Demonstration of an Active Sidestick in the DLR Flying Helicopter Simulator (FHS)

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Abstract

An active cyclic sidestick was successfully integrated in the DLR fly by wire Flying Helicopter Simulator (FHS) in which it was evaluated in flight with 6 pilots taking part in the test program. Tactile cueing functions to reduce pilot workload and to demonstrate operational benefits were developed. These were: 1) a mast bending moment limitation, 2) a g-load limitation with cueing in the longitudinal cyclic axis, and 3) a flight guidance function for a standard rate IFR-turn. The latter 2 functions were evaluated in flight. Positive remarks were received. The flight guidance function was workload rated and showed noteworthy reductions and better situational awareness. Another topic was the evaluation of control force parameters suitable for the short pole highly versatile sidestick.

List of abbreviations

APC	Aircraft-Pilot-Coupling
DLR	Deutsches Zentrum für Luft- und Raumfahrt / German Aerospace Center
FCS	Flight Control System
FHS	Flying Helicopter Simulator
HMI	Human Machine Interface
IAS,TAS	Indicated AirSpeed, True Airspeed
MFD	Multi Function Display.
NASA-TLX	NASA Task Load Index.
SAS	Stability Augmentation System

List of symbols

A_{MM}	Absolute magnitude of mast bending moment
a_z	Acceleration in airframe z axis
β	Absolute tip path plane tilt angle
δ_{lon}, δ_{lat}	Long. and lateral pilot input
g	Gravity. 9.82 m/s^2
k_Ψ,k_Φ,k_p	Control feedback gains in the standard rate IFR turn function
$k_{\dot{\delta}lon}$,k_{az}	Control feedback gains in g-load limitation
Ψ_β, $\Psi_{softstop}$	Direction, relative to x-axis, of: Tip path plane tilt and of softstop
$\Phi_{command}$, $\Psi_{command}$	Commanded bank angle and heading in feedback loop for standard rate turn
$radius_{softstop}$	Distance from inceptor position to onset of softstop force
$softstop$	Control deflection position of force onset of softstop tactile cue.

Introduction

The traditional helicopters mechanical control inceptors are a proven interface between pilot and airframe. Yet, a promising new concept has been emerging for some time now. The active sidestick/inceptor is a control input device that generates the mechanical forces perceived by the pilot using electric motors. This allows a high degree of freedom in the design of the human machine interface (HMI). Not only are the traditional spring-mass-damper forces rendered, but also a wide range of additional tactile (or haptic) elements are possible. The advantages are far ranging: from distinct "helping forces", called tactile cues, perceived by the pilot to adaptability for individual pilot physiology and preferences. This paper treats both subjects and their impact on the situation in the cockpit.

The DLR in Braunschweig is operating the fly-by-wire/fly-by-light research Flying Helicopter Simulator (FHS) shown in figure 1(a). The helicopters mechanical control system was replaced by a full authority fly-by-light control system including an active cyclic sidestick/inceptor (figure 1(b)). The system architecture consists of a multiple redundant core system, fulfilling aerospace safety standards, and a simplex experimental system. These features, together with an extensive instrumentation, allow the helicopter to perform a wide range of operations. It is a versatile tool for a wide range of helicopter research topics, and with the integration of an active sidestick, even greater possibilities are opening. The sidestick was first flight tested in spring 2007. During the late summer it was tested with test pilots from DLR and from industry as well as pilots from the German army.

(a)

(b)

Figure 1: The FHS and the sidestick onboard the FHS in flight

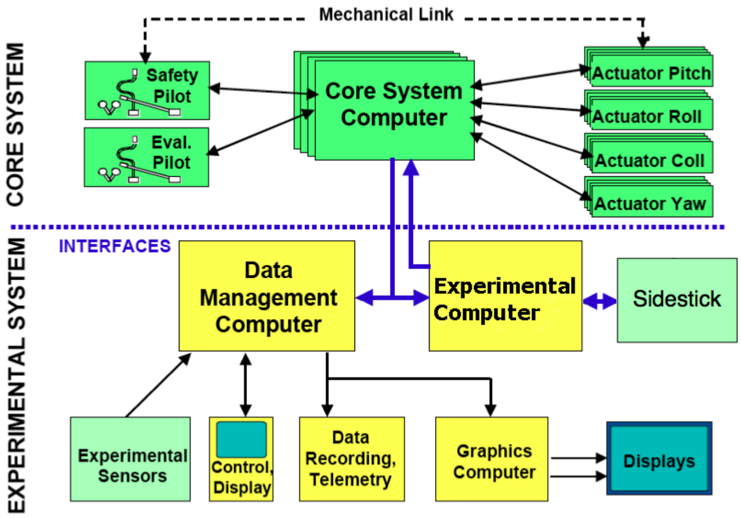


Figure 2: FHS core system and experimental system, *figure based on figure from [4]*

Advantages of active inceptors

Simulator studies show the great potential of tactile cueing and active control technology [1], [2], [3]. The advantages range from tactile cueing for envelope protection to adaptation of force characteristics for individual pilot preferences. The underlying motivation is to reduce the workload and, almost equivalently, increase situational awareness of the future helicopter pilot. This is the key message of this paper: to show how active inceptors can be an advantage to the operational helicopter. The paper will

- Introduce the system of the FHS and its features
- Shortly discuss the choice of workload rating scale
- Treat issues regarding force feel characteristics of the active sidestick
- Discuss the developed tactile cueing functions and the flight testing

Flight control system of the FHS

The basis for research on the FHS is its flight control system [4], which will be introduced in this paragraph. The FHS can serve as a test platform for experimental software and hardware which may have a failure probability higher than the aerospace standard of 10^{-9}/flight hour. Yet the entire flight control system *must* meet this exact criteria. To bridge this gab between safety and flexibility, a two-sided architecture and a safety pilot/ experimental pilot scheme is used. The flight control system (FCS) (figure 2) is divided into two regions:
1)a quadraplex core system whose software and hardware are fixed and guarantee a failure probability of less than 10^{-9} per flight hour. During experiments, the core system will accept actuator commands from the experimental system and feeds these to the actuators. The safety pilot constantly monitors actuator positions and he may, at any time, end the experiment and return to direct control on the helicopter.

