DEFINITION AND VERIFICATION OF ACTIVE INCEPTOR REQUIREMENTS FOR A FUTURE TILTROTOR

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Abstract

In this paper the requirements of the primary controls of a future tiltrotor are specified and verified. The focus is on active inceptors which can transfer realtime adjustable tactile information to the pilot. The specification effort not only covers the inceptor requirements itself, like the force deflection characteristics, the kind of limit cues and the synchronisation of the pilot and copilot inceptors, but also how such active inceptors should be integrated into the tiltrotor cockpit. This includes a proposal of a novel type of power inceptor which promises to reduce the tiltrotor flying workload. The definitions have been verified in a mock-up study and in intensive piloted simulation trials.

1. Introduction

Starting in the early 1950, the effort for combining the advantages of a helicopter (hover) and those of a fixed-wing aircraft (high cruise speed) created an aircraft type which is named tiltrotor. Starting from the XV-3 this aircraft type evolved over a military (V-22) to the civil version of the BA609. The extended flight envelope is achieved by tilting the nacelles forward or upwards, depending on the desired flight status. Fig 1 shows the ERICA tiltrotor design, where additionally to the nacelles the outer wing section can be tilted in order to reduce drag.

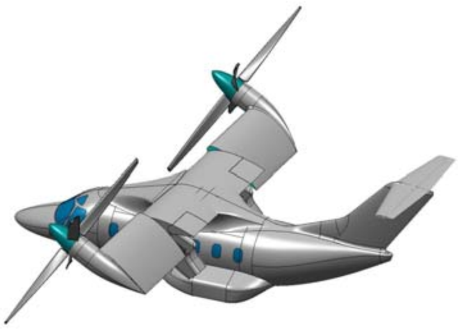

Fig 1 : ERICA tiltrotor design

Flight control of a tiltrotor is a very demanding task. During conversion a "conversion corridor" has to be followed which imposes minimum and maximum airspeed restrictions on the aircraft as a function of the nacelle angle. Further, it is possible for one or both rotors to enter the vortex ring state (VRS) at low airspeeds - this leads to a catastrophic loss of roll control and must be avoided at all cost.

The advantage of a fly-by-wire compared to a mechanical Flight Control System (FCS) is obvious for a tiltrotor: A fly-by-wire system as it is used for the V-22 and the BA609, can replace the complex and heavy mechanical control (especially for a tiltrotor, see XV-15, Ref 5:) and allows reducing the workload significantly by introducing limit protection (e.g. for the conversion corridor or VRS limits).

However, with the removal of the mechanical linkage the tactile information interface to the aircraft is lost and if the flight control computer (FCC) eventually limits the pilot's inputs without providing immediate tactile feedback the handling qualities might deteriorate even more.

The path to overcome this disadvantage is to artificially provide tactile information. This is done by switching from a "passive" to an "active" inceptor.

Definition: An inceptor is called active if it is able to mimic a mechanical linkage, all physical parameters of which can be adjusted by the flight control computer in realtime, depending on the status of the aircraft.

With having an active inceptor available, not only the disadvantages of the missing tactile feedback can be overcome, but also additional tactile cues can be added to improve the handling qualities and/or to reduce the workload further (see also Ref 3:).

In Fig 2 a possible model following control structure for an active inceptor is depicted. The lower right parts represent the inceptor plant, the top two boxes the pilot and the two lower left boxes the inceptor controller. By being able

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to change the inceptor model box in realtime the active inceptor functionality could be ensured.

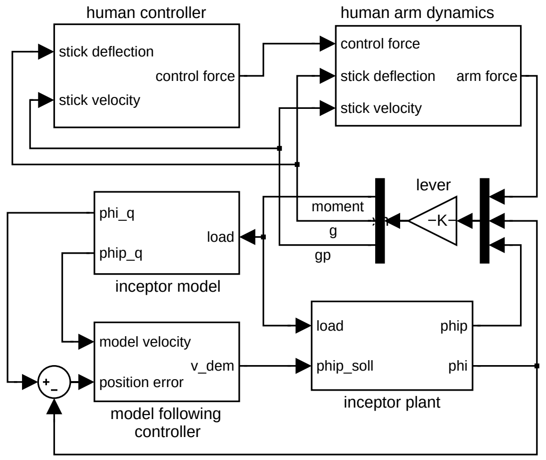

Fig 2 : Model following controller architecture (phi = Plant stick angle, phip = Plant stick angular velocity, phi_q = Model stick angle, phip_q = Model stick angular velocity, g = Deflection at FRP, gp = Velocity at FRP, v_dem = Demanded velocity)

The quality of the active inceptor is proportional to the amount of information that can be transferred to the pilot, which is equivalent to the tactile bandwidth [1].
If such active inceptors are be used to control the tiltrotor several questions arise:

- What are the hardware requirements of such devices?
- How should the tactile feedback look like for a tiltrotor (for normal and degraded operation and for limit warning)?
- How can the active inceptors be integrated into the tiltrotor cockpit?

As very few literature exists which covers these questions (Ref 1: unfortunately does not give any numbers) they will be addressed here: In section 2 the requirements for active inceptors for a tiltrotor are given. Section 3 defines the corresponding cockpit layout. Section 4 and 5 describe the mock-up and the piloted simulation trials, respectively, by which some of the previous definitions have been verified. The description of the trials allows the reader to identify which definitions of section 2 and 3 have been covered. Final conclusions are given in section 6.

2. Inceptor Requirements

2.1. Assignment of Control Degrees of Freedom

With a tiltrotor (TR) being a hybrid between a helicopter (HC) and a fixed-wing (FW) the primary controls need harmonization.
The pitch/roll and the yaw control input for helicopter (HC) and aircraft (AC) mode can be handled in the same way by commanding the attitude or rate in the respective direction. For pitch/roll a sidestick controller for the right hand side and for yaw pedals are foreseen.
The control of power is different for a HC and a FW. In a HC the power is increased by pulling the left hand collective lever (changing the collective blade pitch), while in a FW the throttle angle is opened by pushing the left hand throttle lever (for the right pilot). Especially during conversion mode this contradicting control directions demands harmonization. Two solutions to overcome this contradiction are proposed:

- With the high gain task being the hover mode, a HC left hand active inceptor is chosen also for thrust control in AC mode (like a conventional collective lever).
- A two degrees of freedom active inceptor is used in order to adjust the control direction parallel to the rotor thrust vector (i.e. approximately the nacelle angle).

2.2. Active/Passive

Since the most important limit cues need to be transferred via the pitch/roll and power inceptor these are required to be active. The yaw inceptor, however, can remain passive, as there are no active cues which could justify rendering it active.

2.3. Hands-Free Characteristics

The pitch/roll inceptor needs to have a breakout characteristic capable of maintaining the inceptor's position whilst under the influence of the inceptor grip's weight and normal levels of vibration and turbulence. The location of the breakout and spring datum is manually adjustable via the pitch/roll trim switch and automatically adjusted via an appropriate active autopilot mode. For an active pitch/roll inceptor, these characteristics and behaviour are provided by appropriately driving the inceptor's internal actuators as a function of inceptor position, beep trim inputs and autopilot control laws.
The collective/power inceptor needs to have a friction characteristic capable of maintaining the inceptor's position whilst under the influence of the inceptor grip's weight and normal levels of vibration and turbulence.
As the tiltrotor exhibits no cross-coupling pedal inputs will be needed much less compared to a HC. Thus, the pedals are defined to be permanently centre sprung. No pedal trimming function is required. The yaw autopilot mode is

[1] In this sense a conventional inceptor which is trimmed by the autopilot is passive as the damping, inertia, etc. can not be changed.

disengaged/overridden by the pilot's feet touching the pedals.

