

ACTIVE INCEPTORS IN FHS FOR PILOT ASSISTANCE SYSTEMS

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ABSTRACT

Pilot assistance systems or their functions can help the pilot to easier perform a safe and effective 24h all weather operation by a combination of advanced visual cueing and intelligent control augmentation. This classical two dimensional optimization problem can be extended by a third dimension, namely tactile cueing. With increasing level of control augmentation for helicopters, driven by fly-by-wire technology, also their handling qualities (flying qualities) are tailored by using advanced control modes like attitude command or translational rate command. To get fully access to the overall active rotorcraft, also the pilot inceptors are considered to exhibit active features, which are the dynamic force-displacement characteristics. This allows the adaptation of these characteristics to the control law and control modes, and in addition tactile cueing or feedback in an integrated approach. This reduces the workload and increases the situational awareness. DLR has integrated two active sidesticks into its flying helicopter simulator FHS: one stick replaces the cyclic centrestick, the other one the collective lever and optionally the pedals.

1. INTRODUCTION

Since 2002, DLR operates an EC135 helicopter as an in-flight simulator named FHS, see Figure 1. The helicopter is designed and developed in a common effort by Eurocopter Germany, Liebherr Aerospace Lindenberg, Germany, the German Military Procurement Office (BWB) and the German Aerospace Center (DLR) and is now used as an advanced rotorcraft technology demonstrator and research testbed. The FHS is the first helicopter developed with a full authority four times redundant (quadplex) fly-by-light primary flight control system incorporating a simplex experimental flight control computer [1]. After delivery of the helicopter to the DLR, several research programs have been conducted with internal and external partners. The DLR continues to expand the capabilities of the FHS. One of the achievements was the extension of the flight envelope for landing the helicopter in experimental mode, i.e., with the simplex flight control computer in the loop.

Another important achievement was the integration of active sidesticks into the FHS and their certification to be used in experimental mode. As in the fixed wing world, the usage of active sidesticks for helicopters has been made possible through the integration of fly-by-wire/fly-by-light (FBW/FBL) technology. The sidesticks were already planned during the project definition phase of FHS (1993), but the realisation was postponed due to technology risks and budget restrictions. In 2004 the decision was made to integrate these devices into the FHS in an upgrade program and to demonstrate the operational benefit in military as well as in civil operations. The Institute of Flight Systems was contracted to integrate two active sidesticks into the FHS to be operated by the evaluation pilot on the right-hand seat. The overall procedure was managed

in a project and divided into three steps:

- A feasibility study
- Project phase I: right-hand stick
- Project phase II: left-hand stick

The feasibility study was conducted 2004 in a common effort together with Eurocopter as the helicopter's manufacturer. Eurocopter also conducted the modifications necessary to convert the EC135 into a flying simulator. In the years 2005-6 the work concentrated on the integration and certification of the right-hand stick, which was procured from Stirling Dynamics Ltd. The first flight with this sidestick was performed in Feb. 2007. The integration of the left-hand stick was prepared in parallel. The phase II started in 2007; this sidestick was developed by Liebherr Aerospace and the first flight was performed in September 2009. The integration process is described in chapter two.



Figure 1: EC135 Flying Helicopter Simulator (FHS) and team after successful maiden flight with two sidesticks

The global goals are to make helicopter flight *safer*, *easier* and *cheaper*. To show the operational benefit of active inceptors with respect to these goals so-called

demonstrator functions were developed, tested and evaluated already during the integration phase of the sticks. Now, in the user phase, a more integrated approach is selected which considers the active inceptor technology as part of the overall active control systems and imbeds it into pilot assistance systems. This is the topic of the chapters three and four.

2. SIDESTICK INTEGRATION PROCEDURE

The following chapter describes the three steps of the integration project, the integration into the experimental system of the FHS and results of the first flights with a left hand sidestick.

2.1. Feasibility study

A feasibility study was conducted in 2004. A main goal of this study was to have a technical description of the system integration, a cost estimate and a time schedule. In addition, this study should give an outlook on the operational benefits of the usage of active inceptors.

A literature review was used in order to get an impression of the potential of active inceptors to improve handling qualities regarding flight condition, flight envelope limits, load limits and system status, see, e.g., [2], [3], [4] and [5]. In addition, tactile switching, prioritization in dual pilot operation and individualization of the human machine interface (HMI) was listed. Benefits for operation by tactile feedback, faster reaction by additional tactile information and finally reduction of pilot workload were investigated.

Another chapter of the feasibility study summarized and evaluated international and DLR activities, the requirements regarding the variation of force characteristics, additional functions, and the need of an exchangeable grip with switches, ergonomics, geometry and weight, and system interfaces.

With respect to the certification sidesticks need to meet the crash requirements for the cockpit installations listed in JAR 27 for small helicopters. Additional requirements are listed in the specification of the experimental system installed in the FHS.

A market study (Europe only) was conducted to have an overview of the available hardware. The available hardware was then rated against a list of weighted criteria to find the best candidate, and with a modified weighting to identify an off-the-shelf solution. The result of this study was presented to the management to assure the financing.

2.2. The right hand stick

An output of the study was that the “Goldstick” from Stirling Dynamics Ltd. was the best candidate for the integration. An important factor was its compact design fitting into the limited space available between the pilot seat and the window frame. The off-the-shelf stick was ruggedized due to cockpit installation requirements and the specification of the experimental system. An emergency exit for the right hand pilot was realized, see Figure 2, [6], [7].



