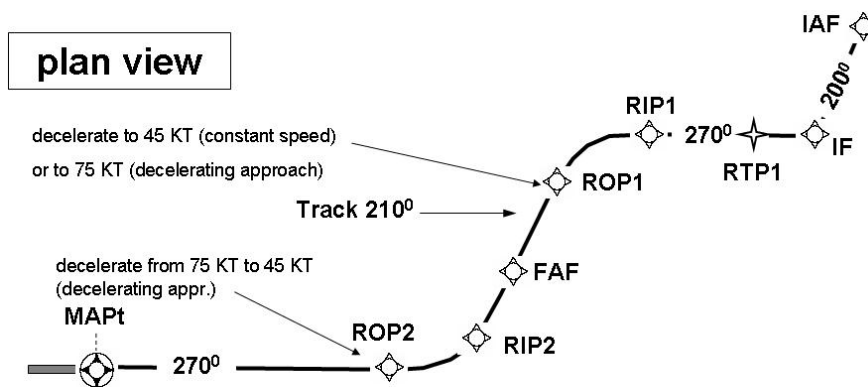




Executive summary

On the flyability and Handling Quality aspects of steep straight or curved/segmented rotorcraft IFR procedures



Problem area

With the busy environment of modern airports, the addition of rotorcraft IFR operations imposes a still heavier burden on airport capacity, environment, etc. One way to reduce the impact is the use of the so-called SNI concept: Simultaneous Non-Interfering operations, whereby the rotorcraft operates on specially developed IFR procedures, which, by design, have the flexibility to be laid out such that independent IFR procedures for rotorcraft will be possible. With the rotorcraft's potential of flying at much steeper glideslopes than "normally" done, and their greater performance capabilities due to their lower speeds (e.g. smaller turn radii), it is possible to design IFR procedures with turns or curves on the final approach segment, with glideslopes that are in the range of 6° to 10°. The flying quality issues

and pilot acceptability of such procedures have not yet been investigated.

Description of work

In the course of the EU-funded project **OPTIMAL** a number of rotorcraft IFR procedures were developed and tested in a simulated environment. These procedures are characterised by a steep glideslope of 6° -10° and curves or turns on the final segment (as well as on the intermediate segment). Also 2 types of guidance displays were designed to help the pilot fly these novel procedures, containing turn and/or curves.

Results and conclusions

In a first, "stand-alone" simulation exercise the flyability and handling qualities aspects associated with the particularities of these novel procedures was investigated using

Report no.

NLR-TP-2009-446

Author(s)

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Report classification

UNCLASSIFIED

Date

August 2011

Knowledge area(s)

Helicopter Technology

Descriptor(s)

IFR procedure
curved-final approach
SNI
simulation

pilot-in-the-loop simulations. The presence of fly-by turns or curved segments in a procedure deteriorated the handling quality ratings, the lateral tracking performance and increased workload, with fly-by turns being less detrimental than curves. The presence of a flight director improved this situation. Correlating the lateral cyclic control activity with handling quality ratings for HQR predictive purposes was not successful. For practical applications pilots recommended to lengthen the procedures and to have a stabilised approach at least below 500 ft, if not 1000 ft. Improved procedures should be based on a

much lower deceleration rate than used in the design of these procedures

Applicability

The novel, flexible, steep IFR procedures can be used at busy airports that already have capacity limits, and can therefore not easily accept additional rotorcraft IFR flights. The experience and knowledge gained in this simulation will be used to design and test such an “SNI”-type of IFR procedure for acceptance by ATC at a typical, busy airport environment, in a helicopter-ATC integrated simulation.



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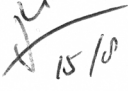

This report is based on a presentation held at the Rotorcraft Handling Qualities Conference, Foresight Centre, Liverpool, United Kingdom, 4-6 November 2008.

The contents of this report may be cited on condition that full credit is given to NLR and the authors.

This publication has been refereed by the Advisory Committee AEROSPACE VEHICLES.

Customer	European Commission
Contract number	----
Owner	NLR
Division NLR	Air Transport
Distribution	Unlimited
Classification of title	Unclassified
	August 2011

Approved by:

Author  9-8-'11	Reviewer  15/10	Managing department 
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On the flyability and Handling Quality aspects of steep straight or curved/segmented rotorcraft IFR procedures

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Abstract

In the course of the EU-funded project **OPTIMAL** a number of rotorcraft IFR procedures were developed and tested in a simulated environment. These procedures are characterised by a steep glideslope of 6° or more and curves or turns on the final segment. In a first simulation exercise the flyability and handling qualities aspects associated with the particularities of these procedures was investigated using pilot-in-the-loop simulations.

The presence of fly-by turns or curves in a procedure deteriorated the handling quality ratings, the lateral tracking performance and increased workload, with fly-by turns being less detrimental than curves. The presence of a flight director improved this situation. Correlating the lateral control activity with handling quality ratings for HQR predictive purposes was not successful. For practical applications pilots recommended to lengthen the procedures and to have a stabilised approach at least below 500 ft, if not 1000 ft. Improved procedures should be based on a much lower deceleration rate than used.

Glossary

ANOVA	ANalysis Of VAriance	IFR	Instrument Flight Rules
CFIT	Controlled Flight Into Terrain	ILS	Instrument Landing System
DA/H	Decision Altitude / Height	ITP	Initial Turning Point
FAF	Final Approach Fix	MANOVA	Multiple ANalysis Of VAriance
FD	Flight Director	MAPt	Missed Approach Point
FDP	Final Descent Point	N _R	rotor rpm
FROP	Final Roll-Out Point	OPTIMAL	O ptimised P rocedures and T echniques for the I mprovement of Approach and L anding
FTP	Final Turning Point		Proportional-Integral-Differential
GBAS	Ground-Based Augmentation System		Roll-In Point
GPA	Glide Path Angle	PID	Required Navigational Performance
GPS	Global Positioning System	RIP	Rate Of Descent
h, h _c	altitude (commanded)	RNP	Roll-Out Point
HPS	Helicopter Pilot Station	ROD	RNP Transition Point
HQs	Handling Qualities	ROP	
HQR	Handling Quality Rating	RTP	
HSI	Horizontal Situation Indicator		
IAF	Initial Approach Fix		
IF	Intermediate Fix		

¹ Senior research scientist



SBAS	Space-Based Augmentation System	VPA	Vertical Path Angle
SISO	Single Input/Single Output	V_w	wind vector
SNI	Simultaneous Non-Interfering	γ, γ_0	(reference) glideslope
V_{w10}	“tower wind”	z	altitude

1 Introduction

In the European Commission Framework VI project **OPTIMAL** steep curved-segmented rotorcraft IFR procedures have been developed in order to increase airport capacity, improve the efficiency and reduce the noise footprint. The two most distinguishing features are 1) a final segment, starting at the final approach fix ‘FAF’ from where a steep descent is started, which need not be aligned with the landing direction, but rather may have one or more turning points or curves, and 2) a glideslope angle that is clearly more than the currently accepted value, i.e. in the order of 9°-10°. This allows such a procedure to be oriented such that restricted areas, associated with other (fixed-wing) IFR traffic (e.g. the so-called ILS areas), or restricted areas arising from noise-abatement or obstacles, can be avoided. With such an application of the flexibility of the approach procedure in an airport environment the rotorcraft will be able to operate simultaneously with standard fixed-wing IFR traffic without interfering with the flow of traffic. This concept is called SNI: Simultaneous Non-Interfering.

The motivation for designing these rotorcraft procedures are:

- Busy airports make addition of rotorcraft flights troublesome
- Rotorcraft on IFR flights can fly different procedures; they are not bound by straight-in paths owing to lower speeds and greater manoeuvrability
- The new rotorcraft procedures can be oriented out of the “standard” flow of traffic, thus allowing rotorcraft IFR to operate without interfering with fixed-wing IFR approach traffic
- With the presence of new navigational capabilities such as a ground-based or space-based GPS augmentation system (GBAS, SBAS) it has become possible to provide vertical guidance, hence increasing

the flight safety of these procedures, alleviating the risk of controlled flight into terrain (CFIT).

