is implemented on the side stick using Equation 2.

2. G-loading for low velocities

As mentioned before, the stick neutral position commands a load factor of one. If the velocity drops too low, hence too far to the left on Figure 6, zoomed on Figure 8, returning to load factor one is not sufficient to re-enter the safe flight envelope and the pilot has to be informed that immediate action is required.

This is again done by shifting the neutral point of the side stick. The prerequisites for this cue is that: the current safe load factor is below one (star on Figure 8) and the current load factor is above the safe load factor. The magnitude of the change is then proportional with the difference in current and safe load factor (Δn_{req}) and implemented using Equation 2.

III.B. Forcing function

If an additional forcing function is added to the control device, the whole profile is shifted vertically up or down. Depending on the magnitude of the cue, it can change the control device location. As this cue is predominantly used to alert or warn in this design, not to impose a required control input, the forcing function used should be of small period, or small amplitude. Since the effect is short in timespan, the effect on the haptic profile is shown by an added graph as shown in Subfigure 7(c), where zero time is current and times to the right represent past times. A pragmatic approach is used to evaluate whether the cue complies with the assumption of small period or amplitude. Within the forcing function cues, two groups can be distinguished: discrete and periodic cues.

Note that the addition of a forcing function and a pure change of neutral point both result in a change of position of the control device. Nevertheless, their driving principle is different: a forcing function does not have a predefined effect on the control position, for example adding a small force in the breakout results in almost no control device displacement. In contrast, a pure neutral point shift results in one desired control input as to guide a pilot through a maneuverer.

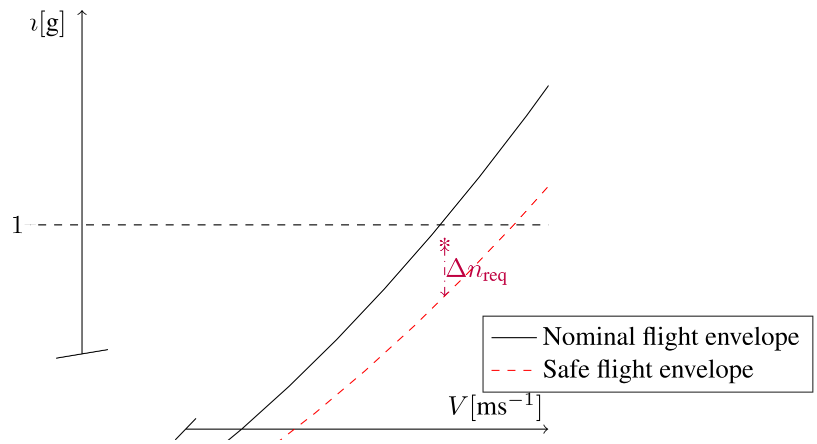


Figure 8. The amount of load factor change required when flying at low velocities, inset from Figure 6

1. *Discrete cue*

Discrete cues are limited in time and can have a wide variety of shapes, ranging from a square block signal to a noise input. They can be a useful tool to warn the pilot of entering a certain region, while not giving a constant signal.

One region which can be entered, with or without the intention of the pilot, is the protected region close to the edge of the FE. An example when entering this zone can go unnoticed by the pilot, is when he/she is scanning the instruments, or when busy with other tasks. Therefore, to provide a clear transition cue when exceeding the SFE shown on Figure 6 by the dashed line, a warning cue in the form of a discrete block signal (width $0.1s$, magnitude $10N$, shown in Subfigure 9(a)) is given. By adding this cue, the pilot is triggered about the SFE departure and the attention is drawn to the event.

The direction of the cue is the correct action for the pilot to follow if he/she wants to solve the limit violation. Hence a stick forward cue is given for extreme positive load factors, high angles of attack for positive load factors, and low velocity violations. A stick backward cue is given at all other boundaries.