Figure 2: The right hand stick in flight

2.3. The left hand stick

Many envelope and structural limits, especially engine and gearbox torque, are mainly influenced by the collective pitch inputs. Traditionally, a helicopter pilot controls the collective pitch lever (which is a long-pole, floor-mounted lever) with his left hand. To achieve a higher bandwidth of the active inceptor, a short-pole sidestick seemed more adequate than using a traditional but active collective lever configuration. This led to a change in the cockpit ergonomics. To get knowledge about the feasibility, an acceptance study as proof of this concept was performed at the end of 2006 [8]. The study was carried out with five helicopter pilots from the German Army Aviator School in Bückeburg, who participated as test pilots. The pilots tested a system which combined an active short-pole collective stick and an active right-hand stick in the FHS ground simulation (Figure 3).



Figure 3: Assembly of left hand (1) and right hand sidestick (4) and conventional inceptors (collective (2), centrestick and pedals (3)) in the helicopter simulator

This configuration also enabled the optional addition of a yaw-control on the second axis of the stick. The pilots repeatedly flew a simple flight pattern with different cockpit configurations (conventional controls, right-hand sidestick, and left-hand sidestick). After every trial they were interviewed. As result the pilots generally were able to control the helicopter, and an active short pole was judged acceptable for the collective control, see Figure 4.

After this acceptance study, the integration work for the active collective stick into the FHS was started. A Liebherr-developed active sidestick was first flight tested in September 2009 (Figure 5). The left hand sidestick is horizontally and vertically adjustable and

tiltable. In the tilted position the short pole stick is controlled in the same manner as the classical collective. The upright position allows new cockpit studies in a symmetric side-by-side configuration. The key data of both sidesticks can be found in Table 1.

Table 1: Key data of the integrated sidesticks

		
Type (Position):	Liebherr Aero-space (LLI) Sidestick 3rd Generation (lefthand)	Stirling Dynamics Goldstick (righthand)
Key data:	longitudinal / lateral axis: +/- 16° / 14° +/- 170 N / 75 N	both axes: +/- 25° +/- 150 N
Operative since:	2009	2007

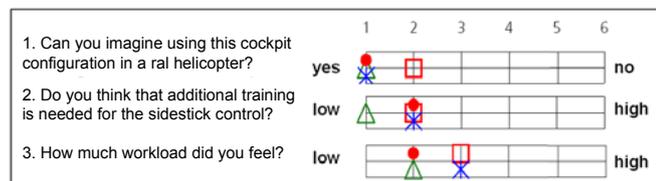


Figure 4: Pilot questionnaire results from acceptance study (1 of 5 pilots removed due to simulator sickness)



Figure 5: Liebherr sidestick in FHS (upright)

2.4. Experimental system

The FHS has a dual pilot safety concept. A safety pilot always monitors the system via mechanical feedback from the actuators. He may at any time regain control by simply gripping the stick firmly. This allows the integration of software and hardware which do not fully meet the safety requirements of classical flightworthiness. One example is the sidestick in prototype status, which must “only be ruggedized”. Such hardware is connected to the experimental system and only used in experimental mode, see [1].

Figure 6 shows that the classical signal flow from the evaluation pilot’s inceptors to the actuators is directly via the core interface computer when the FHS is operated in basic condition, the switch S2 connects the inceptors’ position sensors (LVDTs) with the actuators.

The signal flow in experimental mode and with sidesticks handled by the evaluation pilot can be seen from the other position of switch S2. The inceptor signals are sent via the Experiment Computer (FCC, Flight Control Computer) to the Core Interface Computer (COS, Core System) and finally to the actuators.

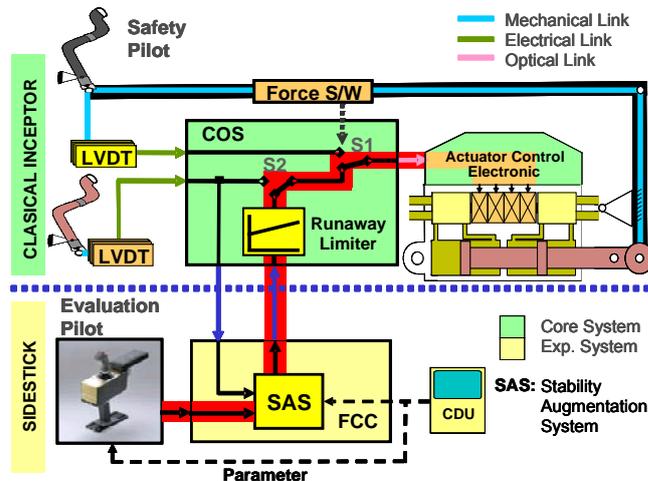


Figure 6: Signal flow chart from sidestick to actuator

This connection is only allowed in experimental mode of the FHS, the safety pilot is then monitoring the system via the feedback by the mechanical link. The two sidesticks are also operated by the evaluation pilot, but - in contrast to his classical inceptors - are not directly connectable to the actuators.

A duplicate of the experimental system is integrated in a ground based system simulator. All hardware and software designs are tested in this simulator before they are released for flight.