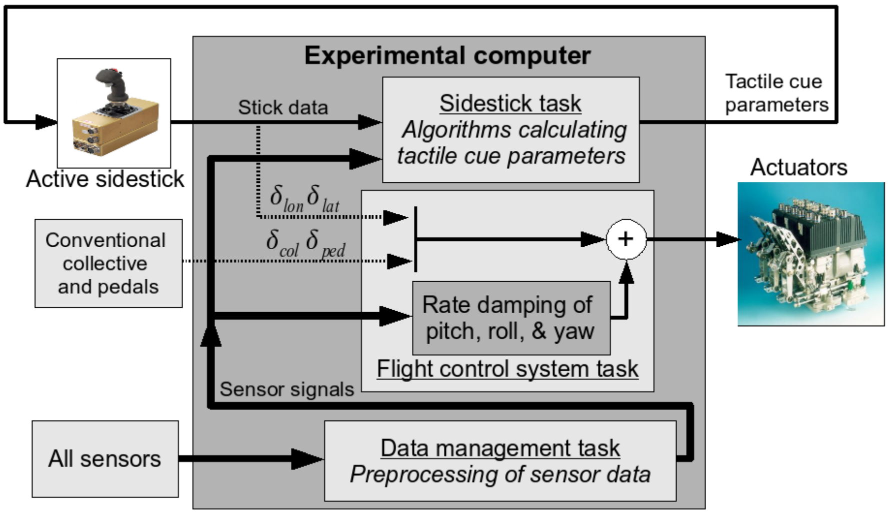


Figure 3: Layout of flight control system with sidestick

2) The experimental system allows execution and flight testing of software and hardware. These do not have to fulfill airworthiness standards, making the process of experiment development highly flexible and fast. A data management task performs processing and distribution of every available sensors data to any software task. For the sidestick evaluation, the outputs of the tasks are divided: the flight control task generates actuator commands, the sidestick task generates interface parameters for the sidestick, and the navigation task interfaces with a navigation computer. This structure prevents contradictions and provides a clean interface between all software tasks. Experimental tasks are programmed in C and C++ and code development is made in *Matlab/Simulink* © and compiled using *Real-time Workshop* ©.

Pre flight testing and development is performed in a fixed base simulator which features electronic hardware and software identical to that on the FHS. The system simulator runs a real time model fulfilling requirements for simulation of the FHS. The experimental hardware in the simulator is an exact duplicate of the flying experimental system.

During sidestick flight tests, a basic SAS resembling that of the series EC-135 could be engaged. Figure 3 gives an interpretation of the topology of the system as it was configured for the flight tests. The sidestick position signal is fed directly to the actuators. Only a modest feedback from p, q, r without *turn coordination* is added.

Choice of rating scale

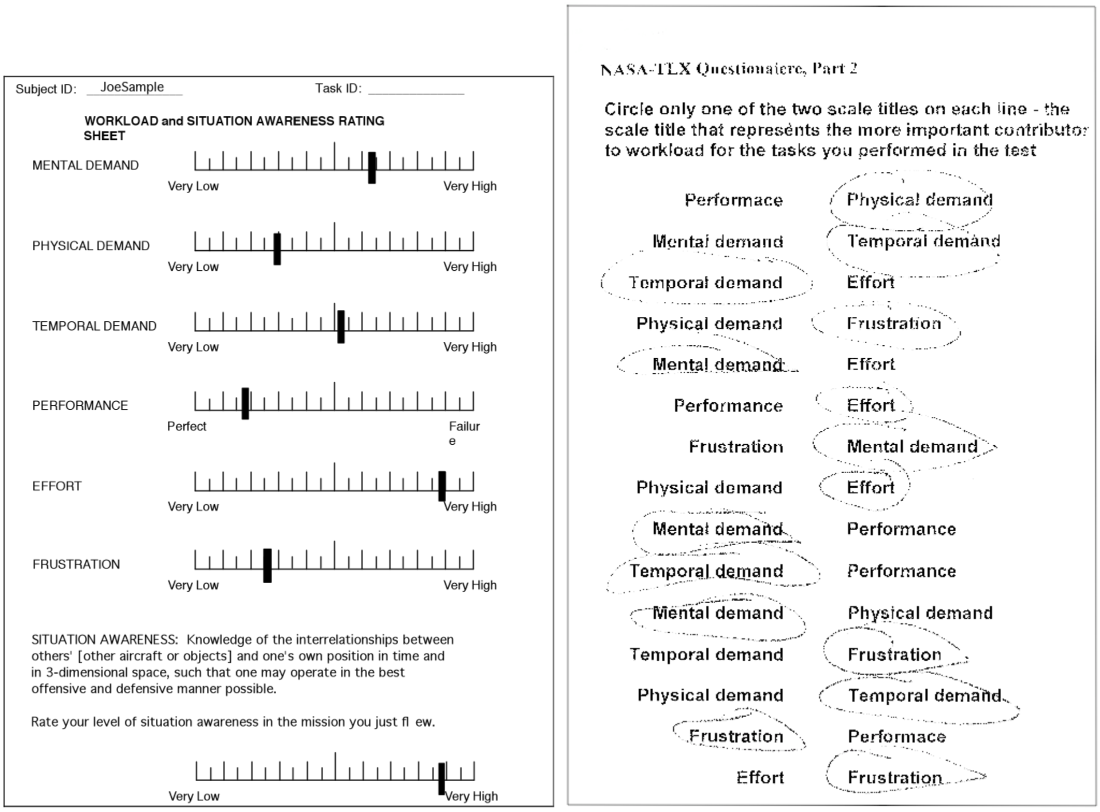
As the main objective of the flight tests was to demonstrate pilot workload reductions through tactile cueing, a rating scale able to measure this had to be used. A quantitative and generally accepted workload rating scale would be the best way to interpret and publish the findings. As the group of intended test pilots also included pilots without experience in returning handling qualities ratings, it was found that the rating scale should be easy enough to learn and understand during not too long preparation sessions. Initial pilot interviews raised concerns that the Cooper Harper [5] method might not be easily accessible to pilots unfamiliar with this method. The choice therefore was the NASA-Task Load Index (NASA-TLX) which during simulator trials was found to be quickly understood by pilots. The practice of using the simulator to make pilots familiar with the NASA-TLX method as well as the HMI of the active functions was well received by the pilots.

The NASA-TLX defines 7 rating "dimensions"

1. **Mental demand.** How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

2. **Physical demand.** How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

3. **Temporal demand.** How much time pressure did you feel due to the rate or pace at which the


Subject ID: JoeSample Task ID: ____________

WORKLOAD and SITUATION AWARENESS RATING SHEET

MENTAL DEMAND — Very Low … Very High

PHYSICAL DEMAND — Very Low … Very High

TEMPORAL DEMAND — Very Low … Very High

PERFORMANCE — Perfect … Failure

EFFORT — Very Low … Very High

FRUSTRATION — Very Low … Very High

SITUATION AWARENESS: Knowledge of the interrelationships between others' [other aircraft or objects] and one's own position in time and in 3-dimensional space, such that one may operate in the best offensive and defensive manner possible.

Rate your level of situation awareness in the mission you just flew.