2.4. Force Trim Release

The pitch/roll inceptor needs to have a force-trim-release function. When this function is activated, there should be no spring forces at the finger reference point (FRP). For an active pitch/roll inceptor, this characteristic is provided by appropriately driving the inceptor's internal actuators.

2.5. Model to be Followed

General: In general the behaviour of the movement of the FRP is defined by a second order model:

$$Mx(t)'' + dx(t)' + cx(t) + K(t, x, x', x'') = F(t)$$

With M, d and c being the inertia, the viscous damping and the stiffness of the inceptor hardware, respectively, F the force at the FRP, t the time, x, x' and x'' the displacement, velocity and the acceleration of the FRP, respectively, and K the forces due to tactile cueing actions (e.g. soft-stops)

While F and K are changed during operation c, d and M stays constant.

During nominal operation the apparent inertia and the apparent viscous damping at the FRP is fixed to a predefined value.

Specific: More specifically, the following active inceptor characteristics shall be adjustable by the FCC in realtime in the following way:

- Soft-Stops (at least 3 soft-stops in any one axis and direction, individual soft-stop magnitude up to 50N with a gradient of at least 50N/mm)
- Breakout Forces (capable of being symmetric or asymmetric, magnitude up to 50N with a gradient up to 50N/mm)
- Force gradients (capable of being symmetric or asymmetric, with a magnitude of at least 2N/mm)
- Friction Forces (range of at least 1 to 20N)
- Viscous Damping
- Apparent Inertia
- Stick Shaker

In this way it is be possible to define non-linear force/displacement, force/velocity and force/acceleration characteristics, adjustable with time.

2.6. Behaviour in Case of Failures

In case of inceptor failures certain behaviour of the inceptor and/or of the FCC has to be ensured:

- The force-feel system shall be designed such that upon failure, its ability to exert an intolerable force on the inceptor is extremely improbable and there shall be no tendency for the inceptor to move under the influence of it's own weight or under the influence of normal vibration and turbulence levels. In addition, passive friction forces at the pitch/roll inceptor finger reference point shall not exceed 15N and passive friction forces at the collective/power inceptor finger reference point shall not exceed 20N.
- Upon failure of a force-feel system axis, all appropriate autopilot modes shall disengage and be disabled.
- If the transient from a displacement based to a force-based piloting strategy is not acceptable jamming of the stick shall be extreme improbable. If the transient is acceptable and pure force control is acceptable while the stick is fixed, a safe locking mechanism needs to be ensured.
- A full-time pilot/copilot demand selection buttons shall be employed which informs the FCS which set of inceptor positions to use for flight control. It shall be impossible to switch to a pilot/copilot set of inceptors if its force-feel system has failed. The FCS will not automatically de-select pilot/co-pilot set of inceptors if their force-feel system has failed.
- Upon force-feel system failure any associated beep-trim function shall be disabled.
- No flight envelope protection or load alleviation feature implemented within the FCS shall be reliant upon the successful operation of the inceptor’s force-feel system.

2.7. Dual pilot issues

- One set of inceptors shall be used as an primary (priority) input for the flight control computer.
- The bandwidth with respect to a position input on one and the position output on the other of two corresponding inceptors shall not be less than 25 Hz[2]. The same bandwidth shall be reached for a force input and output of the same set of inceptors. The bandwidth shall be reached, no matter which of the inceptors is the primary, or secondary one. By this way it shall be possible to simulate a rigid link between the two inceptors.
- In the event of a force fight between pilots the force transmitted by the primary set of inceptors shall have priority (maybe leading to a temporary loss of

[2] This value is taken from adequately performing hardware.

synchronisation between pilot and copilot inceptor positions).

- The primary set of inceptors shall be designated by a annunciation on the respective inceptor or on the flight display
- Either pilot shall be able to assume primary input with a "takeover button",
- Either pilot shall be able to disconnect all active modes with a "panic button" and fly passive mode
- To avoid excessive change-over transients, it shall not be possible to change over to the other set of inceptors if it is not synchronous.

2.8. Inceptor Travel

Pitch/roll The range of translational travel of the finger reference point shall be between 80 and 120mm in pitch and roll. The distance of the finger reference point from the centre of rotation shall be between 150 and 200mm.
Collective/Power The range of translational travel of the finger reference point shall be between 120 and 140mm. If the two degrees of freedom active inceptor is chosen the direction of the translation should be aligned to the rotor shaft.
Pedal The range of pedal travel shall be between 75 and 130 mm.

2.9. Maximum Nominal Forces

The inceptor's internal actuators shall not be able to generate a steady force in excess of 150N at the finger reference point, but during normal operation at least 80N.

2.10. Maximum Force Gradients

In general, for active inceptors the achievable maximum force gradients shall be as high as possible in order to optimize the tactile feel of the controlling hand. The maximum achievable force gradient is strongly dependent on the bandwidth of the inceptor: The higher the bandwidth the higher the achievable force gradient.
For the pedal the force gradient shall be in a range of 8.8 to 17.5 N/cm, according to ADS33-C.

2.11. Required Bandwidth

The bandwidth is calculated for the transfer function, which is defined by the force acting at the FRP as the input and by the translational stick position in the direction of the applied force as the output.
The bandwidth requirements are constrained by the following items:

- Rotational resolution of 5° 10^{-6} (which is equivalent to a translational resolution of 0.75 10^{-3} mm at a pivot-distance of p=150mm, i.e. at the FRP)
- Maximum achievable angular velocity shall be 500°/s
- Bandwidth of 25 Hz in the low and
- of 5 Hz in the high deflection domain

For the pitch/roll inceptor the latter constraints can be summarised according to Fig 3.

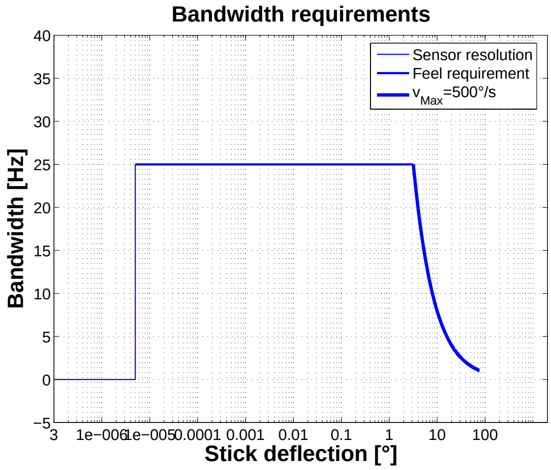

Fig 3 : Bandwidth requirements for the pitch/roll stick

Fig 3 is also valid for the collective/power inceptor, if the abscissa is converted to mm (assumed arm lever of 150mm).

2.12. Signal Noise

Noise in the system leads to stick vibrations. The resulting deflections at the skin of the gripping hand in normal and tangential direction to the skin surface shall not exceed the following values defined, in Fig 4.