2. *Stick shaker*

A periodic cue is a signal which is repeating itself in time, which can be used to alert the human operator of an imminent critical state. An example is the motor priming used by Navarro et al. to warn the driver of a lane departure event in the automotive field.[17]

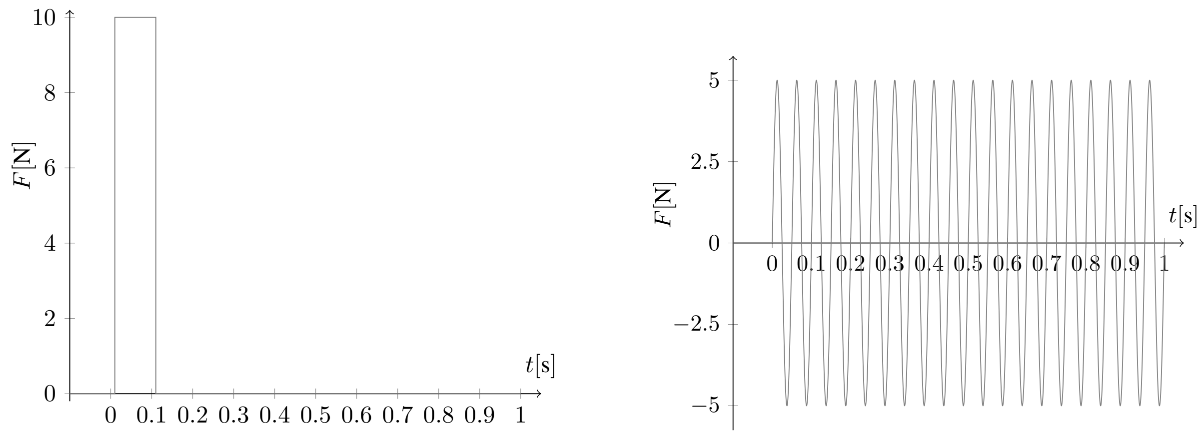
In analogy to the lane departure event which results in failure, in aerospace one limit in particular has to be avoided at all times: exceeding the maximum angle of attack. If this would occur, as mentioned before, a stall occurs which could potentially lead to a crash if not properly handled. To have extra attention to the proximity for this angle of attack limit, a second forcing function is added: a stick shaker following a sinusoidal forcing function with a frequency of $20Hz$ and $5N$ amplitude as shown in Subfigure 9(b).

The stick shaker is activated when the velocity drops below half of the protected range (hence $\frac{V_{\alpha_{\text{max}}} - V_{\alpha_{\text{prot}}}}{2}$). In terms of the flight envelope, this means that close to the left limits of the FE, indicated on Figure 6 with a stripe-dotted line, the stick shaker activates.

III.C. Spring coefficient

Finally, the change in spring coefficient is only observable for positions away from the neutral point, hence when the pilot is actively controlling. Therefore this haptic cue does not change the control input itself. The effect of this change in profile can be seen in Subfigure 7(b) where k^+ is increased, hence the slope of the profile is higher above the neutral point. This cue can be used to indicate a non-desired control deflection to the pilot.

In order to transfer information on the relative distance to the maximum values, this continuous spring cue is used. Starting from the boundary of the SFE to the maximum value of the nominal FE, the stiffness of the side stick is increased in the direction of the violation of both the load factor and the velocity. Note that for this cue, the haptic



(a) Stick push function

(b) Stick shaker

Figure 9. Continous Forcing functions used

display triggers on the maximum and protected angle of attack instead of the velocity, nevertheless these variables can be linked using Equation 1.

The violation region of the SFE is shown in Figure 6 where the violation starts at the dashed line (the SFE) and is most severe at the solid line (the nominal FE). For both the load factor and the angle of attack, here ν is used as generic symbol, the default stiffness is multiplied with a factor K_k, determined by the gain K_ν and the severity of the violation. The severity is defined as the ratio of the violation of the SFE ($\nu - \nu_{\text{safe}}$, where ν_{safe} is the value at the border of the SFE) and the distance between the safe and nominal FE ($\nu_{\text{nom}} - \nu_{\text{safe}}$, where ν_{nom} is the value at the border of the nominal FE).

$$K_k = 1 + K_\nu \frac{\nu - \nu_{\text{safe}}}{\nu_{\text{nom}} - \nu_{\text{safe}}} \tag{8}$$

The direction of the stiffness cue is inversed from the discrete cue, hence the stick feels stiffer for backwards movement for extreme positive load factors, high angles of attack for positive load factors, and low velocity violations. The other violations of the SFE have increased stiffness for forward movement.