2.5. First flights with left hand Sidestick

After completing the integration of the left hand sidestick the maiden flight took place and the controllability of the helicopter with a left hand sidestick control for collective and optionally for yaw control was approved. More flights for familiarization, basic parameter optimization and system demonstrations to customers followed. Two test pilots from DLR and three instructor pilots from the Empire Test Pilot School (ETPS) were test flying the system. Several inceptor configurations were presented to each pilot: left hand stick for collective control, with pedal steering for yaw control and yaw control via lateral stick axis. The left hand stick was reconfigured from tilted to upright position during the flight. The cyclic was initially controlled by the centrestick and switched to right hand stick control later. The flight time was about 1 h each. After a very short time the pilots were familiar with the higher sensitivity of the short pole stick. After that, they continued flying manoeuvre under own decision.

Important findings of the first flights were the following:

- Both, friction and spring force characteristics for the sidestick collective axis are flyable with different advantages. While the classical friction characteristic is already known by the pilots, the spring characteristic memorizes a trim point as origin for short time manoeuvre corrections. Releasing the

stick after the manoeuvre brings it back to the trimmed position. The friction setting frees the pilot from the need to press any button to trim the stick; he simply releases the stick where he wants it to be. Both concepts should be further investigated in combination with higher control modes.

- The side-by-side configuration with the tilted left-hand stick was described as a comfortable seating position. The steering without “moving the whole body” was found favourable.
- The yaw control with the tilted left hand sidestick in combination with the roll control by lateral movement of the right hand stick was described as harmonious: Both stick movements lead to the effect of an equal orientated heading change. It was also valued as intuitive that both roll and yaw movement are represented by the orientation of the corresponding inceptor axis. It is important to mention here that this holds only for the situation where the left hand stick is tilted: Then the axis of rotation of the lateral stick movement and the helicopter yaw axis nearly coincide. Yet, it does not account for the situation with an upright left hand stick. Actually this led to confusion: The pilots now had difficulties to mentally separate the roll and yaw controller axes, although they were on two different sticks. For this position the pilots recommended a twistable stick, with an additional degree of freedom around its own yaw axis, to create an intuitive control situation again. The twist grip is subject of current research activities at DLR.

The first flights approved the controllability of the FHS with side-by-side control. It is now ready for service for the exploration of the tactile interface for pilot assistance in a real flying helicopter.

3. GENERAL ASPECTS

With active inceptors in the control loop the traditional ways of pilot assistance systems can be enhanced and the combination of control augmentation system, displays and the use of the haptic modality by active sidesticks makes the overall system more intuitive and safer.

3.1. The active inceptor in the pilot control loop

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 HMI. Not only the traditional spring-mass-damper forces are emulated, but also a wide range of additional tactile (or haptic) cues is 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.

Simulator studies show the great potential of tactile cueing and active control technology [9], [10], [11]. The underlying motivation is to reduce the workload and, almost equivalently, increase the situational awareness of the helicopter pilot. This was the key aim of this work: to show how active inceptors can be an advantage to the operational helicopter pilot.

Figure 7 shows the general signal and information flow when a compliant active inceptor is added to the system 'Pilot ↔ Augmented Aircraft'. The pilot generates a force, and the internal control scheme following the inceptor force-displacement algorithm moves the stick to the position where the force is prescribed. The transitional behaviour of the movement is normally a second order system (mass, spring and damper), see chapter 4.1. On top of this, functions like detents, breakout, softstops etc. can be placed to indicate specific events to the pilot. That means, in addition to the classical visual and vestibular feedback to the pilot, a haptic feedback is added. The challenge is to tailor the basic behaviour for the force-displacement properties of the device to the actual aircraft controller status until an optimum configuration is obtained.

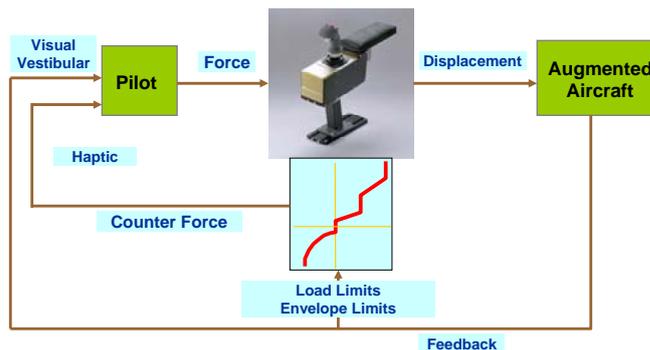


Figure 7: The pilot-inceptor-aircraft loop

3.2. Pilot Assistance on FHS

Pilot assistance systems or pilot assistance functions help the pilot to easier perform a safe and effective 24h all weather operation by a combination of advanced visual cueing and intelligent control augmentation.

In the project PAVE Phase I (Pilot Assistance in the Vicinity of Helipads) a functional prototype of an assistance system was developed to assist the pilot during the take-off and landing phase. The FHS ground based system simulator served as development facility. The flight testing, evaluation and refinement was then conducted in PAVE Phase II, using the FHS. Primarily departure and landing procedures were flown, where the pilot was supported by the PAVE system to plan and perform standard and noise abatement procedures. Manual flight and automatic flight using a developed autopilot were flown and tested regarding the precision of the prescribed manoeuvre. Essential elements of the system were the control augmentation by the autopilot and visual cues. The visual cues were implemented as a combination of a modified PFD, a navigation display and a multifunction display showing maps with the planned route via waypoints. In addition, a tunnel-in-the-sky symbolic was tested.

A follow-up project is currently running, called ALL-Flight (Assisted Low Level Flight and Landing on Unprepared Landing Sites) and aiming at the intuitive operation of a manned helicopter from start to landing on unprepared landing sites and an intermediate low level flight in the presence of obstacles.