Very Low … Very High

NASA-TLX Questionaire, Part 2

Circle only one of the two scale titles on each line - the scale title that represents the more important contributor to workload for the tasks you performed in the test

Performace	Physical demand
Mental demand	Temporal demand
Temporal demand	Effort
Physical demand	Frustration
Mental demand	Effort
Performance	Effort
Frustration	Mental demand
Physical demand	Effort
Mental demand	Performance
Temporal demand	Performance
Mental demand	Physical demand
Temporal demand	Frustration
Physical demand	Temporal demand
Frustration	Performace
Effort	Frustration

(a) Workload rating along 7 dimensions

(b) rating of dimensions depending on highest contributor to workload

Figure 4: NASA-TLX rating sheets

tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

4. **Performance.** How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

5. **Effort.** How hard did you have to work (mentally and physically) to accomplish your level of performance?

6. **Frustration.** How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

7. **Situational awareness.** Knowledge of the interrelationships betwen others' [other aircraft of objects] and one's own position in time and in 3-dimensional space, such that one may operate in the best offense and defensive manner possible.

After each test run, the pilot gives a statement on the workload for each dimension on the questionnaire shown in figure 4(a). Secondly, he weights the dimensions against each other depending on which contributes most to workload as shown in figure 4(b). This paper only presents the workload ratings. The contribution-to-workload weightings have been incorporated into a knowledge base where it will be used in the future. The reader is referred to [6] for more information on the NASA-TLX method.

Control force characteristics and pilot preferences

As the flight tests began, the first result was clear after 5 seconds flight testing: the stick force gradient found in the simulator was too low for flight. The pilots objected to the control sensitivity which was felt to be too high and that the vibrations from the helicopter were coupled biomechanically through the pilots arm into the stick giving rise to concerns about possible Aircraft-Pilot-Coupling (APC). This incident underlined the necessity for a thorough examination of the entire subject of force-feel-characteristics.

An underlying difference between classic long pole stick and the sidestick was observed: With a long pole stick, the pilot generally has a wide input range measured in length x length. Unwanted biomechanical coupling of vibrations into the stick may be relatively

Parameter	Default value
Basic force/deflection	± 40 N for ± 25° equalling 1.6 N/°
Breakout	± 4 N over a width of ± 0.1 °
Detents	None
Frequency and Damping	3 Hz and D = 1
Beep speed	2.5 °/s
Friction	None

Table 1: Default mechanical characteristics derived from the flight tests

unimportant as it is of little magnitude compared to the full control range. For the short pole stick, the same vibrations play a relatively stronger role. To counter this, the force gradient on the active sidestick had to be increased compared to the center stick force gradient.

In expectance of more such issues, the flight tests aimed at establishing a default set for the force parameters. These are listed in table 1. To reach this point, the sidestick control software featured a flexible real time adjustment interface to vary a range of key properties in flight:

1. **The force/deflection curve** or force gradient of the stick can be modified in flight. Also non-linear force/deflection curves may be used.

2. **Breakouts and detents** can be added to the force/deflection curve. Force magnitude and width can be varied.

3. **Beep speed** where the pilot can position the zero force position of the stick using a coolie hat on the stick. The default speed of 2.5 [%/s] could be varied.

4. **Eigenfrequency and damping** are input parameters to the Stirling Goldstick, mimicking a 2nd order system.

During all flights, it was sought to find pilot preferences regarding these parameters. Table 2 (at the end of this paper) gives a complete list of individual pilots and their preferences. These settings are results of flights of approximately one hour per pilot, during which the pilots also had to familiarize with the stick in general. This relatively short time possibly introduces some uncertainty to the results. Yet:

- Most pilots accepted the default settings with only minor individual changes.

- As a possible representative for future pilots, a younger pilot (#6) with fixed wing and PC joystick experience was included in the test pool. He was included to represent someone with basic flying skills but with less *die-hard-habits* and preferences than a highly experienced helicopter pilot. Interestingly, he preferred to fly without breakouts and with lower control forces in general. Whereas the other pilots tended to use force-trim-release much of the time, this pilot did not mind to simply hold the stick as long as control forces were manageable. This raises an interesting question: would more experience change this pilots preferences? Or are his preferences to be seen as an indication of what future pilots, brought up with active control sticks, will prefer?

- The ergonomics of the stick and the seating position were positively regarded. One reason is that the pilots right arm must not any longer cross over his body to reach the center stick. One pilot pointed out that this ergonomic advantage will be even more evident during a winch operation where the pilot is looking over his right shoulder. Having the cyclic stick further to his right leads to less physical strain for the pilot.

- Eigenfrequency and damping parameters of the stick have shown to be parameters where the pilot preferences have not yet reached a steady state. Future papers will treat this subject further.

- The pilots found the force-feel-characteristics with the default parameter set pleasant. An important factor in this respect was the impression of very low latency and no freeplay in the control mechanics. With the correct force settings, a pleasant combination of low force with a comfortable control sensitivity was achieved.

Tactile cueing functions

A main goal of the evaluation was to demonstrate operational benefits generated by using tactile cueing functions on the active sidestick. These functions were chosen depending on a list of criteria: a) they should apply to a situation relevant to operational helicopter flying. b) Secondly, they must be suited for use on the cyclic stick[1] c) they should also work with only a basic SAS, d) and above all, they should be simple, comprehensible, and not require an overly long training to un-

[1] Among the list of possible envelope protection functions identified in [7], the majority is related to the collective stick.

(a) (b) (c)

Figure 5: The Bo-105 S3 and a CH53 demonstrating slope landings

derstand the HMI. The three resulting tactile cueing functions are:

- a rotor mast bending moment limitation through softstops in the longitudinal and lateral cyclic axis
- a g-load limitation through softstops in the longitudinal cyclic axis
- a flight guidance function with lateral softstops for support during *standard rate turn*

The mast bending moment limitation

In the hingeless rotor design, like on the EC-135, Bo-105, BK117, etc., the main rotor blade flapping is handled by elastic bending of the blade root instead of by mechanical hinges in the rotor hub. The hingeless designs feature a relatively high equivalent hinge offset enabling the rotor to transfer substantial pitching and rolling moments to the fuselage. This generally allows high control power and maneuverability compared to helicopters with articulated rotor systems. One consequence of this high control power is that it, during one special maneuver, requires the pilot to take care regarding the rotor mast bending moment. This maneuver is the slope landing as shown in figure 5. It is associated with the following pilot tasks:

- Start in level hover with one side of the helicopter oriented towards the slope as in figure 5(a). One of the landing skids makes ground contact.
- The pilot must now transition from level attitude to the sloped attitude shown in figure 5(b).
- The helicopter will tend to slip down on the slope. To counter this, cyclic input is used to tilt the tip path plane and lift vector towards the slope as demonstrated very clearly by a CH-53 (with an articulated rotor) in figure 5(c).
- The tilted rotor tip path plane on the hingeless rotor generates a substantial bending moment.
- The pilot must monitor the mast moment indicator inside the cockpit to avoid structural overloads.
- Simultaneously, the pilot controls attitude and position by looking outside the cockpit using visual references in the surroundings.
- Switching between looking outside and monitoring instruments inside the cockpit results in increased workload.
- If the workload is too high, the pilot will abandon landing rather than risking to exceed limits of the helicopter.