2 Procedure design aspects

Within the **OPTIMAL** project a number of rotorcraft-specific procedure were developed, which may be categorized as procedures with a steep glideslope and with a straight final segment, and those where the final segment is either (laterally) segmented or it contains a curve. They are characterized by the presence of one or more, so called ‘fly-by’ waypoints. When passing these waypoints the rotorcraft is supposed to fly by to intercept the next track, rather than to fly over them. Only the missed approach point has generally been defined as a fly-over waypoint. The consequence of this definition lies in the amount of airspace needed to navigate from one leg to the next.

Procedure design aspects associated with these procedures are:

- a. Straight procedures
 - Deceleration rate. A design value of -1.5 Kt/s was adopted.
 - Vertical path angle VPA. For the initial and intermediate segments the VPA is generally zero or small. For the final segment the maximum value considered is 10°. A value of 6° or more is considered a steep approach.
 - A Rate Of Descent (ROD) limit of 800 fpm. Higher values could possibly lead to safety issues in case of a missed approach, where height loss may increase too much.
 - The maximum allowable groundspeed is linked to the limit in rate of descent and the VPA. With a VPA of 9° the limiting groundspeed is 50 Kt, based on a ROD limit of 800 fpm.

- b. For the laterally segmented procedure with ‘fly-by’ turns an additional criterion is:
 - Maximum turn rate. Since all waypoints are of the fly-by type, standard turn rates apply, i.e. 3°/s. Usually also bank angle limits are in order, however, because of the relatively low speeds, compared to fixed-wing aircraft, the turn rate limit would be reached first.
 - c. For the curved procedure, since it contains a curved segment in general, we have:
 - Minimum radius of the curve. Since it is linked to airspeed and turn rate and with some turn rate margin left for control, it is assumed that the maximum turn rate that may be involved is half the standard value, i.e. 1.5°/s. Coupled with the maximum speed that arises from the ROD limit this limiting value sets the turn radius.
6. (for this paper) Is it possible to relate the pilot’s primary lateral control input to the handling quality ratings that are obtained? Can these control parameters be used to predict the HQR value, for example?

The resulting objectives derived from these research questions are:

- Evaluate the flyability of a segmented and curved procedure. Flyability is expressed in terms of controls activity, HQRs, workload and other pilot comments;
- Evaluate the effect of having fly-by turns or curves on the same parameters by comparing straight (no) turns against fly-by turns or curves;
- Evaluate the effect of the speed concept (i.e. constant-speed or decelerating final approach) on rotorcraft handling, pilot performance and pilot workload;
- Evaluate the effect of crosswind upon the HQRs, pilot’s workload, performance, etc.;
- Evaluate the effect of adding a Flight Director (in “uncoupled” mode, i.e. for manual flight, see section 3.2.5) on e.g. pilot workload, performance, handling qualities, etc.;
- Investigate the possibility of correlating HQRs with some or any of the flight-mechanical variables measured (e.g. deviations, control activity), besides workload and pilot opinions.

From the list of objectives the experimental variables and test matrix are derived. The experimental variables are discussed in the next section. Note that this list is in fact a subset of test conditions that were tested earlier on, see Ref. [2].

3 Experimental design

3.1 Objectives

At the start of the project several questions were asked, upon which the objectives listed for evaluation using piloted simulation were based. The questions were for example:

1. How flyable are steep glideslope procedures, also when including track changes on the intermediate and/or even final segment? How far can one go in terms of complexity of the procedure, glideslope angle, etc.?
2. What type of track change should be made, if any? That is, is there a difference between having a fly-by waypoint and a curved segment to affect the track change in terms of handling qualities, pilot workload, etc.?
3. Should the final approach be flown at one constant speed, or may the speed be varied along the approach?
4. How sensitive are the results obtained to such items like the presence of crosswind?
5. How much reduction, if at all, in the pilot workload and/or improvement in flight performance can be achieved by using a flight director? Is a FD needed?

3.2 Experimental variables

3.2.1 General

It is the intention of the tests to have only one vertical path angle. The suitable Vertical Path Angles in the tests to be performed, however, are 9° for the straight and 10° for the segmented and curved procedures. This relatively small difference between 9° and 10° is not expected to have an impact on the handling qualities and/or piloting workload.

3.2.2 Type-of-turn in the procedure

The type-of-turn in the procedure, viz. ‘none’ or ‘straight’, ‘fly-by’ (rate-one turn) or ‘curve’ (fixed radius turn) was an experimental factor. Because of turns or curves made the roll control response will be more active than for a straight procedure, and more stimuli will be generated in the roll axis. It remains to be seen if this will adversely affect the handling qualities ratings. These types of turn are accommodated through the use of IFR procedures that either contain a fly-by waypoint or a curved leg. In order to add even more variability these types of turn were also flown in level flight (i.e. on the intermediate segment) and in descending flight (i.e. on the final approach segment). The resulting procedures that were derived from this are discussed in chapter 4.

3.2.3 Speed concept

The approach procedure was flown either as a Constant-speed or as a decelerating approach. In case of a decelerating approach the airspeed had to be reduced, from generally 75 Kt on final to the final approach speed, while on final approach. In case of flying with the flight director the deceleration was “programmed” in the FD control laws. The pilot could set the commanded airspeed using a beep switch on the collective lever. In manual flight the pilot had to decelerate on his own accord. Obviously for the constant-speed approaches the airspeed on final was to be kept constant.

3.2.4 Wind speed

In order to evaluate the “sensitivity” of the procedures to environmental conditions like wind, the wind speed was an experimental variable. There either was no wind or there was a 25 Kt crosswind, the wind direction being at 90° (left) to the very final approach course (i.e. “crosswind from the left”). The mean wind velocity was stratiform, i.e. it only varied with height according to the boundary layer model:

$$V_w(z) = \frac{V_{w*}}{k} \ln\left(\frac{z}{z_0}\right) \quad (1)$$

Here z_0 is the roughness length, V_{w*} is the “friction velocity”, and k is the Von Karman

constant; $k = 0.4$. Using a tower-reported wind, the “tower wind”, measured at 10 m height above a mown lawn (then $z_0 = 1.0$ mm, see Ref.[5]) one can solve for the friction velocity. Substituting back in Eq. (1) one can then solve for the wind at altitude as function of the “tower wind” V_{w10} as follows:

$$V_w(z) = 0.109V_{w10} [\ln(z) + 6.908] \quad (2)$$

The wind direction was set to veer 30° from 10 m to 2000 ft in a linear fashion.

3.2.5 Flight guidance mode (manual / FD)

One aspect of piloting, handling qualities and guidance being evaluated was the level of ‘flight guidance’, varying from ‘pure manual’ flight to flight director (‘FD’) manual flight, with the FD in “uncoupled” mode (i.e. not coupled to an autopilot), see also section 5.4. The FD was only applied to the procedures with the ‘fly-by’ or ‘curve’ turn type for reasons of manual effort involved and the scope of the simulation exercise. Of interest is the fact whether the FD would have an effect on piloting control, pilot workload or the flight path performance. Due to initial problems with implementing the flight director it was not possible for the first pilot to perform the tests with the FD.

3.3 Scope of the tests

Six pilots participated, each one participating in the simulator for 2 days. One of them was a qualified experimental test pilot from the Netherlands Air Force, two were highly experienced instrument-rated commercial pilots, one was an Air Force rotorcraft IFR flight instructor, and the final one was a low(er)-time commercial pilot. The amount of training spent per pilot varied from 2-5 hours.

In the course of the experiment execution (with the third pilot) the entry speed was lowered from 150 Kt IAS to 120 Kt IAS to reduce the “strain” of decelerating and so reduce the workload. Since a comparison is made of the effects within each pilot it is assumed that this will not affect the statistical outcome.

3.4 Test matrix

The experimental test matrix for the piloted simulation experiment is given in Table 1. It is a repeated measures, or a “within subjects” (the subject being the pilot) experimental design. With this design the difference in e.g. entry speed, mentioned before, as well as piloting biases, will be cancelled because only differences within the subject are compared. The experiment was performed in February-March of 2006. This test matrix is actually a subset of the tests originally performed; see also the ERF 2006 paper, Ref. [2]. The experimental

With this test matrix there are 20 runs made per pilot to cover it. With 6 pilots this totals to 120 data runs to be processed. All three levels of type-of-turn can be evaluated only in case of manual flight. The effect of the FD can be evaluated only for the ‘non-straight’ procedures.