As the direction is opposite of the discrete cue, this stiffness cue informs the pilot of control actions which will bring the aircraft closer to its limits.

If a much larger spring is suddenly implemented, a large increase in force can be observed by the pilot as a forcing function, not as a continuous cue. Therefore, to avoid these abrupt changes, the change in spring is ramped in using a linear time similar to Equation 3.

IV. Operational test scenarios

In order to show the operational value of the new haptic system, this section discusses two operational scenarios during which the system can give the pilot more intuitive and useful information. The first example describes a case in which the circumstances require the pilot to maneuverer to the edges of the limits: a wind shear. A second example shows how the pilot can use the system when the FE is shrinking, and the limits are the pilot: icing. For both scenarios, the origin of the event, the required actions to be taken by the pilot, and how the new haptic system supports the pilot in giving these actions is discussed in the following subsections.

IV.A. Wind Shear: aircraft moves towards the limits

A wind shear is a meteorological condition in which a larger cylinder of air drops towards the earth.[18] When this cylinder plunges on the earth surface, the air spreads out as can be seen in Figure 10 and the numbers corresponding to the following text. If an aircraft flies through this phenomenon, the headwind initially causes the airspeed to increase as in 2. When the pilots fail to recognize the windshear and do not take action, the following downwind pushes the aircraft towards the ground (3) and the tailwind drastically reduces the velocity (4). Near the final stage of the recovery, the aircraft is flying with high throttles settings and almost level flight, a potential problem is an overspeed (5). All wind vectors combined, this phenomenon forms a severe risk to the safety of the flight, especially during take-off or landing when already close to the ground. Here, it is vital that the pilot uses all available performance of the aircraft to climb irrespective of forward velocity, with one catch: the aircraft should not be stalled.

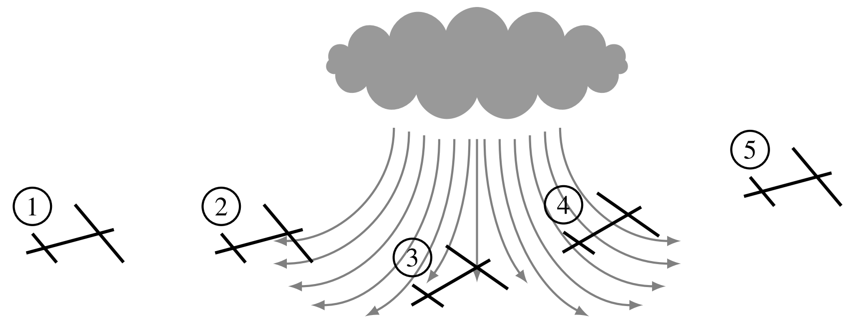


Figure 10. Weather structure during wind shear

If this event occurs with the autopilot active, most actions are handled automatically. Nevertheless, as manual flight is the focus of this research, the autopilot will not be available. Therefore the pilot has to perform a set of actions stipulated by the manufacturer and described in the FCOM.

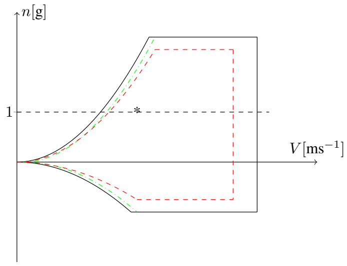
The initial warning for the pilot of the oncoming event is a visual and an oral warning: a red "WINDSHEAR" message on the PFD and a synthetic voice which announces "Windshear" three times. At this point the pilot has to take the following actions:[9]

1. Do not change configuration (flaps, slats, gear) until out of the windshear
2. THR levers at TOGA
3. Initial pitch attitude of $17.5°$
4. Increase pitch if necessary to minimize loss of height above terrain
5. Closely monitor flight path and speed
6. Recover smoothly to normal climb out of shear