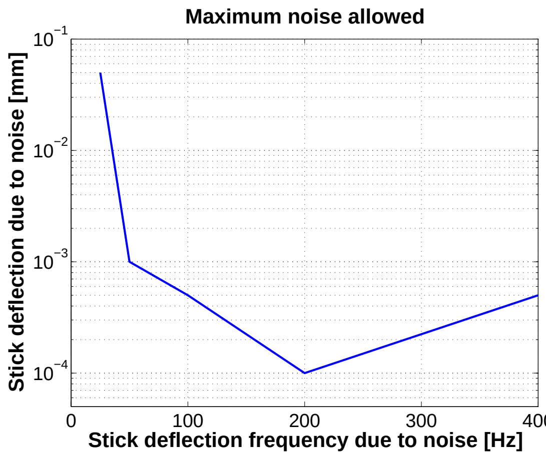

Fig 4 : Approximate human skin sensitivity thresholds

2.13. Force-Deflection Characteristics

The following tables are the recommendations of force-deflection characteristics, resulting from simulation trials at WHL and DLR, see section 5.

Tab. 1: Pitch characteristics

Characteristic	Value at FRP
Travel Range	±50.0 mm (±15.0°)
Trim Rate	±10 mm/s (±3.0°)
Breakout Characteristic	5.5 N over ±0.7 mm (±0.20°)
Spring Characteristic	0.6N/mm(2.0N/ °)
Friction (when active)	0.0 N
Maximum Tolerable Friction (when passive)	15.0 N
Internal Model Natural Frequency	3 Hz
Internal Model Damping Ratio	1
Stick Shaker Characteristic (Low Airspeed Warning)	±10.0 N at 25 Hz
Soft-Stop (High Airspeed Intervention)	50.0 N over 5.0 mm (1.50°)
Soft-Stop (Low Airspeed Intervention)	50.0 N over 5.0 mm (1.50°)

Tab. 2: Roll characteristics

Characteristic	Value at FRP
Travel Range	±50.0 mm (±15.0°)
Trim Rate	±10 mm/s (±3.0°)
Breakout Characteristic	4.0 N over ±0.7 mm (±0.20°)
Spring Characteristic	0.4 N/mm (1.3 N/ °)
Friction (when active)	0.0 N
Maximum Tolerable Friction (when passive)	15.0 N
Internal Model Natural Frequency	3 Hz
Internal Model Damping Ratio	1
Stick Shaker Characteristic (Vortex Ring Warning)	±10.0 N at 25 Hz
Soft-Stop (Vortex Ring Intervention)	30.0 N over 3.1 mm (0.90°)
Soft-Stop (Interconnection Shaft Warning)	30.0 N over 3.1 mm (0.90°)

Tab. 3 : Pedal characteristics

Characteristic	Value at FRP
Travel Range	±64.0 mm (±13.2°)
Breakout Characteristic	32.0 N over ±0.9 mm (±0.18°)
Spring Characteristic	0.6 N/mm (2.8 N/ °)
Viscous Damping	0.16 N/mm/s (0.78 N/°/s)

Tab. 4: Conventional power inceptor characteristics

Characteristic	Value at FRP
Travel Range	±62.0 mm (±15°)
Breakout Characteristic	none
Spring Characteristic	none
Friction (when active)	10.0 N
Maximum Tolerable Friction (when passive)	20.0 N
Internal Model Natural Frequency	2 Hz
Internal Model Damping Ratio	1
Stick Shaker Characteristic	none
Soft-Stop (Continuous OEI Power Warning)	25 N over 0.6 mm (0.15°)
Soft-Stop (Intermediate OEI Power Warning)	35 N over 0.9 mm (0.21°)
Soft-Stop (Transient OEI Power Warning)	45 N over 1.1 mm (0.27°)
Soft-Stop (Vortex Ring Intervention)	50 N over 1.2 mm (0.30°)

Tab. 5: Novel power inceptor characteristics

Characteristic	Value at FRP
Travel Range	±76.0 mm (±25°)
Breakout Characteristic	none
Spring Characteristic	none
Friction (when active)	8.0 N
Maximum Tolerable Friction (when passive)	16.0 N
Internal Model Natural Frequency	2 Hz
Internal Model Damping Ratio	1
Stick Shaker Characteristic	none
Soft-Stop (Continuous OEI Power Warning)	20 N over 0.3 mm (0.09°)
Soft-Stop (Intermediate OEI Power Warning)	28 N over 0.4 mm (0.13°)
Soft-Stop (Transient OEI Power Warning)	36 N over 0.5 mm (0.16°)
Soft-Stop (Vortex Ring Intervention)	40 N over 0.5 mm (0.18°)

2.14. Safety

Depending on which part of the inceptor hardware fails, different modes of operation can be distinguished.

Normal: The inceptor is fully operative. The maximum probability for a failure of this mode shall be 10^{-6}/flight hour.

Reversionary: Actuators do not work, but there is no jamming and the inceptor position is measured properly. There shall be no tendency for the inceptor to move under the influence of it's own weight or under the influence of normal vibration levels. The maximum probability for a failure of this mode shall be 10^{-9}/flight hour.

The same applies for a passive inceptor, but with the passive configuration as the normal mode of operation.

Every mode of operation shall allow controllability of the aircraft (i.e. at least Cooper-Harper handling quality level 2).

2.15. Environment

The environmental requirements can be derived from RTCA DO-160D and FAA regulations and corresponding advisory circulars. With the fly-by-wire equipment special focus is on the EMI requirements.

3. Cockpit Requirements

It was assumed, that the 5^{th} to 95^{th} percentiles of the male population which is defined in the data base of Ref 2: should fit inside the cockpit. Every percentile is required to be able to adjust to the predefined eye-point (Absolute position in mm: x = 4152; y = ± 630; z = 2950, see Fig 5).

The requirements were derived by using a 3D computer model of the cockpit and of the human body and have been verified/adjusted during the mock-trials (see section 4).

The consolidated results are summarized in the following subsections.

3.1. Configuration

According to section 2.1 the primary controls configuration is a sidestick at the pilot's right hand side, pedals for the legs, see Fig 5.

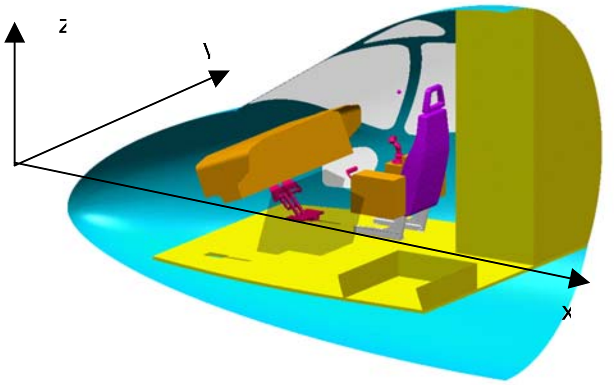

Fig 5 : ERICA cockpit overview.

The adjustment requirements for two kinds of power inceptors at the pilot's left hand side are provided: One power inceptor is a conventional HC collective lever ("rotational inceptor"), the other allows fwd/aft and up/down grip movements, simultaneously ("linear inceptor"). In order to assess the integration of the controls in the ERICA cockpit the seat, the front panel, the interseat console, the fuselage, the rear wall and the corridor are modelled.