Others have already worked on developing tactile cueing functions for mast bending moment limitation and tested these in simulators [8] [9]. The solution proposed in this paper features a HMI where the pilot is freed from monitoring the mast moment indicator in the cockpit. Instead, softstop cues on the cyclic stick appear, showing the pilot the control limits corresponding to mast bending moment limits.

A peculiarity of the mast bending moment is that it is limited in absolute magnitude and can not be treated as fixed limits in separate axes. The sidestick, on the other hand, renders tactile cues axis-wise. To ensure that the pilot perceives the cue as *one* off-axis entity, the cueing algorithm works in polar coordinates. A specially constructed algorithm acts as a driver layer transforming the cues from polar coordinates to cartesian coordinates as used in the interface with the active sidestick. This is rendered in figure 6. It shows a helicopter whose rotor tip path plane is tilted forward and right, leading to a mast bending moment in the same direction. Underneath it is a plot of the absolute stick force over the entire input range. A softstop corresponding to the direction (Ψ_β) of the mast moment is perceived by the pilot. The use of angled softstops has been tested with pilots and found to convey a realistic impression of the corresponding mast bending moment.

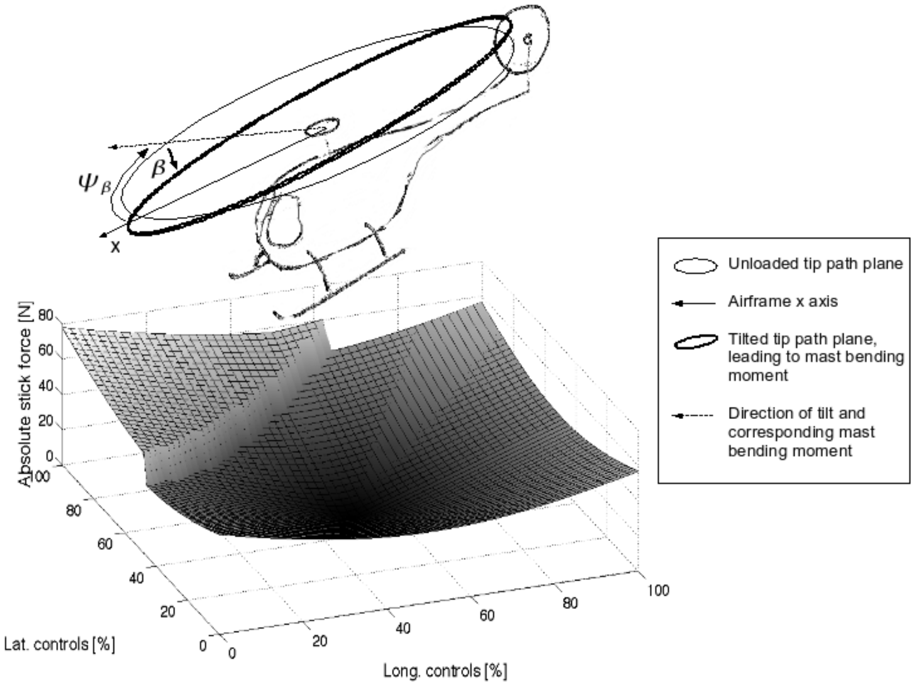


Figure 6: Mast bending moment and resulting absolute stick force

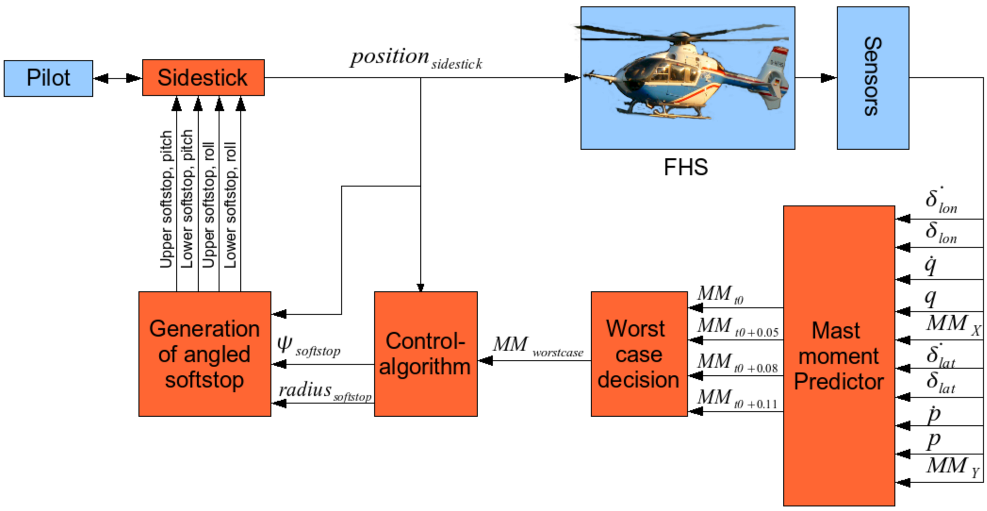


Figure 7: Functional layout of mast bending moment limitation function

System architecture of mast moment limitation

The nature of the mast bending moment was surveyed:

- The mast bending moment of the EC-135 is foremost a function of cyclic input.
- Its transfer characteristics in flight are of transient peak type.
- During ground contact, the transfer characteristic has a content of proportional load in addition to transient peak.