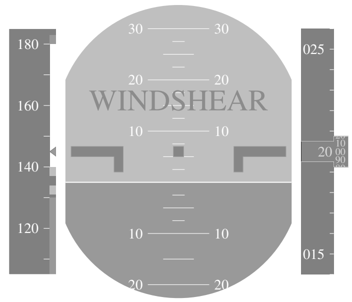
The first step is a straight forward command to make sure no time is lost before starting recovery. Next, step 2 is to make sure maximum energy is available, followed by an initial pitch attitude to start increasing altitude. Steps 4 and 5 are crucial to the safety of the aircraft: this is a trade-off between on the one hand reducing altitude loss and on the other hand keeping airspeed. In case of an extreme wind shear, this recovery procedure might require the pilots to move dangerously close to the limits of the flight envelope, namely at very low velocities as to use all available energy to climb out of the shear. The final step makes sure that, when clear of the dangerous winds yet still with high throttle settings, the velocity does not increase beyond the upper boundary.

Throughout the procedure, the pilot might be suffering from an intensely increased workload and a possible tunnel-vision on the loss of height. Figure 10 shows the windshear, as well as five selected time frames throughout the recovery procedure. The first of these frames is the starting point when the windshear-warning is active, the FE, PFD and corresponding haptic profile can be seen in respectively Subfigures 11(a), 11(b) and 11(c). After this initial warning, the haptic system is expected to help in the following steps (corresponding to the list of actions stipulated by the FCOM):

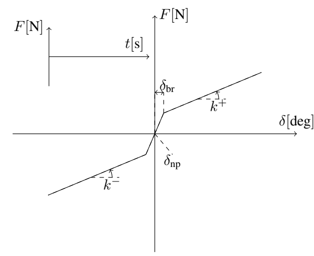
3. If a violent pitch-up maneuver is executed, the pilot is informed of the g-loading limit by the load factor protection cues.
4. During this step as much energy as possible should be used to climb, the haptic system is expected to aid in recognizing the actual limits. The initial cue of approaching limits is the discrete cue, corresponding to frame 3 in Figure 11.
5. As the pilot has to divide the attention over two gauges (velocity and altitude) and possible tunnel-vision is present on the vertical speed, the haptic system is expected to serve as a velocity-monitor aid. This goal can be achieved by both the continuous spring cue and the change in neutral position for low velocities as illustrated in frame 4 in Figure 11. Additionally, we expect the pilot to use the stick shaker as a control aid by "riding the stick shaker": adjusting the input such that the stick shaker remains on the verge of activation.
6. When approaching the upper limit on velocity, the high velocity cues alert the pilot of imminent limit violation with an extra control aid by following the stick backwards position, shown in frame 5 in Figure 11