4 Description of procedures

4.1 General

Five procedures were developed for experimental evaluation, of which 3 were straight, one was a laterally segmented procedure, and one was a curved procedure. The baseline procedure was a straight 6° glideslope procedure, which will not be further considered in this paper. Of the other 2 straight procedures, each having a final glideslope angle of 9°, one was a “vertically” segmented procedure or “dual-slope” straight procedure, with a glideslope of 3° on the intermediate segment and 9° for the final segment. This dual-slope procedure will not be considered in the analysis here either. What is left is one straight procedure, one segmented procedure and one curved procedure that will be used in the analysis. They will be described next.

Table 1 Experimental test matrix; VPA = 9-10°

speed concept	type-of-turn	flight mode	wind		run no
			c	m	
CS	straight	M	c	m	1,2
DECEL			c	m	3,4
CS	fly-by	M	c	m	5,6
DECEL		FD	c	m	7,8
		M	c	m	9,10
		FD	c	m	11,12
CS	curve	M,	c	m	13,14
DECEL		FD	c	m	15,16
		M	c	m	17,18
		FD	c	m	19,20

runs were offered to the pilots in such a sequence so as to evenly distribute any remaining learning effects. For the evaluation of handling qualities in this paper the test matrix had been adapted by re-ordering the experimental factors in a slightly different order, and by deleting some of the original experimental factors (e.g. vertical guidance display).

4.2 Straight procedure

For the purpose of being able to compare across the various procedures the 9° single-slope procedure was selected here. A graph of what this procedure looks like is given in Figure 1, based on a “typical” final approach course of 270°.

The ‘IF’ is a fly-by waypoint. Waypoint ‘RTP1’

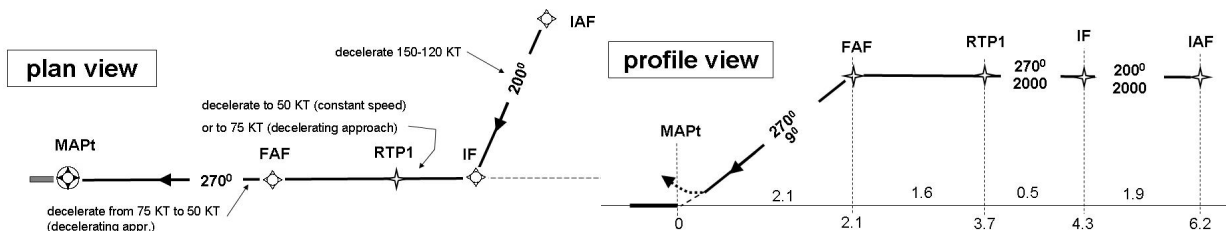


Figure 1 Approach plate of straight 9° slope procedure

is the first RNP Transition Point, where the ILS localizer and/or glideslope sensitivity changed, based on changing RNP values (see also Figure 5). Because of the steep slope the entire final segment, starting at 2000 ft, is only 2.1 NM long. Entry speed is 150 Kt IAS, which is to be reduced to 120 Kt IAS¹ before reaching the 'IF'. Speed on final is 50 Kt IAS when flying a constant-speed approach; in case of a decelerating approach the initial final speed is 75 Kt IAS. Deceleration to 50 Kt IAS should occur at pilot's discretion.

segmented procedure is left to discussion, it is an interesting procedure for reasons of comparison with the curved procedure, as will become evident when discussing the next procedure. Both non-straight procedures have both a turn or curve on the level intermediate segment, as well as a descending segment turn or curve. Each such turn/curve has different aspects of handling qualities because of differences in glideslope and hence airspeed, while at the same time having more or less the same requirement in terms of manoeuvring or turning capability.

4.3 Laterally segmented procedure

The laterally segmented procedure, incorporating two fly-by waypoints, is shown in Figure 2. The first fly-by waypoint is 'ITP', the Intermediate Turning Point on a level segment, the second one is the 'FTP', the Final Turning Point on the descending, final segment. Final

4.4 Curved procedure

A typical approach plate of this procedure is given in Figure 3, based on a final track of 270°. The glideslope is 10°. Entry altitude is 2000 ft.

Entry speed is 150 Kt IAS, which is to be

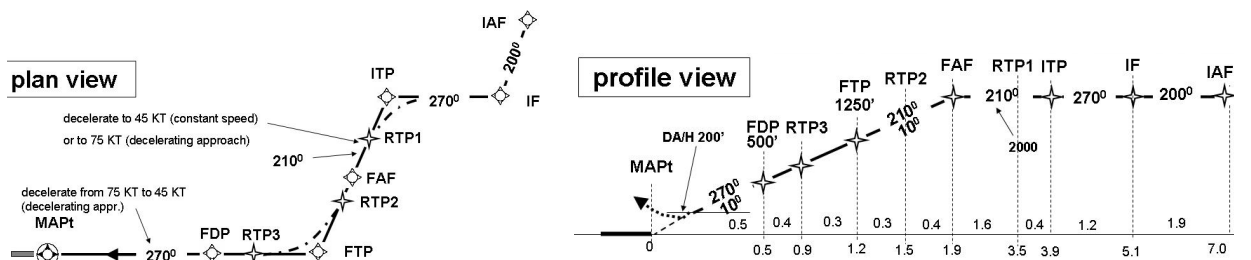


Figure 2 Approach plate of laterally segmented procedure

descent starts at the 'FAF'.

Entry altitude is 2000 ft, and the glideslope is 10°. This calls for a final approach speed of 45 Kt IAS in case of a constant-speed approach. Although the operational usefulness of this

reduced to 120 Kt IAS after passing the 'IAF'. After passing Roll-Out Point 1 the rotorcraft is to be slowed to the final approach speed of 45 Kt IAS (no wind) or 50 Kt IAS in case of wind and a constant-speed final approach. In case of a decelerating final approach the rotorcraft has

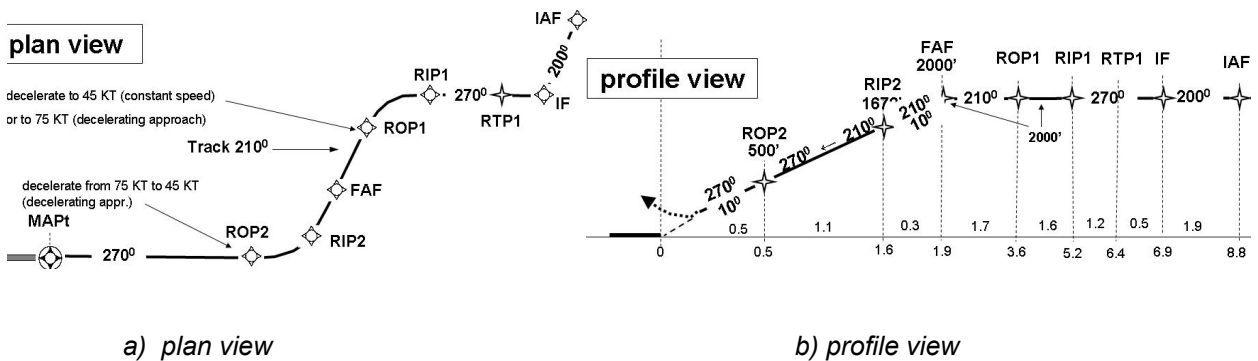


Figure 3 Approach plate of curved approach procedure

¹ With the 3^d pilot and later these speeds were reduced to 120 Kt and 100 Kt IAS respectively, in order to reduce the piloting workload.

to be decelerated to 75 Kt IAS, while on descent, after having passed Roll-Out Point 2,

the speed is to be reduced further to 45-50 Kt, depending upon wind (pilots were allowed to make a wind correction of 5 Kt extra airspeed in case of wind).

track, e.g. after the next waypoint, where either a track or glideslope change may occur, or where a change is made in the ILS-like full-scale sensitivity.

5 Guidance concepts and displays

5.1 General

Part of the new developments made concerned the development of novel guidance displays in order to guide the pilot along the novel procedures.