3.2. Seat

The position and the required adjustability of the neutral seat reference point (NSRP, see MIL-STD 1333) of the pilot's seat is listed in Tab. 6.

Tab. 6: NSRP position and adjustability

Axis	Nominal	Upper Limit	Lower Limit
x [mm]	4290	+45	-45
y [mm]	± 630	+0	-0
z [mm]	2160	+65	-65

3.3. Consoles

The position of the front panel and interseat console is defined according to Fig 6

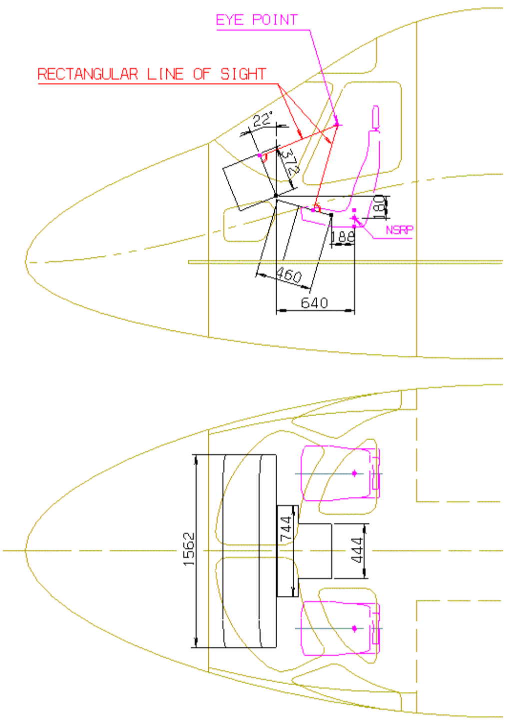

Fig 6 : Positioning of front-panel and interseat console.

3.4. Right Inceptor

Vertical: If it is acceptable with respect to crash requirements to fix the inceptor on the seat, it is recommended to provide a solution where only the armrest is adjustable. The nominal distance of the armrest from the NSRP shall be 239 mm in the positive z-direction with an adjustment range of at least ±20 mm. The FRP is located 52 mm above the armrest.

If the seat needs to be mounted directly on the cockpit floor the nominal distance of the armrest from the floor shall be 549 mm (absolute: 2399 mm) with an adjustment range of at least ± 35 mm.

Horizontal: If it is acceptable with respect to crash requirements to fix the inceptor on the seat, the nominal horizontal distance of the FRP from the NSRP shall be 455 mm in the negative x-direction with an adjustment range of at least ± 60 mm.

If the seat is mounted on the cockpit floor the nominal horizontal distance of the FRP from the NSRP shall be 430 mm in the negative x-direction (absolute: 3860 mm) with an adjustment range of at least ± 30 mm.

Pitch: The results of the mock-up trials are not homogeneous with regard to the required nominal pitch attitude. However, with an active inceptor, the nominal pitch attitude can be adjusted individually. In this case, a range, wide enough to cover all desired nominal pitch attitudes and corresponding control inputs shall be provided. Therefore, a nominal pitch attitude of 25° (fwd) and a range of ±20° is recommended.

Roll: The nominal roll attitude shall be 8° (left) and a range of ±20° is recommended.

Yaw: If an adjustable or active yaw axis is provided the same arguments as for pitch apply. In this case a nominal yaw attitude of -10° (positive around z-axis) and a range of ±15° is recommended.

If the yaw attitude needs to be fixed, a angle of -10° is recommended.

3.5. Left Linear Inceptor

Vertical: If a seat fixed solution is acceptable it is recommended to provide a solution where only the armrest is adjustable. The nominal distance of the armrest from the NSRP shall be the same as on the right hand side, i.e. 239 mm in the positive z-direction with an adjustment range of at least ± 20 mm. The vertical distance of the FRP is 13.5 mm below the arm rest, i.e. counting in negative z-direction.

If the seat needs to be mounted on the cockpit floor the nominal distance of the armrest from the floor shall be 549 mm (absolute: 2399 mm) with an adjustment range of at least ± 35 mm.

Horizontal: If a seat fixed solution is acceptable the nominal horizontal distance of the FRP from the NSRP shall be 391 mm in the negative x-direction with an adjustment range of at least ± 50 mm.

If the seat is mounted on the cockpit floor the nominal horizontal distance of the FRP from the NSRP shall be 381 mm in the negative x-direction (absolute: 3909 mm) with an adjustment range of at least ± 40 mm.

Forward/Aft: A nominal forward/aft position of the power/thrust lever of 30 mm (i.e. absolute position of FRP: 3889 mm), with a range of ±20 mm is recommended.

The maximum total control range shall be 100 mm (starting from 10 mm).

Up/Down: A nominal up/down position of the power/thrust lever of 6 ° (negative around y-axis, z-axis as reference), with a range of 15° in positive (down) and 10° in negative (up) direction is recommended.

Roll: A nominal grip angle of the power/thrust lever of 45° around the x-axis and the y-axis as reference is recommended.

Yaw: A nominal grip angle of the power/thrust lever in yaw direction of the aircraft of 21° (around z-axis, y-axis as reference) is recommended.

3.6. Pedals

The pedals are fixed to a platform the horizontal and vertical position of which can be adjusted.

Platform Position: An absolute approximate adjustment range from 3260 mm to 3460 mm in horizontal (at the pedal attachment point) and from 1838 mm to 1968 mm in vertical direction is recommended.

Pedal Lever Angle: A nominal pedal lever angle of 50° (x-axis as reference) with an adjustment range of ±20° is recommended.

3.7. Left Rotational Inceptor

Vertical: It is recommended to fix the left rotational inceptor on the cockpit floor.

It is recommended to fix the vertical position of the pivot point to 250 mm above the cockpit floor (absolute: 2100 mm).

Horizontal: It is recommended to fix the horizontal position of the pivot point at the cockpit floor in negative x-direction in a distance of 117 mm to the NSRP (absolute: 4173 mm).

Lever Arm: It is recommended to choose the lever arm, such that the FRP has an x-component of 3940 mm in the absolute coordinate system, when the lever arm is at an angle is 0° (i.e. lever arm = 233 mm).

Angular Control Range: A hardware range from -10° to 60° is recommended (x-axis as reference).

3.8. Handles

For the right pilot one handle shall be at the top left of the seat back, a second handle at the cockpit ceiling at the top left of the pilot and, if feasible, a third handle at the front panel, above the primary flight display. Analogous applies for the left pilot.

3.9. Seat Push Back / Immerse Inceptor

If the interseat console is not increased in length a sliding seat arrangement is not imperative. Having in mind, that the space behind the seat is limited, it is recommended to not foresee a seat push back feature. In this case, however, it is mandatory to implement an immersible inner inceptor, if it is of the linear and of the sidestick (left pilot) type.

3.10. Flap/Engine Controls

It is recommended to place the flap control in the middle and bottom of the interseat console. The engine control shall be located at the top of the interseat console or at the bottom of the front panel, in the middle, respectively.

4. Mock-up Trials

4.1. Mock-Up

In order to verify/correct the preliminary definitions derived by the CAD analysis the mock-up requires an adjustability exceeding the specified ones. Accordingly, for the mock-up a seat push-back, an immersible inner inceptor, exchangeable power inceptor types and extended adjustability ranges for the seat and the inceptors have been foreseen. The final mock-up assembly is depicted in Fig 7.