The objective of ALLFlight is the achievement of a safe and effective 24h all weather operation under above

conditions by providing the pilot an optimal combination of assistance, consisting of advanced visual and tactile cueing and intelligent control augmentation, reducing his workload and increasing his situational and mission awareness. Here the classical combination of control augmentation and display sophistication is extended by a third dimension: haptic feedback, see Figure 8.

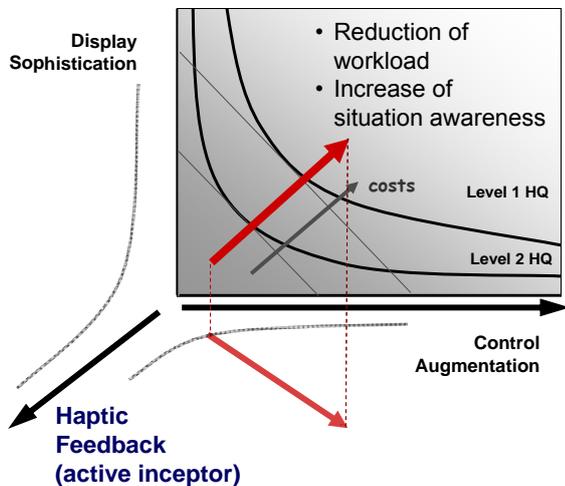


Figure 8: Multi-dimensional approach including haptic feedback

Display Sophistication A range of sensors have been added to the FHS during ALLFlight. The data from these are fused with a terrain database to generate a 3D model of the surroundings [12], [13]. Based on the 3D model, a computer provides curved and unsteady trajectories (in space and time) for all phases of operational helicopter flight (take-off, low level flight, landing) under all conditions (day, night, degraded vision). The trajectory generation incorporates the cognitive pilot's decision processes for trajectory planning [14] in the described scenarios and is based on the sensor-suite data. The generated trajectories can now be flown with an ALLFlight-developed flight control system, based on a model based control (MBC) approach. They can be visualised with a helmet mounted display that is planned to be integrated into the helicopter.

Control Augmentation Several versions of experimental flight control software were flight tested. For handling qualities studies and in-flight simulation, DLR developed a MBC. For research purposes (or cooperation with external partners) other control concepts can be implemented as well. A common characteristic of most of the concepts is the use of rate feedback in the inner controller loops to increase damping and bandwidth, leading to enhanced handling qualities, but also may cause air resonance.

The explicit model based control (MBC) approach forms the basis of most of the control related DLR user programs, e.g., in-flight simulation, upper mode and auto pilot design, handling qualities investigations and pilot assistance technologies. Figure 9 shows the principal layout of the MBC design. A dynamic "inverse plant" type of feed-forward controller is designed to cancel the actual helicopter dynamics and to impose the commanded response dynamics on the aircraft. The feed-forward controller makes use of identified

quasi-linear models for hover and different forward speeds. In addition, a feed-back controller is designed to eliminate response errors due to outer disturbances and remaining model deficiencies. The advantage of the explicit model based approach is the flexibility in the design of the command model. The command model can be adapted to investigate advanced controller systems, variations of basic handling qualities or to simulate other helicopters in flight.

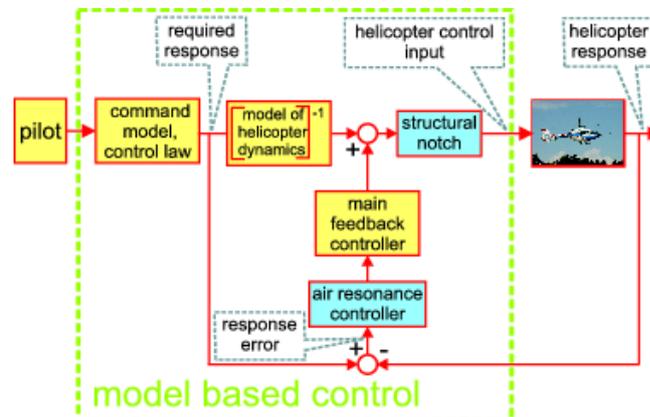


Figure 9: MBC environment

As an example, Figure 9 shows the layout of the MBC with the placement of the air resonance controller in the control loop. The explicit model based control concept is used for most of the handling qualities related studies and for all studies in the field of novel control technologies or pilot assistance concepts (e.g. 24h, all weather flight path following, NOE flight and landings on unprepared landing sites). These concepts enable to vary the pilot assistance from a direct mode, via upper assisted modes and finally to the full automated take off and landing mode, depending on flight mission and environmental conditions. However, other control concepts, e.g., stability augmentation system (SAS), H^∞ or customer defined structures can also be integrated.

Up to now, the MBC command model features decoupled RCAH (rate command attitude hold) with turn coordination, ACAH (attitude command attitude hold) and additional autopilot functions for departure and approach from confined areas, which currently are flight tested.

To avoid structural damages by triggering natural frequencies of structural modes, e.g., fuselage heave, tail boom (lateral and flap) bending or fenestron drive train torque, structural filters were implemented in the feed-forward command path, see Figure 9. They consist of multiple narrow notch filters with different central positions for the respective structural mode.

The air resonance controller architecture and position within the loop are designed to be virtually independent of the main feedback controller performance of the SAS or MBC. The only link to the main feedback controller is the air resonance controller gain which is scheduled by the main controller overall roll rate feedback gain [15].