A feedback control system as shown in figure 7 was developed. Its function consists of the following steps:

1. In order to minimize the required pilot interaction, a brute-force solution that continuously covers both the flight and the ground contact regime

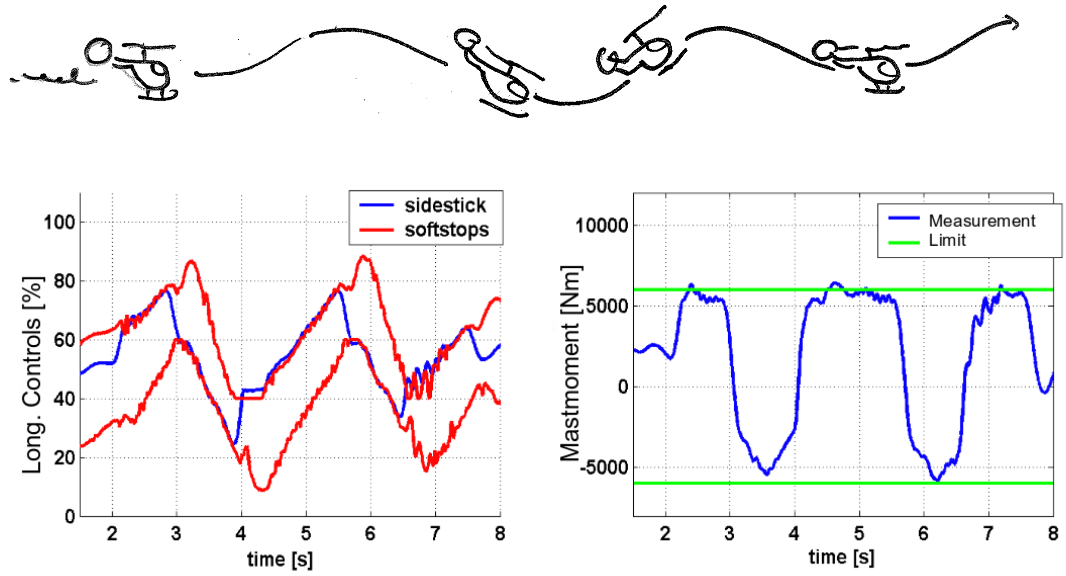


Figure 8: *top:* Porpoise maneuver.*Below left:* Longitudinal control (blue) and softstops (red). *Below right:* Resulting mastmoment

is used. For this, a predictor was trained offline using measured data. It delivers estimates of future mast bending moments: over time horizons of 0.05, 0.08, and 0.11 seconds for both flight and for ground contact regime.

2. A worst case comparison of the predictions and also the actual measurement selects the most critical of these.

3. The control algorithm compares the worst case mast moment to its limit, also taking into account its direction. Accordingly, its output are: 1) direction of the softstop as it is to be perceived by the pilot, and 2) a radius or distance to the softstop. This radius may take negative values if the mast moment limit is exceeded.

4. Finally, an algorithm generates softstops that are perceived by the pilot as *one* coming from a direction according to the mast bending moment.

Test results with the mast moment limitation

Pre-flight tests were conducted in the simulator. These have confirmed the correct function of the algorithm. Figure 8 shows a proof of concept plot of a simulator test with an aggressive porpoise maneuver. The left half of the picture shows a plot of: forward softstop (lower red line), rearward softstop (upper red line), and the stick position (blue line). When the stick encounters a softstop, the pilot feels a gentle cueing force showing him where the limit is. The right half of the plot shows the resulting mast moment as blue and test limits as green lines. The mast moment shows overall good steady state agreement with the imposed limits. Slight overshoots can be seen. These are results of steep transient inputs and were accepted by the pilots under such aggressive circumstances. No flight test data is available yet.

Shortly summarizing the elements of the mast bending moment limitation:

- A tactile cueing function for avoiding mast bending moment overloads has been developed.
- Parts of this system include
  - A predictor, giving estimates of mast bending moment in 0.05, 0.08, and 0.11 seconds, has been developed and trained.
  - A method to render softstops with arbitrary directions on the two-axis sidestick has been developed.
- Promising simulator results have been achieved, suggesting that the function will work in flight.

A g-load limitation function

A second envelope protection function was developed. It was based on using tactile cueing on the longitudinal cyclic axis to limit g-load during forward flight. Pilot interviews made it clear already from the beginning that this function may only show minor applicability to operational helicopters. Yet, the objective was also another: it was sought to use the development and flight

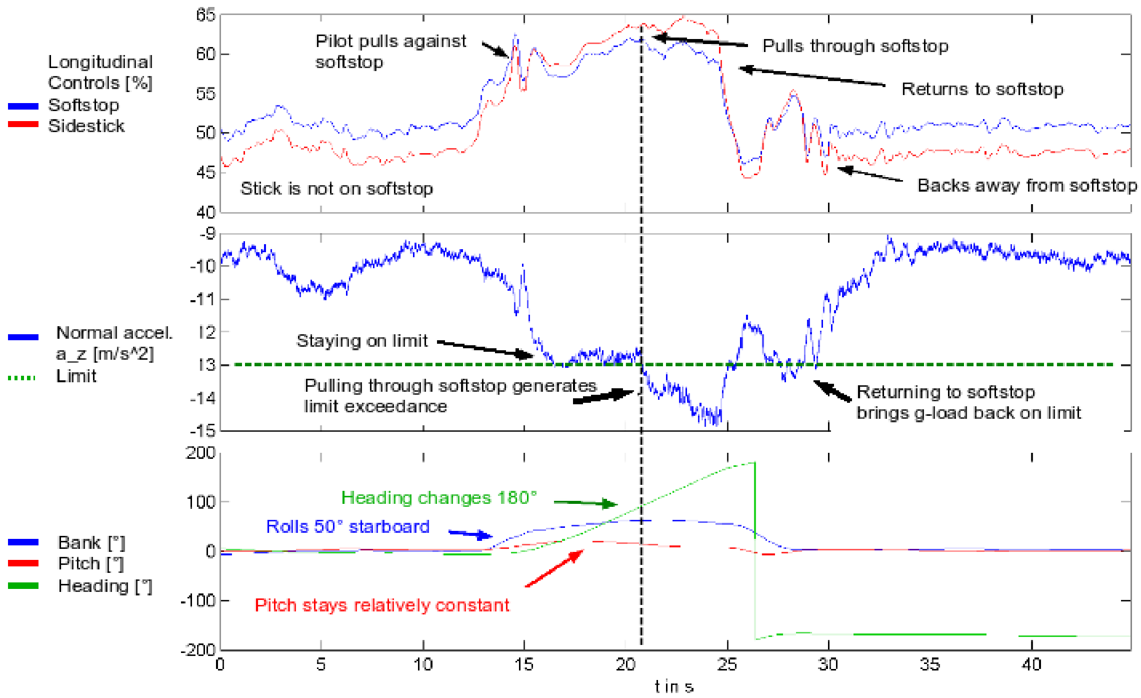


Figure 9: Test of the g-load limitation while flying the task maneuver

testing of this function to gain hands-on-experience and know how in the field of tactile cueing. This was achieved, as the following section will describe.