Fig 7 : Mock-up

4.2. Selection of Test Subjects

In order to check if the selected design fits for the 5th to 95th percentile population it is sufficient to check if the maximum and minimum percentiles fit. In order to find such test subjects the following ergonomic dimensions of a number of people have been measured: Body height, shoulder width, pelvis width, seat height, elbow height, knee height, back to knee depth, forearm length (see Ref 2:). By comparing the measured data with the given data base the percentiles of the dimensions of the test subjects could be evaluated. Those subjects, which best fit to the 5th or 95th percentile limits were selected for the mock-up trials. Additionally, a large and a small pilot was added in order to receive pilot specific comments. For the body height this comparison is shown in Fig 8.

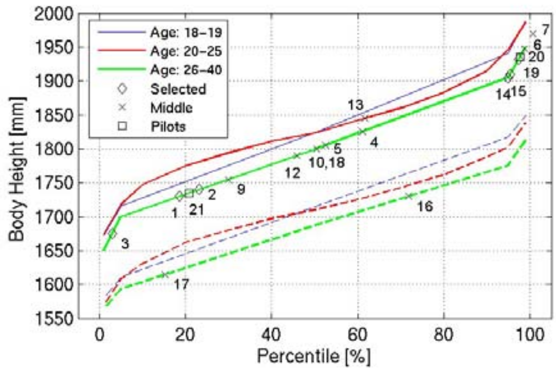

Fig 8 : Classification (solid: male, dotted: female)

4.3. Trials

In the beginning of the trials the test subjects were asked to adjust the seat such that they could fit to the defined eye point. Subsequently they had to perform following tasks:

- Adjust the inceptors to a comfortable position and determine the acceptable range of adjustments.
- Determine the optimal control range of the inceptors.
- Determine the required number and position of handles, the necessity of a seat push-back and of an immersible inner inceptor for a comfortable in- and egress.
- Determine the optimal in- and egress procedure.
- Use pens of different colours to mark the arm range on paper attached to the front panel and interseat panel. This should be performed with the left and right arm, left and right seated and loosely and firmly belted.
- Determine the optimal position for the flaps and the engine controls.

All subjects had to fill out a questionnaire.

4.4. Analysis

The collected data was analyzed and compared to the definitions resulting from the CAD design. Section 3 documents the result.

5. Simulation Trials

For further verification and for identification of missing definitions piloted simulator investigations have been performed, which were conducted in two steps: The first step concentrated on the qualitative (i.e. functional), the second step had its focus on the quantitative verification (i.e. fine-tuning, handling qualities) of the definitions and of the results of the first step trial. The first step was conducted using the fixed-base simulator of the "Deutsches Zentrum für Luft und Raumfahrt" (DLR) located in Braunschweig, Germany, the second step at that of Westland Helicopters Ltd. (WHL) in Yeovil, UK.

5.1. <u>Functional Simulation Trials</u>

<u>Simulator Environment</u> The DLR fixed base simulator features a BO105 cabin, one front and one right screen on which the visual cues are displayed on, a left and right configurable front panel display and an active sidestick from Stirling Dynamics Ltd. (SDL) at the right pilot seat. In the interseat console a panel for configuring the sidestick parameters is integrated. For the dual pilot trials a second sidestick from FCS Control Systems (ECol-8000) was integrated at the left pilot seat (Fig 9). The collective inceptors are passive. The ERICA flight mechanics is modelled with HOST and was provided by Eurocopter.

<u>Single Pilot Trials</u> In a first subtask the focus was on the cyclic inceptor during single pilot operation.

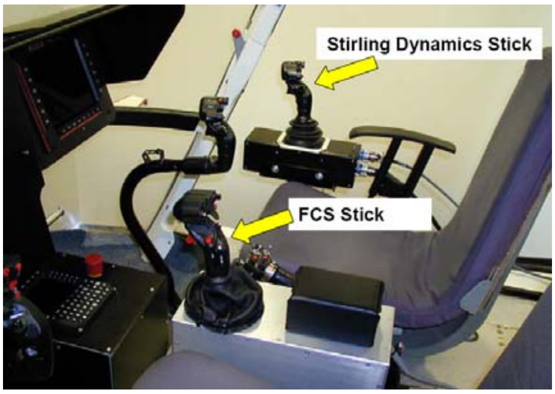

Fig 9 : DLR ground based simulator

In order to limit the test range the following restraints have been accepted:

- The limits to be cued are the boundaries to enter the vortex ring state (VRS), wing stall (WS), the limit torque of the shaft interconnecting the left and right engine (ICS) and the limit torque of the engine gearbox with all engines and one operative (AEO, OEI).
- The applied limiting cues are vibration, soft stop (i.e. push though is possible) and hard stop (i.e. push though is impossible).

To prevent multiple active cues the following priority scheme has been applied (A>B means A has priority over B): VRS > WS > ICS > AEO > OEI and hard stop > soft stop > vibration.

Three pilots conducted the following tasks during the trials:

- Offline adjustment of the sidestick characteristics, i.e. spring forces, damping, model frequency, friction, beep trim speed and break out.
- Offline adjustment of the limit cues:
  - Vibration: Force amplitude and frequency
  - Soft stop: Width and height of the force step
- For three flight states the applicable cue combinations were evaluated for those limits which are in danger to be exceeded in this state:
  1. In low speed hover (< 45 kts, nacelle = 90°) VRS and ICS, both in roll axis.
  2. In conversion mode (< 30 kts, nacelle = 75°) VRS in pitch and roll axis.
  3. In low speed forward flight (140 kts, nacelle = 0°) WS in pitch axis.

Results: The sidestick characteristics and cue adjustments found were used as a starting point for the WHL trials. The finally recommended values are documented in section 2. For all above mentioned flight states the most preferred cue combination was a vibration warning once a certain distance to the limit has been exceeded and a superimposed soft stop once the limit is reached.

<u>Dual Pilot Trials</u> The second subtask was concerned about the link performance of two electronically linked active inceptors and the procedures to transfer, prioritize and limit control. The link of the two sidesticks was achieved according to Fig 10.

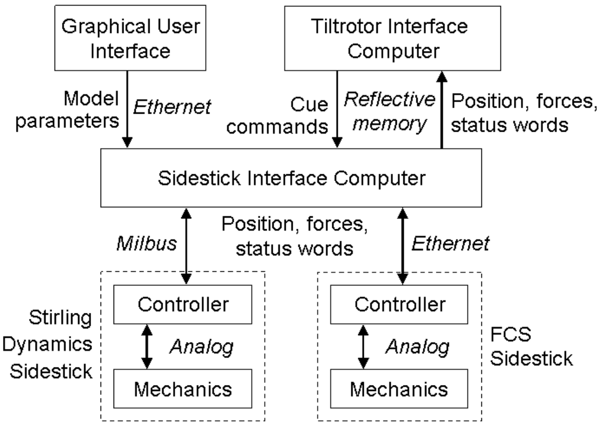

Fig 10: Control architecture

The two sidesticks are connected to a common interface computer. It collects the model data from a graphical user interface, the cue commands from the tiltrotor interface computer (TIC) and provides it in an appropriate format to each sidestick. Further, it receives the position and force information from each sidestick; those of the primary sidestick are transferred to the TIC as the valid aircraft command. On both sidestick grips a switch allows to select this as the primary controller set.