All necessary parts of the flight control system are designed with MATLAB/Simulink. The Real Time Workshop is used to generate C-Code which is run

directly on the experimental flight control computer. After successful pilot in the loop – Hardware in the loop tests in the ground based system simulator the code is directly transferred to the FHS system for flight tests.

4. HAPTIC FEEDBACK VIA ACTIVE INCEPTORS

When the pilot applies a force to the active inceptor it responds dynamically and the inceptor's displacement controls the augmented helicopter. The classical feedback loop leads to the visual and vestibular pilot perception. The haptic perception generated by the counter force of the inceptor is already existent with non-active inceptors. By closing the feedback loop to the inceptor control system, it is possible to indicate helicopter load limits or flight envelope limits to the pilot by adding cues or varying force gradients.

The ongoing activities can be divided into three groups which will be discussed in the following chapter:

- Inceptor characteristics
- Classical tactile cueing
- Flight path guidance & Haptic flight director

4.1. Inceptor characteristics

The response characteristics of the aircraft can change between rate command (RC), attitude command (AC), translational rate command (TRC), or mixtures of these. It has been found that the handling qualities can be improved when the force characteristics of the sticks are adapted to these different control modes. This requires modifications of the static (spring stiffness) and dynamic characteristics (natural frequency, damping) of the stick, Figure 10.

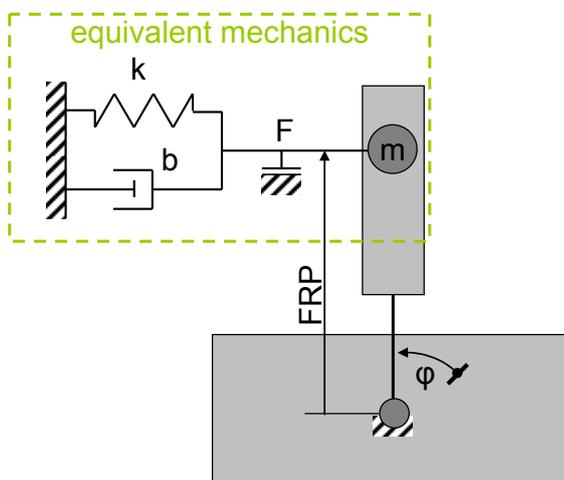


Figure 10: Equivalent sidestick mechanics with spring (k), damper (b), mass (m) and friction (F) in translational notation at Finger Reference Position (FRP)

Different basic parameter sets have to be found for the different response characteristics. Beginning in natural rate command, the first parameter set was found in flight. This happened iteratively by modifying the parameters independently, to get a baseline for further optimization, Table 2.

A systematic approach to get the ideal parameter set for the AC mode is currently in progress. Based on the parameter set for the RC mode different parameter

combinations are evaluated in flight. Additionally, knowledge about the influence and boundaries of the different parameters is obtained.

Table 2: Basic parameter set for rate command

Parameter	Default value
Basic force/deflection	$\pm 40\text{N}$ for $\pm 25\text{deg}$ @ FRP = $0.170\text{m} \approx 539\text{N/m}$
Breakout	$\pm 4\text{N}$ over a width of $\pm 0.1\text{deg}$
Detents	None
Frequency	3Hz
Damping	1
Friction	None

The analysis was limited to the roll axis so far. For each parameter variation the pilots were flying a roll task, before giving a handling quality rating. An important finding is that the spring gradient is an important factor, which should be less in AC than in RC mode. This is due to the fact that pilots need to keep the stick deflected for longer periods than in RC mode.

4.2. Classical tactile cueing

To display flight envelope limits or helicopter load limits, different tactile elements like softstop, detent, or stick shaker can be used. This leads to “improved safety” when flight envelope limits are avoided and to “reduced costs”, when overriding load limits is avoided.

Many limiting functions implemented on active sidesticks (e.g., load limits and flight envelope limits) have been investigated in simulator studies at helicopter companies, research establishments and universities. The implementation of these functions requires predictive formulas for estimating these limits, such as mast bending moments, torque or bank angle limitations. They have been categorized in [10] into three groups critical with respect to:

- Proportional response
- Transient peak response
- Integrated response

The grouping describes the dynamic behaviour of the limit considered with respect to pilot control inputs.

An example for weight reduction and service life extension, i.e., cost reduction, was demonstrated lately by using a load alleviation control and tactile cueing system on the RASCAL helicopter [16].

Figure 11 shows a classical cockpit scenario with a primary flight display (PFD) and a VEMD (Vehicle and Engine Monitoring Display) on the left. This indicates the status of torque, turbine outlet temperature and engine rpm. It is a classical visual cue, which combines several parameters in one display, easing the monitoring task in contrast to several gauges, each for one parameter. However, this display needs to be monitored constantly to remain within the limits. There are additional acoustical cues to indicate a limit exceedance. But these are too late: when they occur, the limit has already been exceeded.

This problem can be solved by cueing the pilot in a tactile way, by local changes of the stick forces. A counter force at right stick position is an unambiguous

cue, which not only warns the pilot of the proximity to a limit, but intuitively also recommends the correct action to prevent it: do not override this counter force!



Figure 11: Cockpit with PFD (right), limit indicator display (left) and collective sidestick (front)

A combination of active sidestick and limit display - as presented in Figure 11 and Figure 12 - seems to be an ideal setup. It combines the advantage of both: the tactile cue indicates an ultimate controller position precisely to the point while the visual gauge gives an overview to classify the current limit and correlates it to the other limits.