5.2 ILS-squared display concept

For lateral and vertical guidance on the procedure at NLR a so-called “ILS-squared” symbology was developed. Below in Figure 4 this symbology is shown on the HSI. For lateral guidance the pilot uses 2 lateral deviation bars,

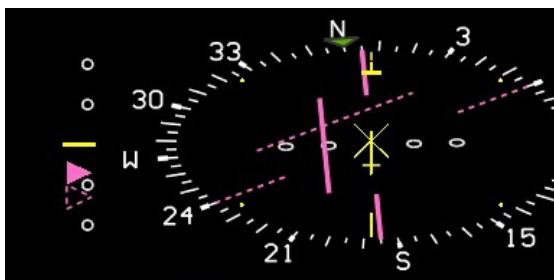


Figure 4 ‘ILS-squared’ symbology

one solid and one dashed, while for vertical guidance the pilot uses 2 ILS glideslope-like bugs, one solid and one dashed, that move along a vertical scale to the left of the compass rose.

The solid symbols provide deviation information (in dots) with respect to the *present* track, while the dashed symbols provide deviation information with respect to the *next*

5.3 Guidance display sensitivity scaling

In order to drive the ILS-like “glideslope” and “localizer” bugs during the entire approach the deviation bug sensitivities were varied along the approach. This was varied according to the RNP value that applied for each procedure segment. There were RNP Transition Points, denoted as ‘RTP’, where the RNP value changed from one RNP level to another (lower) level, thus increasing the sensitivity of the lateral and vertical guidance symbology. The transition occurred gradually, in a linear fashion. The sensitivity was not an experimental factor but given. A typical sensitivity scaling for the curved procedure is depicted in Figure 5.

5.4 Flight Director

Another aspect of guidance was the use of a flight director. It was surmised that the workload would become quite high with the curved or segmented procedure, so a flight director had been implemented and was part of the experimental investigation. A simple roll

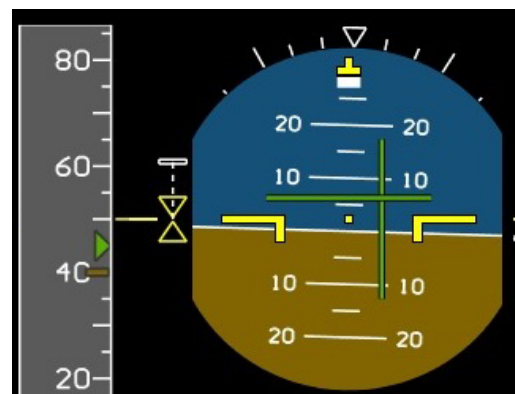


Figure 6 Flight Director bars on ADI

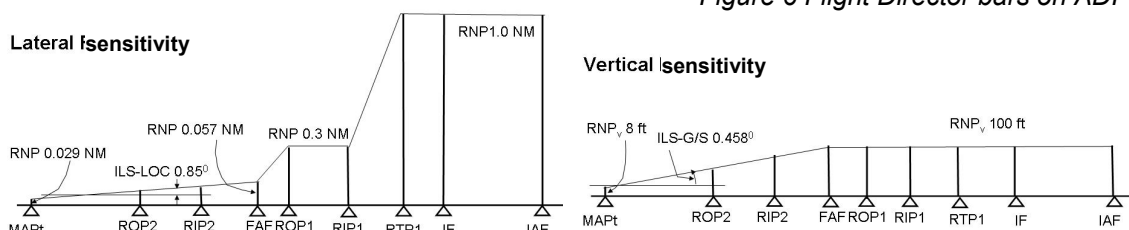
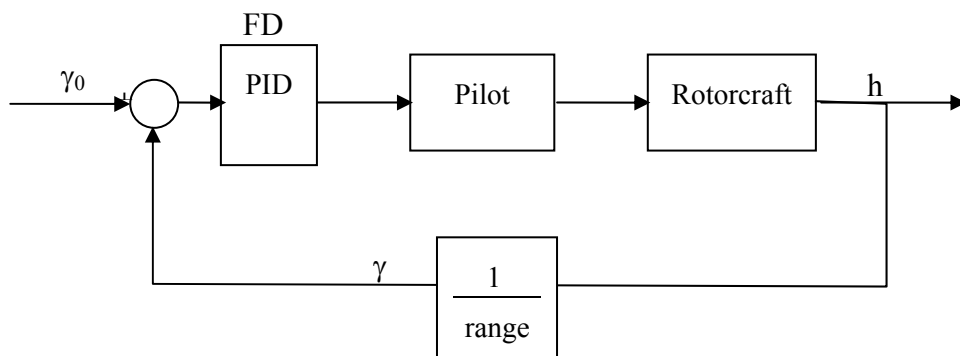


Figure 5 Lateral and vertical deviation sensitivity scaling for curved procedure

and pitch bar are present, plus a collective cue. The sign of this cue was reversed from that originally implemented. For deceleration a value of 1.5 Kt/s was adopted as standard. An example of what the FD bars look like is shown in Figure 6.

The FD is used in the “uncoupled” mode (i.e. not coupled to an autopilot), so it only displays PID-type corrective signals to the pilot for him to zero, i.e. the basic FD-Pilot-Rotorcraft structure looks like sketched below for the vertical (glideslope) loop.



The pilot reacts to the signals displayed by the flight director. In fact the system the pilot is to control has been augmented with the PID control laws acting upon the glide path/slope error. The ‘range’ is a time-varying gain, in fact the distance to the landing threshold point, usually computed from radio height:

$$\text{range} = \frac{\text{radio height}}{tg\gamma_0}$$

where γ_0 is the reference glideslope of the procedure. The PID block transforms the error signal to a collective command signal, to which the pilot responds.

right-hand seat was available (now there are 2 seats available). Three overhead projectors project a CGI on 3 white-painted panels. Overall the field of view offered by this facility is 135° horizontal x 33.5° vertical (i.e. 11.5° up, and 22° down).

Sound cues to represent engine and rotor sounds are generated as a function of engine torque (in this case) and rotor rpm N_R and are fed through audio boxes within the control room.



Figure 7 Fixed-base Helicopter Pilot Station “at work”

6 Simulator set-up and models

6.1 Helicopter pilot station

All manned simulations were performed using NLR’s Helicopter Pilot Station ‘HPS’. This is a fixed-base simulator, consisting of a digital control loadings block, upon which is mounted the seating and cockpit panel, made from plywood. At the time of the simulations only a

The rotorcraft flight mechanical model is driven by the FLIGHTLAB™ real-time simulation tool/model.

An impression of the HPS (2-seat version) is given in Figure 7. A glass cockpit applies, with 2 large displays per pilot/co-pilot and a centre pedestal.

6.2 Rotorcraft model

The rotorcraft model implemented in FLIGHTLAB was a Eurocopter AS365N Dauphin medium-class helicopter, at 4.3 tons of mass. The modelling data was received from the University of Liverpool, which obtained the specific model data from ONERA, France within the framework of the OPTIMAL project.

To augment the handling qualities of the bare model for the purpose of the experiment a simple 3-axis SAS was built in, and a ball-centring yaw channel control law was implemented, which was de-activated below 25 Kt. Originally this switch-over speed was set at 40 Kt, but this turned out to interfere with the operations.

The AS 365N rotorcraft was basically a Level-2 vehicle owing to its (Dutch) roll axis dynamics, according to ADS33 small-amplitude frequency and damping data criteria for forward flight (Ref. [2]).

The roll response eigenfrequencies/damping ratios were obtained from a linearised model of the AS365N, for two conditions, viz. 100 Kt level flight (e.g. intermediate approach) and 50 Kt at 9° glideslope (final approach). The “actual” situation is more or less between these two.

The eigenvalues of the linearised model for the two conditions are shown in Figure 8. The linearised model was derived using the linearisation option in the simulation tool FLIGHTLAB™.

The Dutch roll mode at $-0.676 \pm 3.43i$ ($\omega_{dr}=3.5$ rad/s, $\zeta_{dr}=0.19$) at 100 Kt moved to a lower frequency with more or less the same damping ratio, $-0.3428 \pm 1.5466i$ ($\omega_{dr}=1.58$ rad/s, $\zeta_{dr}=0.22$) when going to the second flight condition, while the Phugoid mode at $-0.1515 \pm 0.1799i$ ($\omega_{ph}=0.24$ rad/s, $\zeta_{ph}=0.64$) moves into the right-half plane. These were the only poles affected most by the change in flight condition. The other, a-periodic unstable mode at $+0.2$ moved further to the right to about $+0.5$.