Three pilots conducted following tasks:

- Assessment and comparison of both sidesticks in hover flight with respect to their force deflection characteristic and limit cues.
- Assessment of the synchronisation of the sidestick position. One pilot is moving the primary stick back and forth and sideways. The other has his hand on the secondary stick feeling how it is backdriven.
- Assessment of force-limited secondary sidestick control over the primary sidestick. One pilot is pushing the secondary stick back and forth and sideways. The other pilot holds the primary stick fixed, feeling how it is backdriven. The secondary forces acting on the primary inceptor were limited to values between 0 and 100N.
- Assessment of following switch strategies:
  1. The right pilot can only take over when the left pilot lets go of the button. The left pilot can always take over.
  2. The secondary pilot can take over only when the primary pilot button is released.
- General evaluation of switching the priorities and also of the backdriving of the primary sidestick by the secondary pilot input in hover, forward flight, light and aggressive manoeuvring flight (HC) and fixed-wing mode.

Results: The comparison of the two sidesticks revealed, that they largely behave similar. Just the apparent inertia of the SDL stick is judged "slightly high", which is due to the relatively high gearing.

The position and force synchronisation of the sidestick position was judged offline and in flight as insufficient. Due to a time lag of 150ms between the sidesticks just a maximum bandwidth of about 3Hz could be reached. Based on their experience with an insufficient bandwidth, all pilots regarded the capability to simulate a mechanical linkage as mandatory for the synchronisation of pilot and copilot inceptors.

The limited force transmission from the secondary to the primary pilot was judged as useful just for a student/teacher mission. For this case a force limit of 30 to 50 N was judged as practicable. During normal operation a rigid link between the sidesticks is preferred.

Similar results apply for the switching strategy: For student/teacher situations strategy 1 is acceptable, for operational flight (two rated pilots) strategy 2 is mandatory.

5.2. <u>Quantitative Simulation Trials</u>

<u>Simulator Environment</u> The WHL fixed-base simulator features a EH101 cabin, a dome for displaying the visual cues, two left and two right configurable front panel displays, one configurable interseat display, two active sidesticks from SDL at the right pilot seat: One is used for the pitch/roll control at the right hand side the other for the power control at the left hand side. Two types of power inceptors can be installed: One, which resembles a conventional collective lever with a fixed control degrees of freedom (cdof) in vertical direction (type 1), and the other with the cdof staying aligned with the moving rotor axis (type 2). The alignment is achieved by rotating the sidestick on a circular path with the grip as the pivot. Fig 11 gives an idea of the two types of power inceptors.

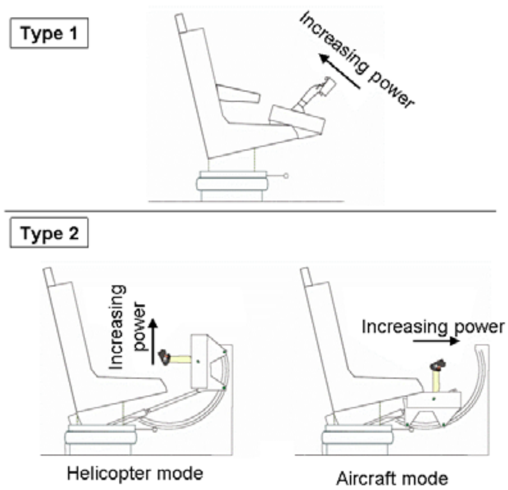

Fig 11: Two types of power inceptors

The ERICA flight mechanics was modelled by Glasgow Caledonian University with FMC.

Unique for a tiltrotor is the need for displaying the conversion corridor (i.e. velocity and nacelle angle), VRS (i.e. decent rate) and ICS (torque) limits. In order to analyze the influence of the type of display on the handling qualities two versions of primary flight displays (PFD) have been assessed: The PFD type 1 (Fig 12) displays the conversion corridor by marking the forbidden zone with yellow arcs at the velocity (top left) and nacelle angle indicator (middle left). The ICS torque display is located below the velocity indicator. Below the nacelle angle indicator is the engine speed and the engine power indicator (left and right, respectively). The vertical speed indicator is located in the middle of the right side. Again a yellow arc marks the forbidden zone. The PDF type 2 combines the velocity and nacelle angle indicator by displaying the conversion corridor itself, with an added digital speed readout, see Fig 13.

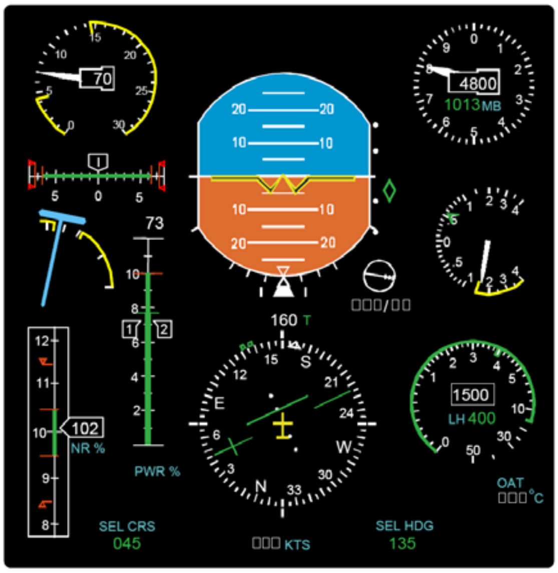

Fig 12: PFD type 1

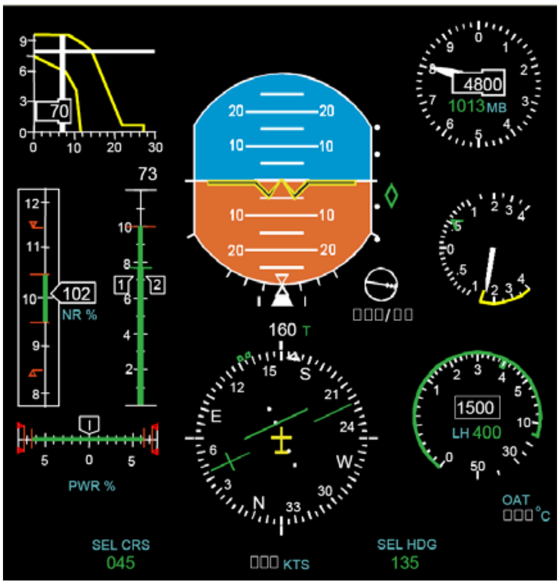

Fig 13: PFD type 2

Trials Four pilots assessed the PFD and power lever configurations according to Tab. 7.

Tab. 7: Assessed configurations of pilots A, B, C and D

		Power lever type					
		1			2		
PDF type	1	A	C	D	C	A	B
	2	B	D	C	D	B	A

The following seven flight test manoeuvres and test regimes were flown, which were developed in order to optimally assess and fine tune the sidestick characteristics and limit cues. After a description of the manoeuvre it is explained for the assessment of which cues it has been designed for:

1. Hover turn (about the pilot's eye point):
In an environment which is sketched in Fig 14, starting from facing North at a height of 20ft the pilot was asked to rotate two times 90° to the right, first at low then at high rate of aggression (suggested turn time was 20 and 10 seconds, respectively). The final heading should stay within ±5° (tolerated: ±10°). Aim was to maintain the aircraft's height (by keeping at least half the post's white band in front of the wall's white band) and the pilot's eye point position within the road width. However, height deviations of ±20ft and position deviations of ±6m were tolerated.