Figure 12: VEMD (Vehicle and Engine Monitoring Display)

Mast Moment Indication by haptic cue Mast bending moment limitation and testing in a simulator environment was described in [17] and [18]. In hingeless and bearingless rotor designs, like on the Bo105, BK117, EC135, 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 manoeuvrability, compared to helicopters with articulated rotor systems. One consequence of the high control power is that it requires the pilot to take care regarding the rotor mast bending moment during one special manoeuvre. This manoeuvre is the slope landing as shown in Figure 13.

It starts out above the slope chosen for landing. The pilot then sets down part of the undercarriage on the slope and then performs a slow transition to the sloped attitude shown in the left picture of Figure 13. The helicopter will tend to slip down on the slope. To counteract this, cyclic input is used to tilt the tip path plane and the lift vector towards the slope as demonstrated very clearly by a CH-53 (with an articulated rotor) in the right picture in Figure 13. 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. The switching between looking outside the cockpit and monitoring instruments inside the cockpit results in increased workload. If the workload is too high, the pilot must abandon landing, rather than to risk exceeding the limits of the helicopter.



Figure 13: The Bo-105 S3 and a CH53 demonstrating slope landings

The increased workload during this task can be alleviated by using a softstop cue to show the pilot when he is about to overload the helicopter, as shown in Figure 14.

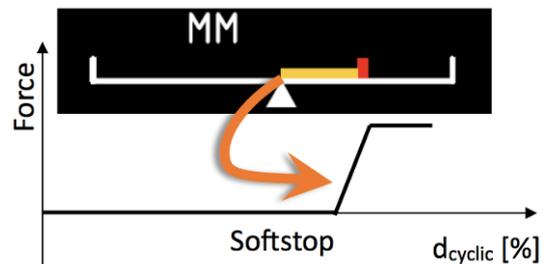


Figure 14: Mast moment indication (on VEMD) and how it correlates to a tactile cue on the cyclic stick

This frees the pilot from monitoring the mast moment indicator in the cockpit. Instead, a softstop on the cyclic stick appears, showing the pilot the control limits corresponding to mast bending moment limits.

System architecture of mast moment limitation

The nature of the mast bending moment was analyzed and it was found that the mast bending moment of the EC135 is mainly a function of cyclic input. Its transfer characteristics in flight is of a transient peak type. During ground contact, the transfer characteristic has a

content of proportional load, in addition to a transient peak. A feedback control system, capable of handling this behaviour, was developed. It estimates future most bending moments for both flight and for ground contact regime. Since the system must be robust, no input from the switches (indicating weight on wheels) is used to switch between regimes. Instead, a worst case of the estimate from the ground and from the airborne regime is chosen and fed back to the softstop calculation algorithm, also taking into account the direction of rotor tip path plane tilt. Finally, an algorithm calculates a softstop such that it is perceived by the pilot as 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 15 shows a proof of concept plot of a simulator test with an aggressive dolphin manoeuvre with artificially lowered limit values. The top 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 bottom half of the plot shows the resulting mast moment as blue and manoeuvre 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 are available yet.

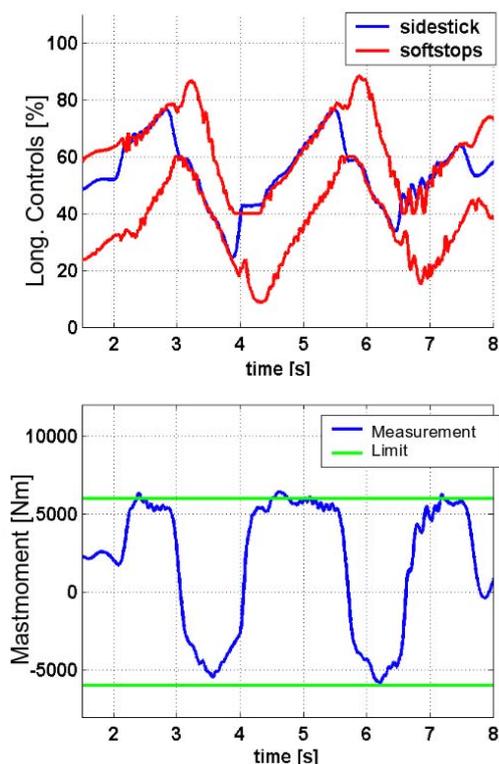


Figure 15: Top: Longitudinal control (blue) and softstops (red). Bottom: Resulting mast moment

Torque protection by haptic cues An important structural limit of every helicopter concerns the drive train. Engine, gearbox and rotor mast may not be over-

loaded. The load is expressed by the torque. There are several limits lying upon another, which may be exceeded only for short time, defined by an absolute limit, which may never be exceeded. During normal operation, the torque should stay below the continuous limit. Only for takeoff this limit may be exceeded for a certain period (30 min for the EC135). Only when an engine failure occurs, in the so called One-Engine-Inoperative (OEI) case, higher limits may be accepted. Of course, the drive train has to be maintained after landing in this case. To get a high flight performance it may be necessary to operate the helicopter at the limit. Because of the risk of overriding the limit, the pilot has to balance high performance versus safety margin.

Traditionally, the torque is displayed visually on an analogue gauge. In the EC135 the torque is displayed on the limit display, a part of the VEMD, Figure 16. Haptic cues can be used to release the pilot from observing the display while “riding” on the calculated softstop position delivers maximum power without exceeding the limits, as demonstrated in flight by NRC [19].