6.3 FMS

For providing navigational information the HPS was equipped with NLR’s Research FMS, or RFMS. The RFMS functions were expanded in

order to be able to navigate along curved legs. The RFMS used the ILS sensitivity information, together with its computed position data to

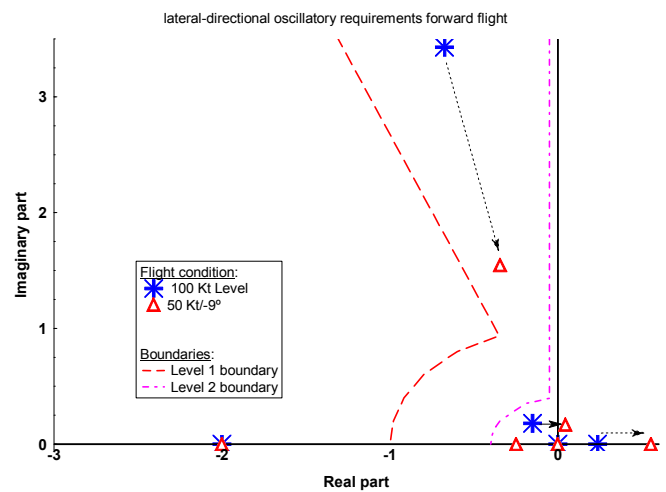


Figure 8 Eigenvalues for the AS365N for two conditions

compute the ILS localizer and glideslope deviations in dots, in order to display these signals.

6.4 Visual scenery

A visual data base of the Amsterdam Airport, “Schiphol” (EHAM) was available and augmented to better present specific runway details. Special focus with the tests was on the General Aviation Terminal Area/Ramp, which is located at Schiphol-East apron. On runway 22, with the intersection with a taxiway, lies the helispot, including marked lighting. Drawback from visual scenery simulation of lights is that they look like coloured spots with equal brightness as the other spots of the same or different colour.

Only daylight conditions were simulated, but cloud base and/or visibility levels were varied to set test conditions conducive to go-around or landings, viz. 250 ft cloud base or less than 200 ft, and/or visibility of 1000 m or less and/or 8 km.

Most if not all the flight was flown by reference to instruments, hence the visual cueing was not of paramount importance.

It was important for the pilot to be familiar with the novel displays, including the guidance displays.

6.5 Data acquisition and recording

6.5.1 Questionnaires

For the purpose of soliciting pilot information several questionnaires were designed, viz. an “in-cockpit” questionnaire, to be filled out after each run, a debriefing questionnaire per class of procedure, as well as a final, overall debriefing questionnaire. All questionnaire data were stored into a file that could be processed by the statistical package STATISTICA™ (version 7.1), see Ref.[6].

The questions asked related to such matters like:

- **Handling qualities** (by use of the Cooper-Harper Rating scale and the McDonnell scale, Ref. [4]). Although the pilots were not trained as an experimental test pilot except one, they all filled out this rating scale, together with supporting questions about why they came up with the rating as they did.
- **Acceptance of the procedure** and/or speed concept, or in combination. Use was made of a “simple” adjectival rating scale (with adjectives from ‘fully rejected’ to ‘fully accepted’).
- **Pilot workload** using the Demand scale of McDonnell (see Ref. [4]). This scale too has been proven to be an interval scale. Additionally the Modified Cooper Harper or MCH scale was used for rating mental demand. This scale, which is very reminiscent of the “standard” Cooper-Harper rating scale, had been developed by NASA (see Ref. [3]).

6.5.2 Performance and control data

The use of the real-time simulation tool FLIGHTLAB™ allowed for a large number of parameters to be output for further processing, mostly time histories of controls, attitudes and rates, flight path, flight speed, etc. All data was recorded at a rate of 10 Hz.

The flight path lateral and vertical deviations from the desired path were transformed into dots deviation, of which the root mean square (‘rms’) was computed per approach segment.

These deviations were also stored per waypoint passage.

A special treatment was given to the processing of the control data for this paper. After analysis it was decided to split the time history of each control parameter into a low-frequency or manoeuvre component and a stabilisation component, per approach segment. For example,

$$x_a(t) \Rightarrow \begin{matrix} x_{a,man}(t) \\ x_{a,stab}(t) \end{matrix}$$

where, from observing the power spectral density of the control input, the lower-frequency manoeuvre component was derived from a time-averaging over 5 seconds. That is,

$$x_{a,man}(t) = \frac{1}{5} \int_{\tau=t-2.5}^{t+2.5} x_a(\tau) d\tau$$

$$\text{and } x_{a,stab}(t) = x_a(t) - x_{a,man}(t)$$

The rms of these ‘man’ and ‘stab’ components was further used. The hypothesis is that it is the stabilisation component that drives the handling qualities aspect of the procedure, while the manoeuvring component may affect workload more than the handling. For a less stable rotorcraft the stabilisation component will be relatively large compared to the manoeuvring component, unless of course much manoeuvring is called for (such as is the case with the non-straight procedures). At first it was endeavoured to use the spectral components of each control input, but that process turned out to require too much time for processing the data given time and budget constraints.

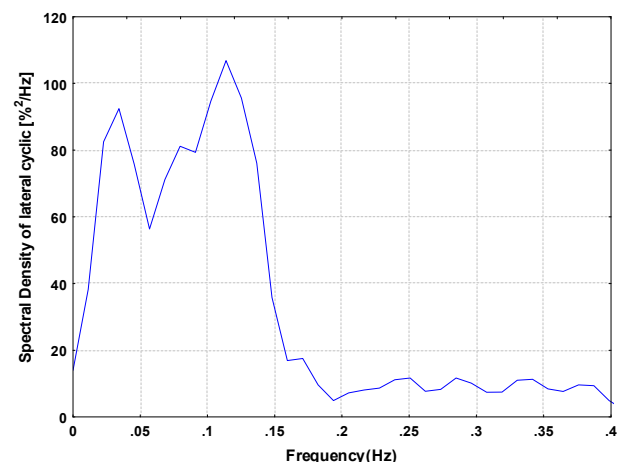
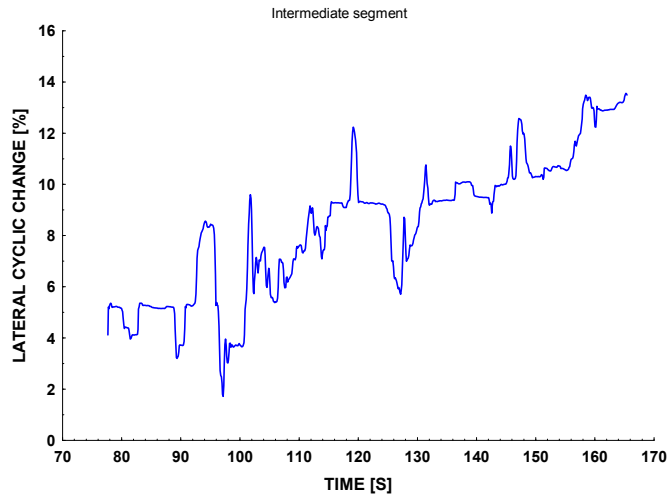


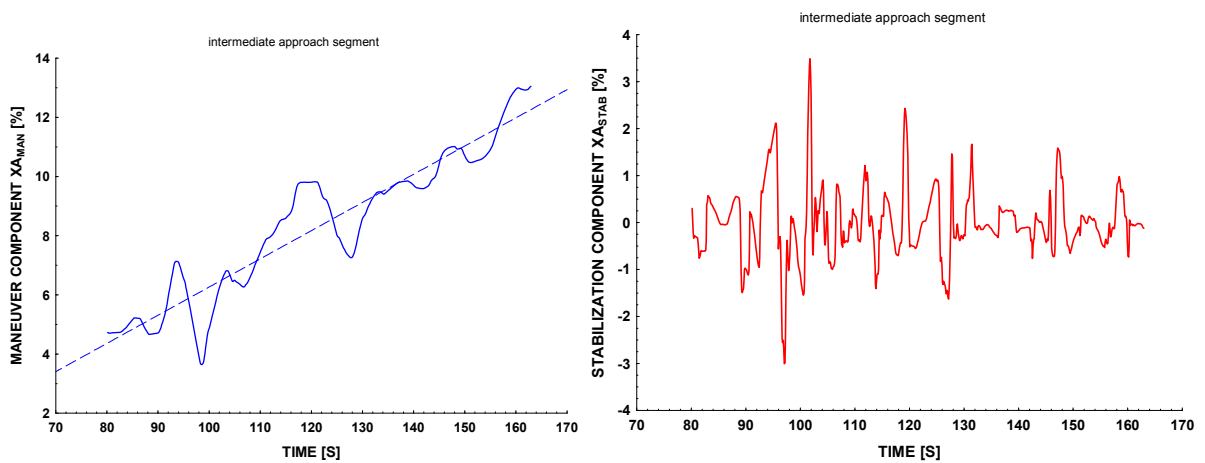
Figure 9 Spectral density of lateral cyclic; intermediate approach straight procedure