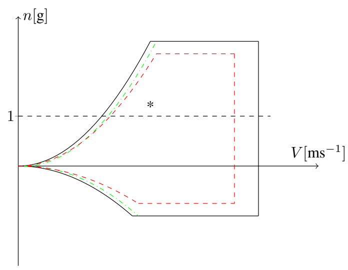
(a) FE for frame 1



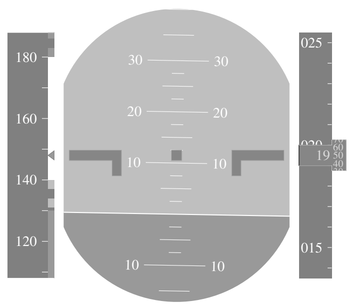
(b) PFD for frame 1



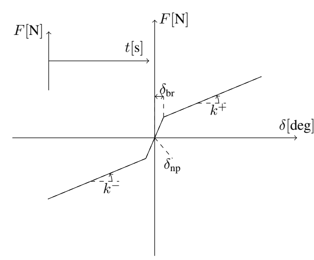
(c) Haptic profile for frame 1



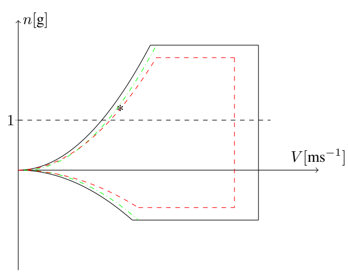
(d) FE for frame 2



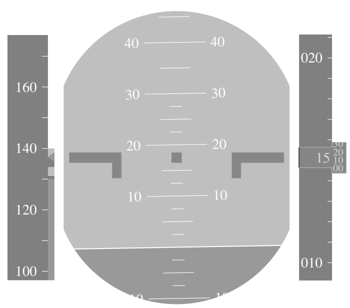
(e) PFD for frame 2



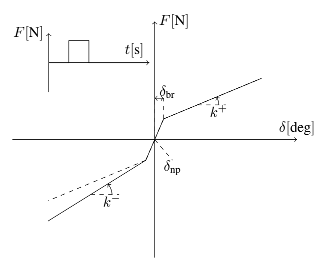
(f) Haptic profile for frame 2



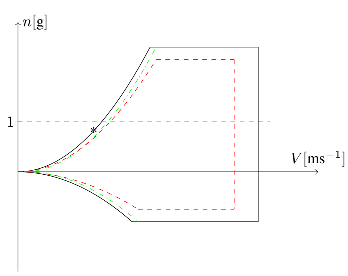
(g) FE for frame 3



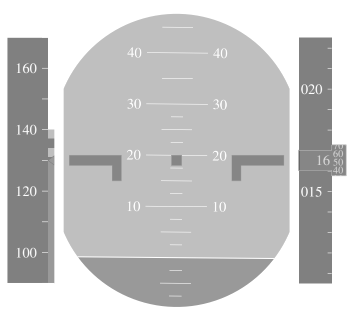
(h) PFD for frame 3



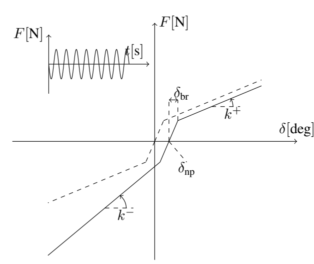
(i) Haptic profile for frame 3



(j) FE for frame 4

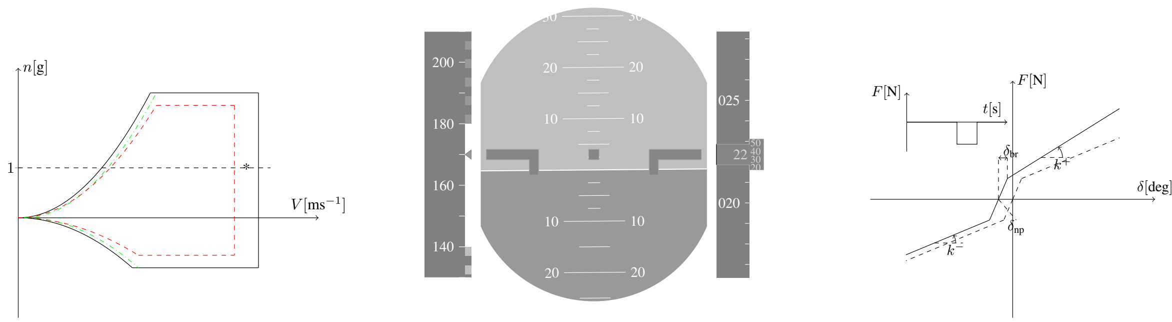


(k) PFD for frame 4



(l) Haptic profile for frame 4

Figure 11. Windshear recovery procedure according to the frame selected in Figure 10. FEs show the current state by a star. PFDs show left velocity, right altitude, and center pitch.



(m) FE for frame 5 (n) PFD for frame 5 (o) Haptic profile for frame 5

Figure 11. Windshear recovery procedure according to the frame selected in Figure 10.
FEs show the current state by a star. PFDs show left velocity, right altitude, and center pitch. (continued)

In general, for each of the steps the discrete block cue is expected to alert the pilot for an approaching limit, followed by the continuous spring cue to communicate the distance to the limits.