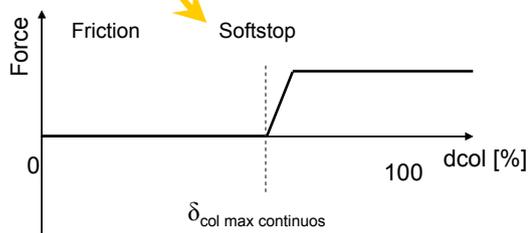


Figure 16: Limit Indicator from VEMD with possible tactile cue representation

Since the quasi-steady torque in general is proportional to the collective control deflection, it is quite easy to calculate maximum controller positions. Several approaches have been published: neural networks, polynomials [11].

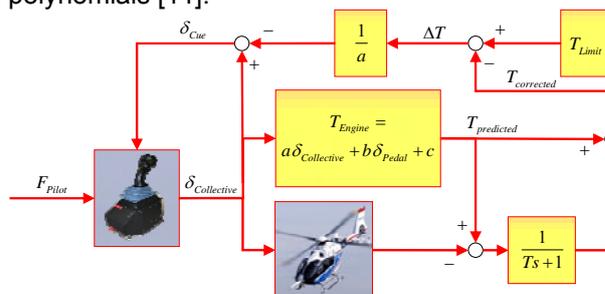


Figure 17: TRQ Protection Structure

Here, a simple polynomial function (dependent of collective and pedal position) was chosen to predict the quasi-steady torque. With the predicted torque, the

structure shown in Figure 17 (with idea from [20]) can be used for the cue calculation. First simulator trials have shown good results. The next step is to test the “haptic torque protection” in flight.

Vortex ring state protection Another important limit for the helicopter is the boundary to the vortex ring state (VRS) [21], [22]. The pilot must avoid too high rates of descent while operating at low forward airspeeds, in which case a recirculation may develop around the rotor, resulting in loss of lift and controllability, Figure 18.

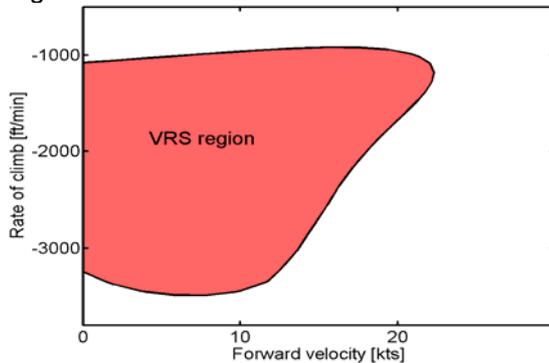


Figure 18: VRS boundary for EC135 at normal operating conditions

Typical VRS related accidents happen during approach and landing when the helicopter is flying at the backside of the power curve, requiring more power as airspeed decreases. If failing to notice the dropping airspeed and increasing rate of descent, the pilot may find himself in the VRS which is felt as an abrupt increase in the rate of descend combined with poor control in cyclic and collective. This - combined with a low and slow scenario produces - a dangerous situation from which there might not be a safe escape.

To counteract the VRS entry, a tactile cueing function for the active collective stick was developed. The cueing function works by giving the pilot a softstop, limiting downward travel of the stick, thereby arresting the rate of descent. A feedback loop continuously recalculates the position of the softstop.

Although the softstop works as a limit, the pilot may still easily override it and use the full range of the collective stick. This ensures that the pilot has the benefit of envelope protection without loosing the freedom of choice.

The VRS avoidance has been performed in close cooperation with Onera, who has a great experience in the field of VRS. Using a model developed by Onera, it has been possible to perform a real-time calculation of the vicinity to the VRS during flight [23], [24].

The cueing function has been tested extensively in the simulator in various scenarios in which pilots have flown different descending tasks as fast as possible. This pushed the pilot towards the VRS region which was to be avoided at all costs.

Figure 19 shows a schematic drawing of one of the tasks. In this task, the pilot had to descend along the hillside while following an S-shaped track and simultaneously staying below treetop height. The workload of this task was rated using the NASA-TLX scale with three pilots and gave the results listed in Table 3, [25].

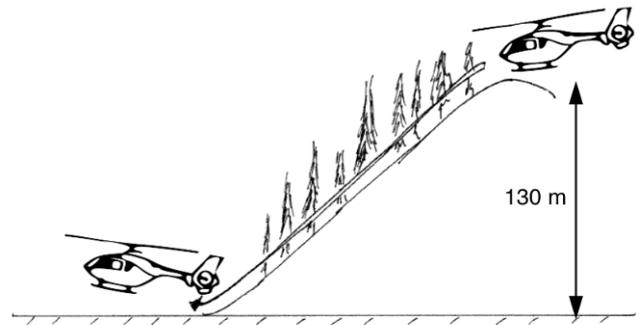


Figure 19: The downhill manoeuvre (not scaled)

Table 3: NASA TLX workload for the downhill VRS avoidance task with and without the VRS cueing function

Workload	Pilot A	Pilot B	Pilot C
No cueing	0.9	0.84	0.99
With cueing	0.52	0.8	0.64

Most pilots experienced a substantial reduction of workload. Furthermore, the recorded data show much less frantic control behaviour on the collective stick. The pilot can adopt a simple strategy in which he simply lowers the stick to rest it on the softstop cue, knowing that the cue will guide him to maintain the optimal rate of descent. It is then not necessary any more to monitor the rate of descent, allowing the pilot to keep his eyes off the cockpit.