As an example the lateral cyclic time history on the intermediate approach of the straight procedure is taken. The power spectral density is shown in Figure 9 (10% tapering has been applied, and the mean and trend had

It is evident there is a slow trend in the manoeuvring component (see the straight line), which is due to a reduction in speed. There is also quite a lot of activity in stabilising, with an average rms of 1.1%. The intermediate segment contained an intercept onto this track from the



a) Total lateral cyclic on intermediate approach; straight procedure



b) Manoeuvre component of lateral cyclic

c) stabilisation component of lateral cyclic

Figure 10 Lateral cyclic split up for intermediate approach segment; straight procedure

been removed). It looks like at 0.2 Hz and higher there is “only” noise. This is the reason for selecting the moving window length at $T=1/0.2 = 5$ seconds.

initial approach segment, since the ‘IF’ was a fly-by waypoint (see also Figure 1), as well as a speed reduction needed to be made.

The time history of the lateral cyclic is shown in Figure 10a), which is split into the manoeuvre component, see Figure 10b) and stabilisation component, see Figure 10c).



7 Experimental results & discussion

7.1 General

The effect of each experimental variable will be evaluated in terms of subjective and objective performance, i.e. in terms of e.g. handling qualities (HQR), workload (Demand), or flight performance (e.g. lateral deviation rms of final segment, control activity). Also interactions between experimental variables may be important.

To ascertain whether or not a particular variable has a significant effect on the parameter investigated a so-called ANalysis Of VAriance (ANOVA) is performed. This analysis applies only to interval-scaled variables. With the F(isher)-test the variance ratio of an effect of the experimental factor is tested for significance, which is expressed in terms of a probability p . Here p denotes the probability of omission, i.e. the probability of being “wrong”. If $p < 0.1$ then the effect is supposed to be weakly significant, $p < 0.05$ denotes a significant effect, and $p < 0.01$ signifies a highly significant effect, in statistical terms.

For ordinal-scale variables (e.g. most of the questionnaire data, except demand on the pilot and perhaps HQR) non-parametric tests are used, e.g. the Wilcoxon matched pairs test, Friedman ANOVA on ranks, etc. More information on these tests, methods and analyses can be found in Ref. [6].

Because of the fact that for the straight procedures no flights were flown with a flight director, the total analysis of variance had to be done in two parts, viz.

- 1 for manual flights only;
- 2 for non-straight procedures only (i.e. turn type can only be ‘fly-by’ or ‘curve’).

The above applies to the analysis of all variables to be evaluated. To save space the ANOVA tables will not be included in this paper.

7.2 Effects on Handling Qualities

7.2.1 Manual flight

In case of manual flight the effects on handling qualities were analysed in a 3 (turn type) x 2 (spd ctrl) x 2 (crosswind) repeated measures ANOVA of HQRs.

The combined effect of both turn type and crosswind is shown by their interaction in Figure 11.

The main effect of *turn type* on HQR was (almost) highly significant ($p < .01$), $F(2,6) = 9.703$, $p = 0.0132$. This is because the HQR for the ‘straight’ turn type (i.e. no turn) was rated highly significantly better (HQR < 4.0), $F(1,3) = 26.4$, $p = .0143$, than for the other two turn types (HQR ≥ 5.0). Between ‘fly-by’ and ‘curve’ there was no such significant difference at all ($p = 1.0$).

Surprisingly also the *crosswind* affected the HQR significantly, $F(1,3) = 8.81$, $p = 0.0592$. As can be observed the effect of 25 Kt crosswind

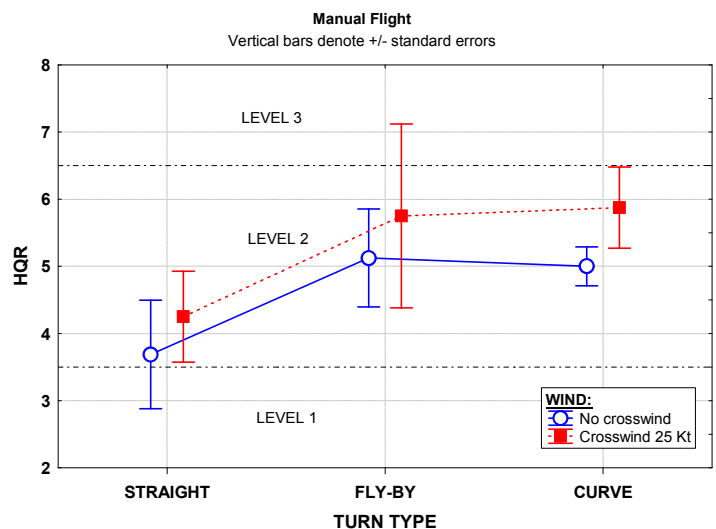


Figure 11 Interaction effect between turn type and crosswind on HQR

worsened the HQR by about 1 HQR, especially for the ‘curve’ turn type. The primary effect of crosswind was expected to be beneficial in that a slight airspeed increase was allowed with a resultant increase in speed stability. However, the data presented above shows the opposite: adding crosswind deteriorates the rated HQR. This can in part be due to an increase in workload associated with performing these

procedures *with* crosswind, especially the non-straight procedures, since with these ones the pilot needs to continuously estimate the influence of wind on the tracking performance after or during each track change. Workload is reflected in the HQR through one of the selection boxes (“can the task be achieved with *tolerable* workload?”).

The *speed concept* had no significant main effect on the HQR ($p=0.41$). For a decelerating approach the mean HQR deteriorated only slightly by an average of about 0.2.

It was hypothesised, due to the required speed changes and associated control inputs, that the low roll stability would adversely affect the handling quality ratings, but this was not the case. It is possible, since a decelerating approach mainly affects the longitudinal dynamics of the rotorcraft, that decelerating made no big difference because of the reasonable pitch characteristics. For the roll axis there would have been greater problems, reason perhaps why the factor of ‘turn type’ had a significant main effect. The cross-coupled effect, i.e. on yaw, from the collective when decelerating had been almost cancelled by the presence of the collective-to-pedal interlink.

Another impression of handling qualities was obtained from the in-cockpit questionnaire, where, before giving a HQR, the pilot had to rate the response characteristics using an ordinal scale, in certain terms that can be associated with the CHR scale (e.g. roll axis response characteristics could be rated as “*satisfactory without further improvement*”, or as having “*minor but annoying deficiencies*”, etc.).

All the levels of speed concept, crosswind and pilots were grouped together, since the Friedman’s ANOVA on ranks can only handle a one-way (i.e. one-factor) analysis. The 3 (turn type) repeated measures ANOVA, analysed with the Friedman’s ANOVA on ranks test, indicated a weakly significant effect ($p<.10$) of turn type on the rating of the roll characteristics, χ^2 ($N=22$, $df=2$)=4.92, $p=.0854$. The effect is shown in Figure 12.