The function works by letting softstops show the pilot the limits of longitudinal input without exceeding certain g-load limits. A simple feedback law (eq. 1) is used to calculate the softstop position.

$$\begin{aligned} softstop_{lon} &= \delta_{lon} + k_{gload} \cdot (a_z - a_{z,limit}) \cdots \\ &\quad + k_{\dot{\delta},lon} \cdot \dot{\delta}_{lon} \end{aligned} \qquad (1)$$

The control law places the softstop relative to present stick position (δ_{lon}) depending on remaining g-load margin. When the g-load is below its limit, the softstop is placed beyond the current stick position and it is not felt by the pilot. If the g-load is equal to its limit, the softstop is placed directly with its onset at the current stick position and the pilot feels that he is at the onset of the softstop. If the g-load is higher than its limit, the pilot accordingly feels that he is beyond the softstop and beyond the g-load limit. The stick speed $\dot{\delta}$ is included in the control law in order to achieve a better closed loop stability.

For the flight testing and workload rating, a task element inspired by the ADS33 [10] was devised:

From level steady flight at min. 90 knots, perform an aggressive high bank turn of 180° as fast as possible. G-load indicator may not exceed red line. Recover to level flight after completing 180° heading change with min. 60 kts. airspeed. Altitude may be sacrificed in order to maintain kinetic energy

The idea of the task element was to force the pilot to use aggressive longitudinal input in order to maintain a high g-load as close to its limit as possible. This forces him to monitor the g-load indicator as well as the outside of the cockpit. With the help of the tactile cueing function, the pilot is relieved from monitoring the g-load instrument. Thus, a higher situational awareness and less pilot stress is achieved.

Flight test results with the g-load limitation

Flight tests showed that the g-load limitation worked as intended. Figure 9 shows an example of a test run. An important feature of the softstop in its role as tactile cue is shown at ≈ 20 s, the pilot deliberately pulls "through" the softstop thereby demonstrating how the pilot is never prevented from using the full control envelope. He can follow the cue as guide or simply override the cue and perform whatever control input is desired.

Yet, the function did also produce critique. For reasons of controller stability, the control law (eq. 1) had been extended to include feedback from stick speed ($\dot{\delta}_{lon}$). This had the additional effect that the pilots felt the stick starting to slow down a few % before reaching steady state limits. Although arguable a meaningful

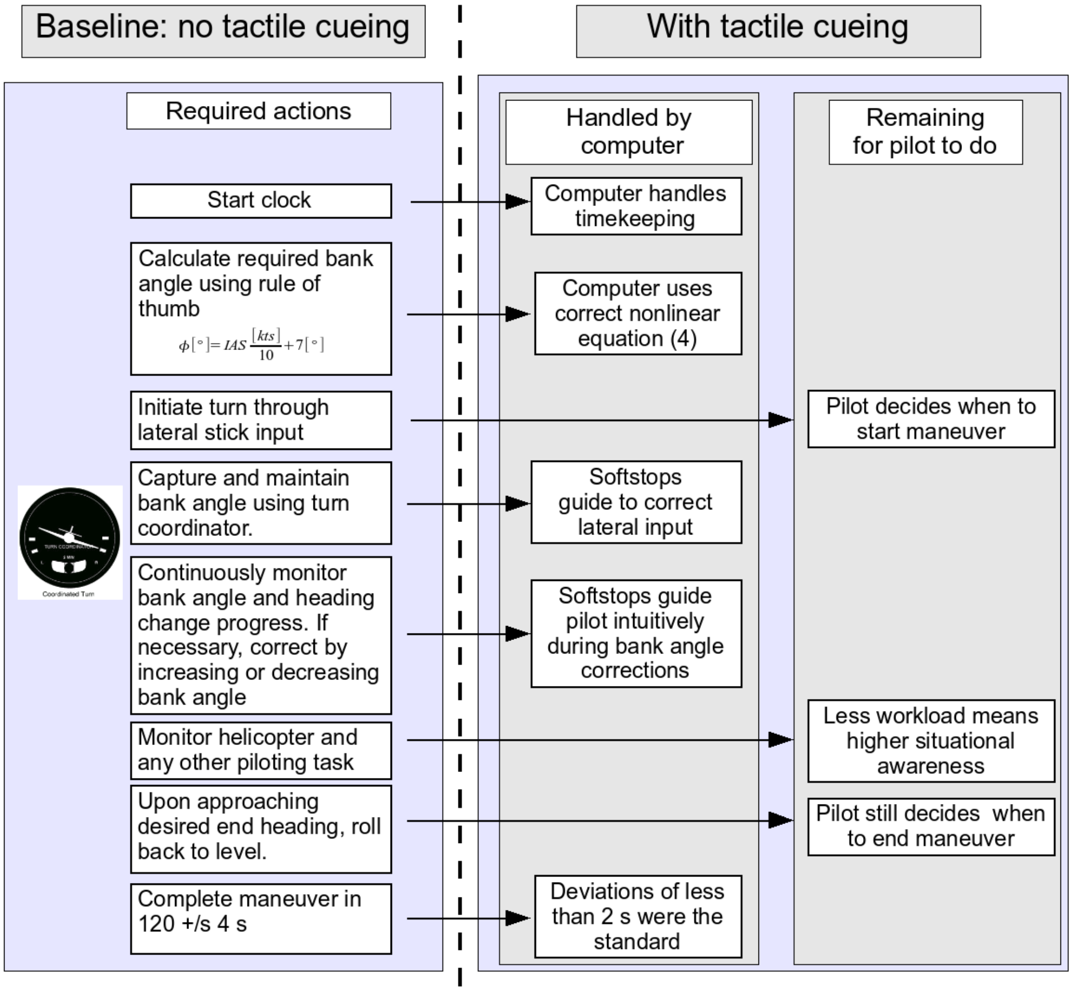


Figure 10: Steps necessary to fly a standard rate IFR turn without and with tactile cueing

feature, it did degrade the pilot impressions slightly. It was felt that the g-load would be rated less well than the third active function being tested during the flight campaign. As a consequence, it was chosen to concentrate the workload rating effort on the *standard rate IFR turn* being described in the following section.

Summarizing on the g-load limitation:

- A g-load limitation function using tactile cues on the longitudinal axis was developed.
- The function was tested in flight and showed correct function.
- It did show the need for improvement of control law parameters.
- Flight tests confirmed that it held only slight applicability for the real operational helicopter
- But through its development and the flight tests, it gave ample room for experimentation and hands-on-testing thereby fulfilling its primary purpose.