The decreased workload was not the only advantage observed. Another one was that the number of dangerous situations close to the VRS was much reduced. This is explained by the fact that the feedback loop is performing better at holding a steady rate of descent than the pilot can be.

4.3. Flight path guidance & Haptic flight director

The active functions can be used in terrain following flight, flying between obstacles, or even flying standard procedures like IFR turns while keeping eyes outside. Either the pilot moves the stick actively against a tactile element like a softstop (indicating the necessary control input), or the neutral force position follows the controller inputs, leading to a semi-automatic flight. In this case, the pilot does not hold the grip tightly, can monitor the flight, and can override the automation always. This leads to “improved handling and safety”. Used as haptic flight director the “required” pilot action is transmitted to the pilot by a combination of changing his stick force and neutral stick position, leading to “easier and improved handling”, [26].

Classical limiting functions were mentioned in the preceding chapter. Other applications may be obstacle avoidance, or more demanding tasks such as terrain or flight path following. One such task has been developed and test flown in the form of the standard “IFR” turn in which the pilot must maintain a constant 3deg/s turn rate [6]. In this implementation, the pilot pushes the stick against a lateral softstop which is generated by a feedback loop so that an exact 3deg/s turn is flown. The pilot intentionally chooses to follow the soft-

stop but retains the possibility to override it. This function was also flight tested and the workload rated as before. The result is shown in Table 4. The task was to fly a 360deg turn within a band of +/-100ft height, +/-5kts velocity, and complete the manoeuvre in 120s +/-4s.

Table 4: NASA TLX workload for the standard rate turn with and without the VRS cueing function

Workload	Pilot A	Pilot B	Pilot C
No cueing	0.87	0.77	0.86
With cueing	0.20	0.41	0.45

The workload ratings clearly state that the cueing function causes a noticeable reduction of the workload. Furthermore, the pilots commented very favourably on this type of cueing function and expressed the opinion that such functions would be a definitive improvement for future helicopters.

Another end of the spectrum of applications is marked by what could be termed *pilot leading functions* or haptic flight director. This is the scenario where the helicopter's autopilot (and trajectory or terrain following) flies the helicopter "through" the stick, which, e.g., is moved by a "ghost hand". The stick is moved to the position corresponding to the trajectory desired by the autopilot. This scenario requires less interaction from the pilot, who no longer is required to perform the control input. He will normally remain with hands on the sticks but for short periods may take his hand off. The function of the pilot is then to monitor the behaviour of the autopilot and to override it, if he should disagree with its action. The applications here range in a spectrum between *limiting* and *leading* the pilot.

5. TECHNOLOGY DEMONSTRATOR RIG

One lesson learned during the development of the active sidestick software was that the process could be accelerated by having the sidesticks right at the desk. This opens the possibility of accompanying testing the force-feel behaviour while working on the software. With a setup like that, a new concept idea can easily be evaluated with little effort, before taking the decision to work it out further for the use in the FHS ground simulation. For that, a simple demonstrator as carrier for the sidestick hardware was built, see Figure 20. The demonstrator comprises of an aluminium rack (which can carry two active sidesticks), together with a helicopter seat, a simulation computer network and a 37" screen. Currently, two active sidesticks from Liebherr Aerospace (LLI) are integrated: The development environment is setup in Matlab/Simulink with a CAN-Bus interface to access the active sidesticks. This environment allows pseudo real-time simulation direct from uncompiled Simulink source code. It ensures a one-to-one applicability of the sidestick control software in the FHS ground simulation and real FHS. The system was successfully displayed as a technology demonstrator on the Berlin Air show (ILA) 2010 in the pavilion of the German Military Procurement Agency (BWB). This stand-alone demonstrator and rapid prototyping environment for active sidestick has been operational since June 2010.



Figure 20: Technology demonstrator for rapid prototyping of tactile pilot assistance

6. SUMMARY AND CONCLUSIONS

The experimental upgrade of the FHS with two active sidesticks is described in the first part of this paper, the second part summarises the use of these devices for pilot assistance:

- Two sidesticks for cyclic and collective control have been integrated into DLR's flying helicopter simulator FHS, leading to a significant extension of its experimental capabilities.
- A feasibility study was conducted to limit the technical, financial, and time risks.
- The right-hand stick is a Gold Stick from Stirling Dynamics Ltd., ruggedized for operation in a flying helicopter. The left-hand stick is a Liebherr design of the third generation.
- For the layout of the collective stick an acceptance study was performed, leading to a solution with a short pole design similar to the right-hand stick.
- The open architecture of the experimental capabilities of the FHS allowed a straightforward implementation.
- For the right hand stick, besides others, a flight path guidance function (IFR-turn & bank angle limitation) was flight tested and the workload reduction demonstrated.
- Examples for load limit cueing, mast moment protection and torque protection, and for flight envelope protection, VRS avoidance are tested and evaluated in simulator and are ready for flight testing.
- The design process has been further improved by the addition of a stand-alone demonstrator for rapid prototyping.
- The side-by-side arrangement with collective and yaw control on the left hand stick was appraised as harmonious and intuitive and also a consequent realization of the sidestick idea: all primary controls are operated by sidesticks.
- With the two active sidesticks the FHS is now upgraded to fully demonstrate the benefits of active control techniques.

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