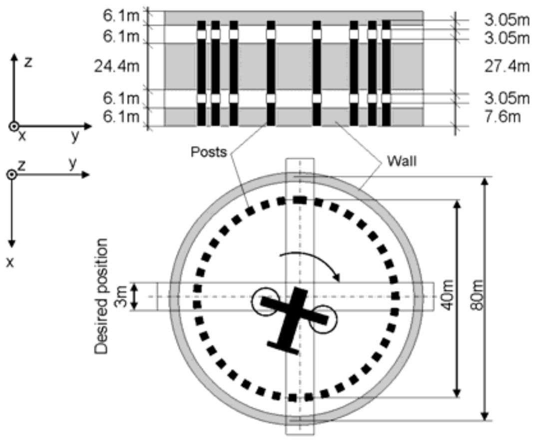

Fig 14: Hover turn

As continuous and small pilot inputs are required in the pitch, roll and yaw axes in order to rotate the aircraft about the pilot eye point (which is substantially in front of the centre-of-gravity), this manoeuvre is ideal for simultaneously evaluating the general characteristics (sensitivity, break-out, friction, spring gradient characteristics) of the pitch, roll and yaw inceptors whilst in the low-airspeed helicopter mode flight regime.

2. Glideslope Capture at 90 kts:
In an environment which is sketched in Fig 15, the manoeuvre was started from 90 knots indicated airspeed (helicopter mode with nacelle at 75°) at a displayed barometric altitude of 2000ft and located 14km from runway threshold. The aircraft's initial course was parallel to the runway and offset laterally by 500m from the runway centre-line.
The pilot was asked to manoeuvre the aircraft on to the localiser within 1 minute while maintaining the aircraft's altitude 2000 ±25ft (tolerated: ±50ft), to remain on the centreline while maintaining the localiser deviation to within ±25% (tolerated: ±50%), to descend on the glideslope while maintaining the deviation

to within ±25% (tolerated: ±50%) and to proceed for a visual landing from 200ft.
Throughout the whole manoeuvre the aim was to maintain the aircraft's airspeed of 90 kts within ±5 kts (tolerated: ±10 kts).

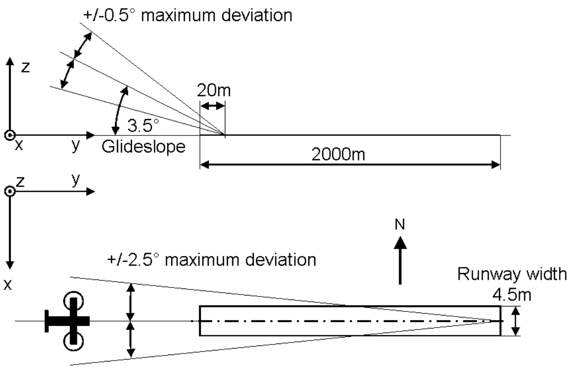

Fig 15: 90 kts Glideslope Capture

As continuous and small/medium pilot inputs are required in the pitch, roll and power axes in order to regulate the aircraft's flight path, flight track and airspeed, this manoeuvre is ideal for simultaneously evaluating the general characteristics of the pitch, roll and power inceptors whilst in the high-airspeed helicopter mode flight regime.

3. Conversion and Reconversion:
In an environment which is sketched in Fig 16 the manoeuvre was initialised in hover, at a height of 100ft at one end of a road.

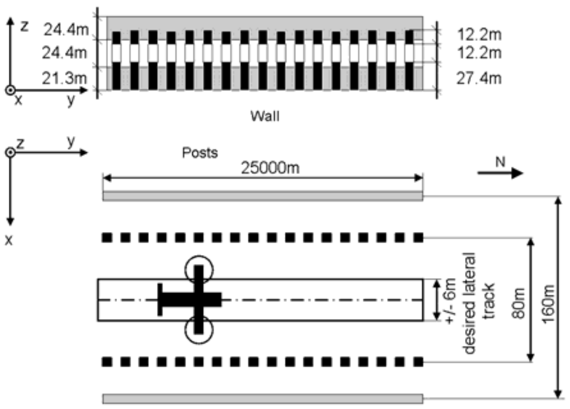

Fig 16: Conversion and Reconversion

The pilot was asked to select flaps down and accelerate to the maximum helicopter mode airspeed (≈70kts) such that the pilot encountered the pitch inceptor's tactile cue, to decelerate back down to 40kts, then to accelerate to 180 kts beeping the nacelles according to the following schedule: beep 90° to 75° at 45kts, beep 75° to 60° at 100kts, 60° to 0° at 130kts. Above 150kts, raise the flaps and select 77% rotorspeed. Then to decelerate to the minimum airspeed (aircraft mode, flaps-up) such that the pilot encountered the pitch inceptor's minimum velocity (stall) tactile warning cue, to accelerate back up to 150kts, to select flaps down and the 100% rotorspeed datum and finally to decelerate to a hover beeping the nacelles. The nacelles angle should be beeped as per the schedule above.
Throughout the whole manoeuvre the pilot should maintain the aircraft's heading within ±5°; height within ±40ft (by maintaining at least half the post's white band in front of the wall's white band) and the pilots eye point position within ±6m (the road width). However, heading deviations of ±10°, height deviations of ±80ft and lateral position deviations of ±12m were tolerated.
As medium-sized pilot inputs are required in the pitch and power axes in order to perform a level acceleration and deceleration of the aircraft in a reasonably aggressive manner (so that minimum and maximum airspeed limits/warnings are encountered) and as the pilot is also required to make inputs via the nacelle angle and flap deployment control devices, this manoeuvre is ideal for simultaneously evaluating: the general characteristics of the pitch and power inceptors during the conversion flight regime; the nacelle angle and flap deployment control devices; and the pitch axis airspeed limit tactile cues.

4. 130 kts OEI Glideslope Capture:
In an environment according to Fig 15, the manoeuvre was initialised at 130 kts indicated airspeed, aircraft mode, flaps down and one engine inoperative at a barometric altitude of 2000ft and located 14km from runway threshold. The aircraft's initial course is parallel to the runway and offset laterally by 500m from the runway centre-line.
The pilot was asked to manoeuvre the aircraft on to the localiser within 1 minute, while maintaining the aircraft's altitude 2000 ±25ft (tolerated: ±50ft), to remain on the centreline, while maintaining the localiser deviation to within ±25% (tolerated: ±50%), to descend on the glideslope, while maintaining deviation to within ±25% (tolerated: ±50), to execute at 200ft a go-around using maximum continuous power and to climb to 1000ft barometric altitude in aircraft mode.
Throughout the whole manoeuvre the aim was to maintain the aircraft's airspeed of 130 kts within ±5kts (tolerated: ±10kts).
As continuous and small/medium pilot inputs are required in the pitch, roll and power axes in order to regulate the aircraft's flight path, flight track and airspeed, this manoeuvre is ideal for simultaneously evaluating the general characteristics of the pitch, roll and power inceptors whilst in the aircraft mode flight

regime. The go-around phase of this flight test manoeuvre gives the pilot the opportunity to experience and evaluate the OEI continuous power tactile cue.