IV.B. Icing: limits move towards the aircraft

The second scenario presented to the pilot is an extreme form of ice formation on the wings of the aircraft. Especially when flying through cold humid air, the risk of such an event is severe.[19] The effect of ice formation is a degeneration of the aerodynamic properties resulting in reduced lift from the wings, hence an increase in minimal velocity. This highlights the main difference with the previous scenario: in this case the limits of the aircraft approach the pilot and he/she has to identify this change and react.

An example case of such an event is during an instrument landing in which the landing is performed in the clouds. If extreme ice accumulation is present, or when the de-icing system is not sufficiently working, the process of ice formation is inherently a slow yet detrimental process. In this way, the pilot might initially not be aware that the aerodynamic properties change.

The pilot can notice the degradation of the aerodynamic properties due to icing primarily from these clues:

1. Increase in drag requires a higher throttle setting
2. Decrease of lift generation requires a higher angle of attack

Especially when the pilot is flying with the auto-thrust active, the increase in throttle setting can be more difficult to notice and, as the Airbus-types by default do not have an angle of attack display, pilots might be unaware of the creeping danger. Nevertheless, the new feedback system uses information on the angle of attack sensor, and therefore the pilot will get new information without adding another element on the, already comprehensive, visual display.

When the icing is forming, the minimal velocity is increasing as stated before. If the pilots do not react to this, the first signal from the haptic display is the discrete cue when exiting the SFE. At this point, the pilots should be aware that something is going on. Additionally, they have received the correct action by the direction of the cue: reduce the angle of attack. When the pilot would keep controlling in the low velocity region, the increased spring coefficient for negative deflections (pull) indicates them that pulling should be executed with caution. Finally, crossing the stick shaker activation threshold gives a clear cue that a stall is imminent.

In conclusion, it can be expected that the new haptic display increases the knowledge of the pilot on the edges of the flight envelope and helps identifying abnormal situations.

V. Conclusion and Outlook

Current Airbus aircrafts, like the A330 and A320, use a passive spring-damper system to generate the feel on the control device. They also employ a hard Flight Envelope Protection system which limits the inputs of the pilot to the system. If a sensor failure occurs, the system reverts back to less protected control in which the pilot is able to go beyond the limit. When the pilot does not realize this, the limits can be approached without being aware of this. Therefore a new intuitive way of conveying this information is required. A possible approach is found in haptics: changing the feel of the control device to convey information on the limits of the Flight Envelope. This paper focuses on the design of such a system.

The feel on the control device, or haptics, is expressed by a relation between control device deflection and force required. Three possible forms of haptics are discussed: first the addition of a forcing function which can be used to indicate a critical and imminent state, secondly a change in neutral position which indicate a required control input, and thirdly a change in spring stiffness for one direction to show a non-desirable control input to the pilot.

Using the Flight Envelope, a relation between achievable velocity and allowable load factor (proportional to vertical acceleration), five locations of haptic feedback are identified. A discrete cue is given when approaching the limits indicating the correct control input to mitigate the violation. Next, the spring coefficient in the non-desired control deflection is increased when approaching the limit even more. Thirdly a stick shaker is activated when getting dangerously close to the minimal velocity, that is, even closer as the previous two cues. Finally the control device is moved to the desired control input during an over speed event, or when a stick neutral position is not sufficient at low velocities.

To show the operational value of the design, two scenarios are elaborated: a wind shear encounter, and an icing event. The first scenario involves a cylinder of air dropping to the ground which the aircraft is traversing. In order not to crash, the pilot should maneuver dangerously close to the limits. It is expected that the haptic system enables the pilots to move closer to the edges of the Flight Envelope. Next the icing scenario decreases the performance limits of the aircraft. In order to execute a safe flight, the pilot should identity this event and use a more cautious approach. For this scenario, the haptic system provides an alerting cue on the changing properties and should help the pilots identifying an abnormal situation.

This paper forms the basis of the design in the current stage. The next step after this paper is to finalize the implementation of this system in the research simulator available in the department. Once completed, professional pilots will be invited to fly scenarios in which the limits are encountered and their behavior and performance is recorded. With the results, the scenarios will be tested and it can be decided whether haptic feedback, in the current setup, is a useful addition to the flight deck.

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