A roll angle limitation providing guidance along a standard rate IFR-turn

With the mast moment protection and the g-load limitation, two functions for envelope protection had been demonstrated. In order to show the broad range of possible applications for active control technology, a third function without structural limits involved was developed. The targeted situation is the standard rate IFR turn which is a maneuver common to the IFR rated pilot. During this maneuver, the pilot is to fly a 360° turn in 120 ± 4 s, equalling a turn rate of $3°/s$. It is, despite its simple sounding description, a contributor to pilot workload as is suggested by the left side in figure 10. It can be seen how all necessary steps must be initiated and maintained by the pilot. The figures right side shows how some of these steps can be

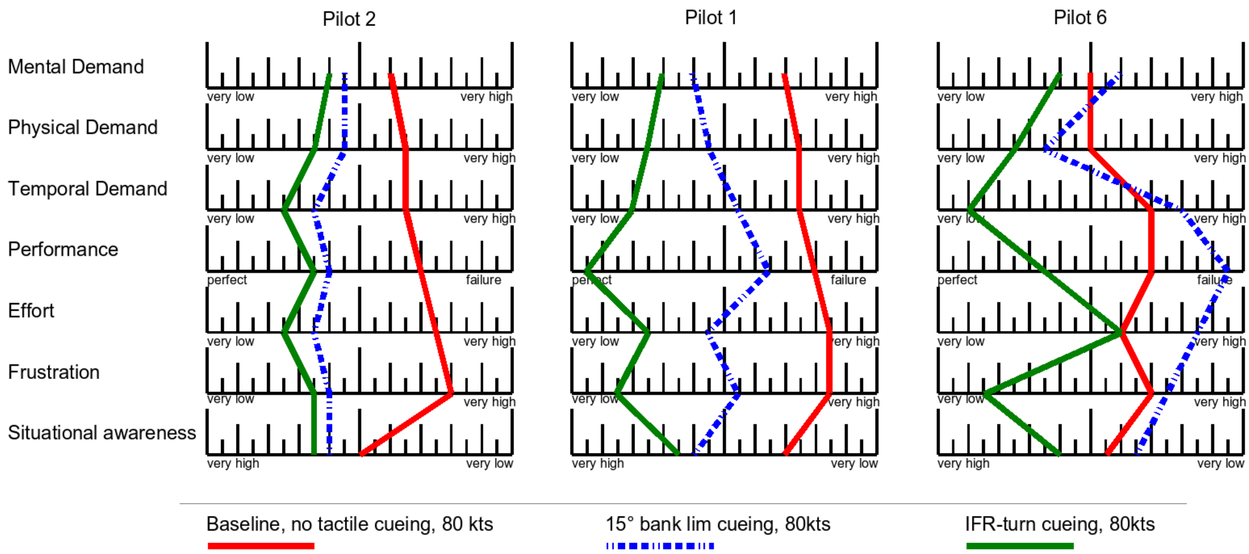


Figure 11: Pilot 2,1, and 6 ratings result at 80 kts

handled by a computer, leaving the pilot with a much reduced workload.

The function uses softstops to guide the pilot in the lateral inceptor axis. The softstops are placed using a simple feedback law:

$$\begin{aligned} softstop_{lat} &= \delta_{lat} + k_{\Phi} \cdot (\Phi_{command} - \Phi) + \ldots \\ & k_p \cdot p + k_{\Psi} \cdot (\Psi_{command} - \Psi) \end{aligned} \quad (2)$$

with

$$\Psi_{command} = \Psi_0 + \int_{t_0}^{t} 3 \cdot (\pi/180) \mathrm{d}t \quad (3)$$

where Ψ_0 is the heading as the maneuver starts and t_0 is the corresponding time.
And

$$\Phi_{command} = \arctan\left(\dot{\Psi} \cdot \frac{\mathrm{TAS}}{g}\right) \quad (4)$$

giving bank angle as a function of yaw rate and airspeed. $\dot{\Psi} = 3(\pi/180)$ [rad/s], TAS in $[m/s]$, and $g = 9.82 m/s^2$

In the final implementation, the equations (2),(3), and (4) are adapted and mirrored to accommodate turns to the right *and* left. The low number of feedback gains allowed a simple hand tuning of parameters.

Flight test results with the IFR turn

A task maneuver description was created:
From horizontal flight with at least 90 knots, start a 3° /s turn. A full 360° curve is flown, taking 120 seconds. During maneuver, decelerate to 60 knots and accelerate back to 90 knots. Maintain Altitude +/- 50 ft. Meet start heading with +/- 3° . Time for circle: 2 min +/- 3 s. Abrupt inputs in order to meet requirements are to be regarded negatively in the rating of performance.

Multiple ratings were performed in a stepwise flight test scheme:

1. Fly maneuver at constant airspeed of 80 kts with no active function (baseline).
2. Fly maneuver at constant airspeed of 80 kts with a fixed 15° bank angle limitation cueing.
3. Fly maneuver at constant airspeed of 80 kts with full *standard rate turn* cueing
4. Fly maneuver at airspeed 90-60-90 kts without cueing
5. Fly maneuver at airspeed 90-60-90 kts with full *standard rate turn* cueing

Three Pilots participated and returned workload ratings for the standard rate turn. Pilot #1 and 2 hold IFR ratings. Pilot #6 does not. Figure 11 shows the ratings of the pilots for the steps 1,2, and 3. Pilot # 1 and 6 found it impossible to meet the task requirements if the 90-60-90 kts task was flown without cueing. Pilot # 2 also flew these advanced steps and gave a rating as shown in figure 12. The feedback from the pilots and the ratings say:

- The tactile cueing function worked and demonstrated correct function. The ability to compensate for varying airspeed was confirmed as shown

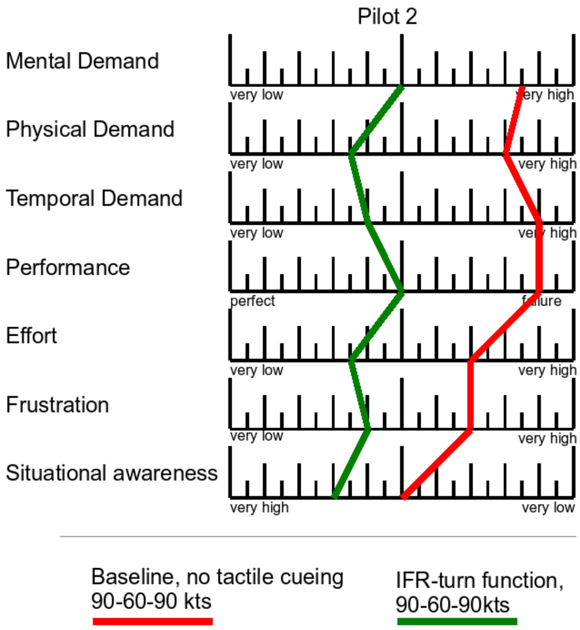


Figure 12: Pilot 2 rating at 90-60-90 kts

in figure 13 that plots measured states from a 90-60-90 kts test run.