Here it was mostly the ‘curve’ turn type where the roll characteristics were rated as having

close to ‘*moderately objectionable deficiencies*’ (i.e. equivalent to HQR=5), while for the other turn types it was rated slightly better, see Figure 12. Only the difference between ‘straight’ and ‘curve’ turn type was significant in statistical terms ($p=.0578$). This trend is not quite as similar as the HQR in Figure 11, where the greatest differences were between the ‘straight’ turn type and the other turn types. This indicates that the correlation between HQR and this

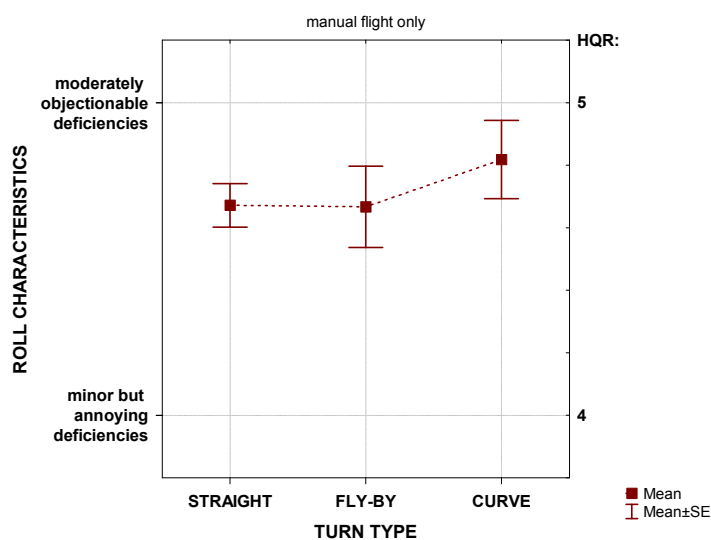


Figure 12 Main effect of turn type on roll characteristics ratings

rating will not be close to 1.0, or that pilots were not quite consistent in their HQR ratings.

7.2.2 Non-straight procedures

In case of non-straight procedures with/without the FD a 2 (turn type) x 2 (flight guidance) x 2 (speed concept) x 2 (wind) repeated measures ANOVA was performed.

The results showed that the only significant effects on the HQR are a (weak) main effect of the *flight guidance*, $F(1,4)=4.84$, $p=0.0927$, and *speed concept* ($F(1,4)=10.56$, $p=0.0314$) and 3 significant ($p<.05$) *interactions*, viz. turn type x Fl. guidance x speed concept ($F(1,4)=40.09$, $p=0.00319$), turn type x speed concept x crosswind ($F(1,4)=58.78$, $p=0.00156$) and Fl. guidance x speed concept x wind ($F(1,4)=5.828$, $p=0.0732$).

The main effect of the flight guidance is to lower the HQR in case of the FD by about 0.7.

The turn type x flight guidance x speed concept interaction is shown in Figure 13.

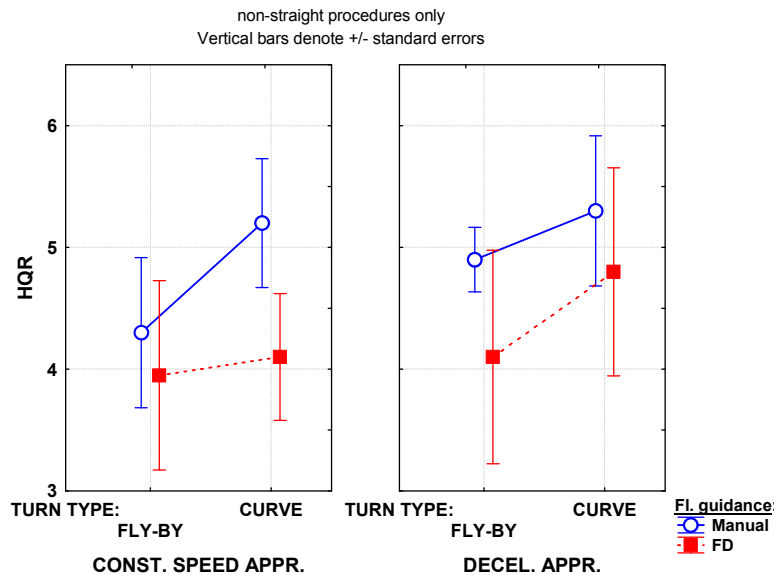


Figure 13 Turn type x Fl. guidance x speed concept interaction on HQR; non-straight procedures

In this figure the main effect of *flight guidance*, i.e. to have a lower (better) HQR in case of the FD, is clearly visible.

As for *turn type*, The HQR tended to be worse (i.e. higher values) for the ‘curve’ turn type than for the ‘fly-by’ turn type, but this effect (of turn type) was not significant statistically. Only in case of constant-speed approaches with manual guidance the effect of turn type was significant, $F(1,4)=9.53$, $p=0.0367$, where the HQR varied from about 4.2 for the ‘fly-by’ turn type to 5.2 for the ‘curve’ turn type.

As for *speed concept*, although the main effect was highly significant, $F(1,4)=10.56$, $p=0.0314$, the average increase in HQR for decelerating approaches compared to constant-speed approaches amounted to only a very small amount (0.4).

The strongest increase, see Figure 13, is for the case of FD guidance with the ‘curve’ turn type, where the average HQR increases from about 4.0 to 4.8. Because of the continuous tracking of heading in the curves, a closed-loop task as reported by the pilots, the pilots were activated by the FD to provide closer tracking with the Level 2 rotorcraft, thereby being hampered by the roll characteristics.

The difference in roll response between the ‘fly-by’ and ‘curve’ turn types on the final segment for a decelerating approach is shown for one particular pilot in Figure 14, just to illustrate the effect of the turn type on handling qualities. Both runs were flown with the flight director. As can be seen, for the ‘fly-by’ turn type there is a larger range of roll angle used than for the ‘curve’, with especially between 9,000 m and 10,000 m oscillations in roll for the ‘fly-by’ case. In general with the ‘fly-by’ turn there are more small-amplitude oscillations visible than with the ‘curve’.

In summary, generally the HQR ratings were worse for the ‘curve’ turn type than for the ‘fly-by’ turn type, but were “improved” by adding a

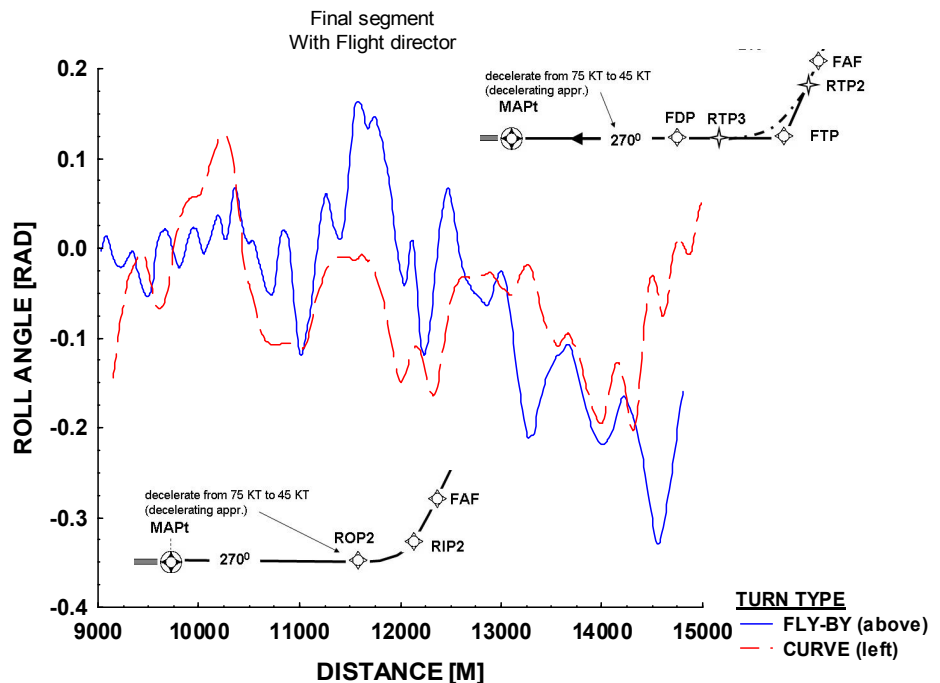


Figure 14 roll angle for two turn types; final approach

flight director. The flight director itself led to lower (i.e. better) HQRs, but less so for the ‘curve’ turn type than for the ‘fly-by’ turn type.



This obviously had to do with the open-loop ('fly-by') versus closed-loop ('curve') lateral tracking of the path deviations with the flight director. This implies that a mental aspect also comes into focus.

7.3 Effects on lateral performance

7.3.1 Manual flight

For the lateral performance the rms of the lateral path deviation for the intermediate and the final segments were calculated and analysed. The data was analysed in a 3 (turn type) x 2 (speed concept) x 2 (wind) repeated measures ANOVA, grouped per approach segment, viz. segment 2 and 3 (intermediate and final segments).