5. Rapid downward reposition and OEI upwards reposition:

In an environment which is sketched in Fig 14, the manoeuvre was initialised at zero ground speed with the pilot’s eye point at the centre of the cross-roads, facing North with a displayed radar altitude of 120ft.

The pilot was asked to descend at a rate greater than 1500 feet per minute to a displayed radar altitude of 20ft such that he encountered the power inceptor's vortex-ring state tactile warning cue and to maintain the aircraft's new lower height within ±10ft (tolerated: ±20ft) (by keeping at least half the post’s white band in front of the wall’s white band). The aircraft then experiences an engine failure. The pilot was required to ascend to a displayed radar altitude of 120ft whilst respecting the transient (30 second) power limit such that he encountered the power inceptor's continuous, intermediate and transient power rating tactile cues. The pilot was asked to maintain the aircraft's new higher height within ±10ft (tolerated: ±20ft).

The aim was to maintain the aircraft's heading within ±5° and the pilot’s eye point position within ±3m (the road width). However, heading deviations of ±10° and position deviations of ±6m were tolerated.

As aggressive pilot inputs are required in the power axis in order to rapidly descend and ascend the aircraft, this manoeuvre is ideal for experiencing and evaluating the power inceptor’s general characteristics as well as its vortex-ring and OEI continuous / intermediate / transient power tactile cues in the low-airspeed helicopter mode flight regime.

6. Rapid lateral/downwards reposition and OEI lateral/upwards reposition:

In an environment according to Fig 17, the manoeuvre was initialised at zero ground speed with the pilot’s eye point the centre of the left-most road junction, facing across the slope with a displayed radar altitude of 60ft.

The pilot was required to attempt to descend at a rate greater than 1500 ft/min and translate to the right using roll rates in excess of 20 degrees/second (following the slope of the ground) such that he encountered the power and roll inceptor's VRS warning tactile cues. The pilot needed to come to a hover at the next road junction (at the bottom of the slope). The aircraft then experience an engine failure. The pilot was asked to gradually translate right until the aircraft is hovering over the next road junction. The pilot was required to ascend and translate right (following the slope of the ground) whilst respecting the intermediate (2 minute) power limit such that he encountered the power inceptor's continuous and intermediate power rating tactile cues and roll inceptor's ICS power limit tactile warning cues. Finally, the pilot needed to come to a hover at the next road junction (at the top of the slope).

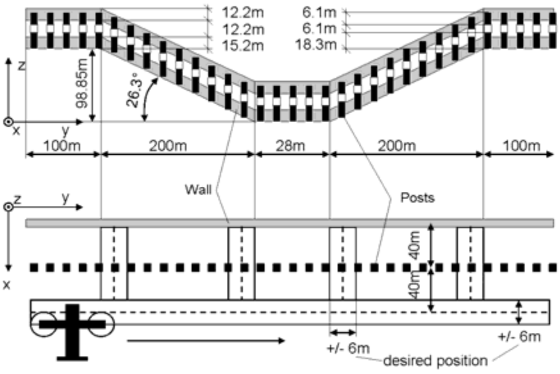

Fig 17: Rapid lateral/downwards reposition and OEI lateral/upwards reposition

The aim was to maintain the: aircraft's heading within ±10°; aircraft's radar height within ±20ft (by maintaining at least half the post’s white band in front of the wall’s white band); the pilot eye point position within ±6m (the road width). However, heading deviations of ±15°, height deviations of ±40ft and lateral position deviations of ±12m were tolerated.

As aggressive pilot inputs are required in the roll and power axes in order to rapidly descend and laterally translate the aircraft as well as to rapidly ascend and laterally translate the aircraft, this manoeuvre is ideal for experiencing and evaluating: the roll and power inceptor’s general characteristics; the vortex-ring tactile cues on the roll and power inceptors; the OEI continuous/intermediate power tactile cues on power inceptor; and OEI ICS power tactile cues on the roll inceptor.

7. Rapid descent and deceleration:

The aircraft was initialised at 50 kts indicated airspeed (helicopter mode) at a displayed barometric altitude of 2000ft.

The pilot was required to rapidly establish a descent rate of 2000 ft/min whilst maintaining airspeed. The pilot needed to acknowledge the proximity of the vortex ring state by the tactile warning cues on the power and pitch inceptors. According to Fig 18 the pilot then was asked to decelerate through the minimum helicopter mode speed (45 kts) whilst maintaining the descent rate such that he encountered the pitch inceptor's minimum velocity (VRS) tactile intervention cue. Upon passing through 500 feet the pilot needed to stop his descent.

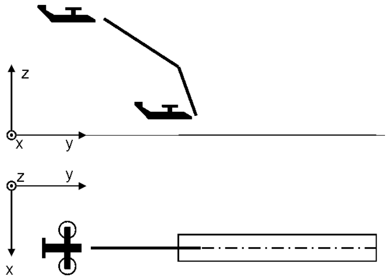

Fig 18: Rapid decent and deceleration

As aggressive pilot inputs are required in the pitch and power axes in order to rapidly descend and decelerate the aircraft, this manoeuvre is ideal for experiencing and evaluating: the pitch and power inceptor's general characteristics in the high-airspeed helicopter mode flight regime as well as the vortex-ring tactile cues on both inceptors.

Results For each manoeuvre the task performance has been measured with respect to desired and tolerable limits. The handling qualities (HQ) according to ADS-33 have been evaluated on the Cooper-Harper scale for active and simulated passive inceptors.
With help of statistical methods it could be found, that there is a probability

- of 45% that the performance and of 13% that the handling quality rating does depend on the selection of PFD type 1 or 2.
- of 78% that the performance and of 90% that the HQ rating does depend on the selection of the power inceptor type 1 or 2. The novel power inceptor improves the mean value of the performance from 3.2 to 2.8 and of the HQs from 5.3 to 4.9.
- of 99% that the performance and of 99.5% that the HQ rating does depend on the active or passive status of the inceptors. The active inceptor could improve the mean value of the task performance from 3.9 to 2.9 and of the HQ ratings from 6.3 to 4.9, with respect to a passive inceptor.

Thus, even though the pilots complained about the bad ergonomics of the type 2 power inceptor it is relatively probable, that this configuration yields better results.
The display format seems to have no influence on the system performance.
The mean value of 6.3 for the HQ rating suggests that the parameters of the passive inceptors should not be allowed to be degraded further if HQ ratings of 7 and worse are not desired.
The consolidated results for the sidstick characteristics and limit cues are documented in section 2 and were the basis for the simulator trials in Ref 4:.

6. Conclusions

In this paper a detailed definition of the use of active inceptors in a future tiltrotor is provided and it has been verified by trials. Inter alias the functional requirements of the inceptors and their integration into the cockpit have been covered.
Even though the chosen tactile cues are found to be optimal, they depend strongly on the given environment: Higher bandwidth inceptors might allow improved optimal cues. Also, a verification in a real (i.e. vibrating) cockpit environment is required for the final freeze of the cues parameters.
If the type 2 power inceptor could be ergonomically enhanced, its ability of improving the HQ rating would fully show to advantage. Further development in this field is promising.

7. Acknowledgement

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