- The upper plot show the airspeed change during the test.
- The second plot from above shows the stick position (red) and right softstop (blue). At $\approx$ 40 seconds, the pilot makes a lateral input to the right. During the following 120 seconds, the pilot simply holds a light pressure against the softstop. Upon reaching the desired heading, he eases back from the softstop and levels out.
- Third plot from above shows bank angle during turn. It can be seen that the bank angle is adjusted depending on airspeed.
- The lowermost plot shows the progress of the heading during the maneuver. An almost linear heading curve can be seen during the circle.

Regarding the effect of the active function, it can be said that

- The standard rate turn cueing function allowed a significant workload reduction, confirmed by all three pilots.
- The difference between using the tactile cueing and not using it was measured as an improvement in all rating dimensions for all pilots (with the exception of pilot # 6 who gave equal ratings for *effort*).
- Although the 15° bank angle limitation did not actively seek to meet the 120 seconds criterion, it did still produce a workload reduction for two out the three pilots.
- Workload reduction was also reproduced at two different levels of difficulty (steps 1-2-3 and 4-5).
- The pilots commented affectionately and positively on the cueing function. Remarks like "fun", "relaxing", and "the stick makes it all by it self" (in a positive sense) were heard.
- One objection to the cueing function was that it tended to move the stick too much. This requires a short explanation:
  - The movement of the stick is a consequence of flying with a basic SAS where the basic rate command of the helicopter is retained.
  - With a tactile cueing function providing attitude command on a rate command system, the tactile cue must "force" the stick back to center in order to keep the new attitude. The *force* is generated by softstops.
  - Once understood, the feedback behind this "pushing action" was accepted by the pilots. Still, it was regarded as undesired.

  This special subject is also treated in [2].
- With the tactile cueing, durations of 120 $\pm$ 2 second were repeatedly achieved.

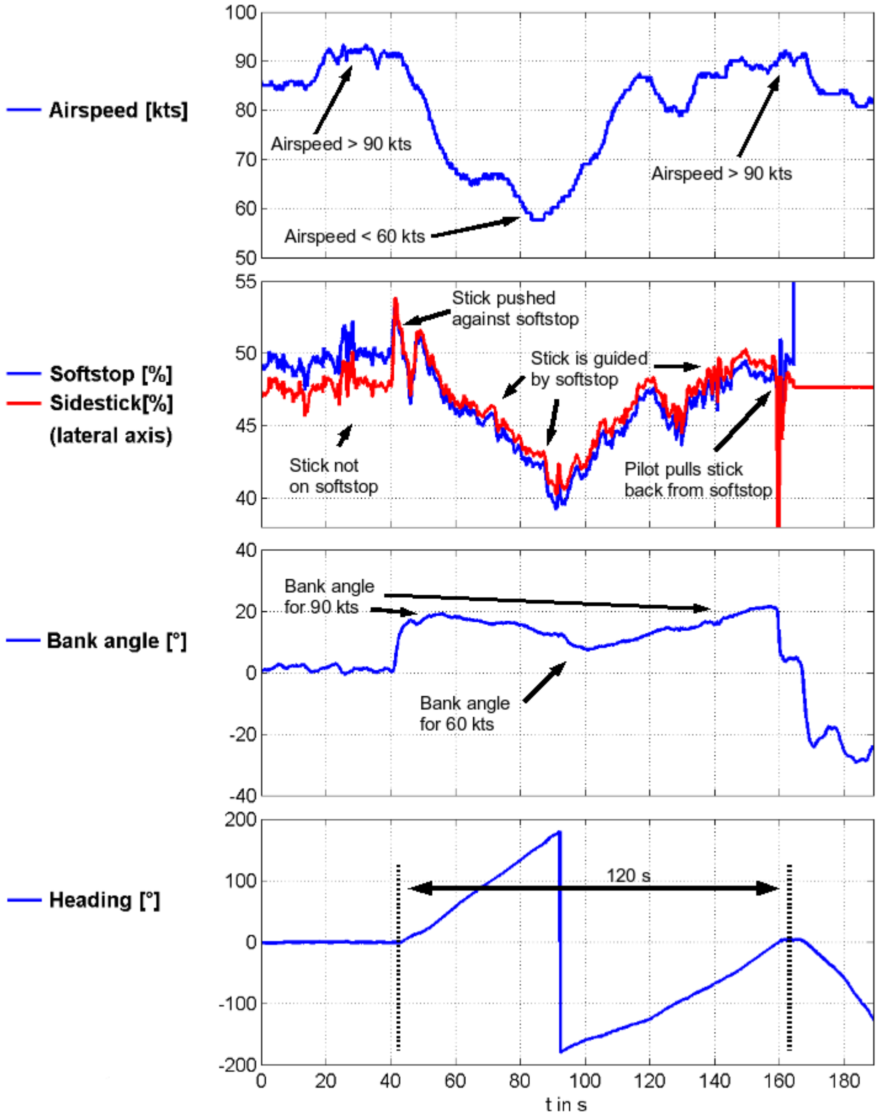


Figure 13: Plot of standard rate turn with variable airspeed

Summary

- The active sidestick was flight tested and active functions for workload reduction were demonstrated.
- The high adaptability of stick forces was used to seek optimal control force parameters. A set of default parameters was found which was well received by the participating pilots.
- An envelope protection function for the rotor mast bending moment has been developed and tested in the simulator showing good results.
- A second envelope protection function in the form of an active g-load limitation demonstrated correct function but also a slight necessity for control law optimization.
- A flight guidance function for a standard rate IFR turn was demonstrated and received very positive remarks. An workload rating was performed using the NASA-TLX rating scale. Three pilots returned ratings that all showed substantial workload reductions for the given task maneuver.
- The active sidestick has now passed the phase of implementation into the DLR FHS and is an active part of the system. First flight test results have been gathered. The results are positive and already give indications to the advantages of the active stick as natural element in the helicopters of tomorrow.

Pilot	Setting	Hover preference	Forward flight preference
1 2000 helicopter hours	Breakout Force curve Beep speed	Default Default Default	Default Default Default
2 4500 helicopter hours	Breakout Force curve Beep speed	Default Default Default	Default Default Default
3 500 helicopter/f.w. hours	Breakout Force curve Beep speed	Default Default x2	not flown
4 8000 helicopter hours	Breakout Force curve Beep speed	None - No clear preference - Default	Default Default
5 3000 helicopter hours	Breakout Force curve Beep speed	None Pitch: x1.25, roll: x1.5 Pitch: x0.25, roll: x0.5	Default Pitch: x1.25, roll: x1.5 Pitch: x0.25, roll: x0.5
6 300 fixed wing hours	Breakout Force curve Beep speed	None Default or even lower forces Default	None Default
7 8000 helicopter hours	Breakout Force curve Beep speed	Default Default Default	not flown

Table 2: List of pilots and force-feel parameters chosen during flight tests

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