The main effect of **crosswind** was also (highly) significant, $F(1,10)=9.352$, $p=0.0121$. The effect of crosswind was mainly to increase the lateral deviation rms on the final segment by about 0.15 dots for the 'fly-by' turn type and by about 0.1 dots for the 'curve' turn type.

The main effect of **turn type** was also highly significant, $F(2,20)=9.76$, $p=0.0011$. It is obvious that the changing tracks associated with the non-straight procedures introduced more lateral deviation than with the simple 'straight' turn type, aggravated by the crosswind, which further increased the lateral deviation. And because of the greater lateral sensitivity the largest lateral deviations occurred on the final segment. All (mean) deviations (rms), though, remained below 1 dot.

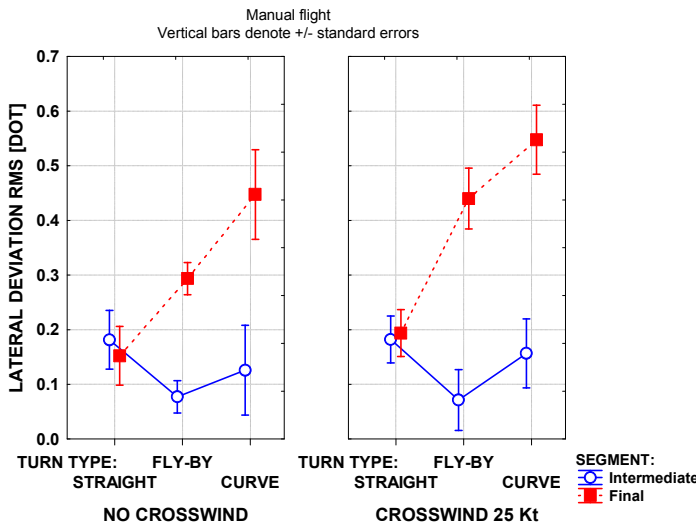


Figure 15 Turn type x crosswind x approach segment interaction effect on lateral deviation rms

The effect of several factors and interactions reached statistical significance. It is perhaps best to show the interaction between turn type, wind speed and approach segment, see Figure 15.

The main effect of approach **segment**, for example, was highly significant, $F(1,10)=43.57$, $p=0.000061$. It is obvious that on the final segment the lateral deviation was larger than on the intermediate segment, except for the 'straight' turn type, even though in general the deviation sensitivity increased for the final segment (this should lead to larger deviations in dots).

7.3.2 Non-straight procedures

For the non-straight procedures a 2 (turn type) x 2 (fl. guidance) x 2 (speed concept) x 2 (wind) repeated measures ANOVA was set up to analyse the lateral deviation rms.

As expected, segment had a highly significant main effect ($F(1,8)=34.92$, $p=0.000358$) on lateral deviation rms, as well as Fl. guidance ($F(1,8)=33.50$, $p=0.000411$). The turn type x Fl. guidance interaction was highly significant ($F(1,8)=16.35$, $p=0.00372$), and so was the turn type x Fl. guidance x segment interaction, $F(1,8)=9.104$, $p=0.0166$.

The main effect of **segment** on the lateral deviation rms is that on the intermediate segment the lateral deviation was less than on the final segment, going from 0.083 dots on the intermediate segment to 0.317 dots on the final segment.

The main effect of **Fl. guidance** was to reduce the lateral deviation rms from 0.267 dots for manual flight to 0.133 for FD guidance. So the FD gave quite an improvement in the lateral performance. The significant interaction between FD and segment indicates that this improvement occurred mostly on the final segment. This interaction is shown in Figure 16.

It is on the final segment where the lateral deviation rms "explodes" from about 0.1 dots on the intermediate to about 0.4-0.5 dots on the

final segment for manual flight. It is here where the flight director gave a highly significant improvement, but for the ‘curve’ turn type only. There is a drastic improvement – reduction – in

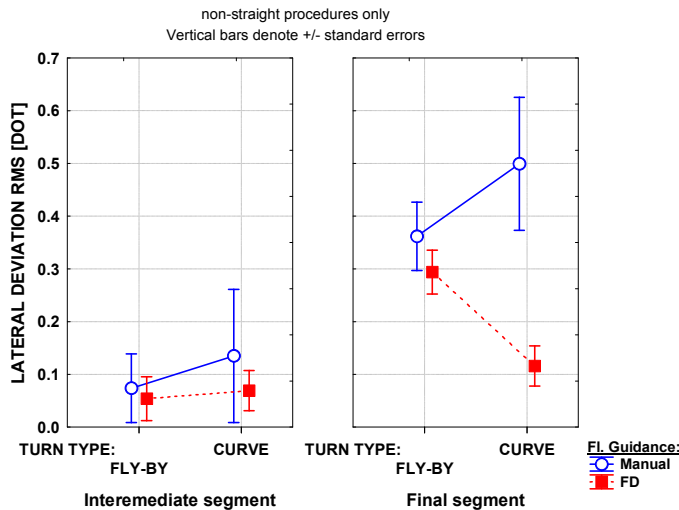


Figure 16 Turn type x Fl. Guidance x segment interaction effect on lateral deviation rms

lateral deviation rms from about 0.5 dots to 0.1 dots on the final segment, $F(1,8)=62.67$, $p=.000047$. The presence of the FD has therefore been very beneficial in terms of lateral performance for ‘curve’ turn types, where more continuous tracking is to be done, rather than the open-loop navigation around fly-by waypoints. For procedures with ‘fly-by’ turns the flight director did not contribute to the improvement in lateral steering accuracy.

7.4 Effects on pilot’s demand

7.4.1 Manual flight

Regarding only manual flight a 3 (turn type) x 2 (speed concept) x 2 (wind).repeated measures ANOVA was carried out.

The main effect of **turn type** was highly significant, $F(2,4)= 28.82$, $p=0.00421$. The workload increased to high levels, from “mildly demanding” for the ‘straight’ turn type to “very demanding” for the ‘curve’ turn type with crosswind.

The turn type x crosswind interaction is shown in Figure 17. The main effect of **crosswind** was not significant ($F(1,2)= 6.547$, $p=0.125$), although for the ‘curve’ turn type the crosswind effect almost reached statistical significance ($F(1,2)=8.02$, $p=0.105$), where due to the crosswind the workload increased from

“demanding” to “very demanding”. It is evident that with crosswind the variations (‘standard error’) in the demand per turn type were larger than in case of no wind. Apparently pilots had a greater variability, or difficulty, in rating workload when flying with a crosswind than without, which could have to do with the pilot’s technique of compensating for varying winds along the various track changes.

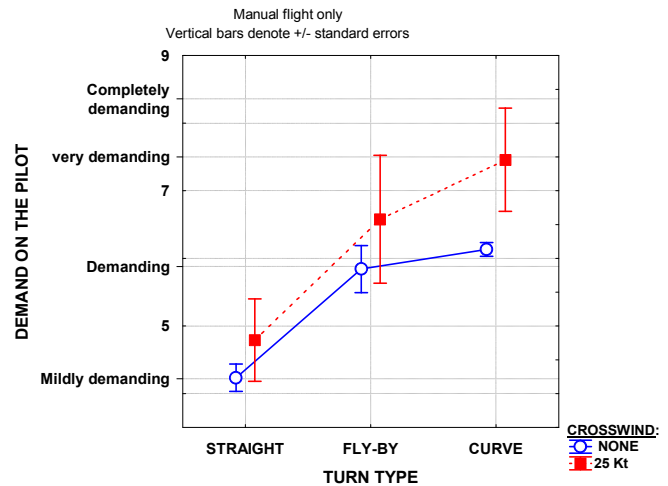


Figure 17 Demand on the pilot as function of type-of-turn and crosswind

7.4.2 Non-straight procedures

The effect of the experimental parameters on workload in case of non-straight procedures was analysed using a 2 (turn type) x 2 (Fl. guidance) x 2 (speed concept) x 2 (wind) repeated measures ANOVA.

The results showed that only **turn type** had a weakly significant main effect, $F(1,2)=8.56$, $p=0.0996$. The main effect of **Fl. guidance** was just (not) weakly significant, $F(1,2)=7.73$, $p=0.109$. Other main effects or interactions did not reach statistical significance.

An impression of how turn type, the flight director and the speed concept affect the pilot’s workload is given in Figure 18.

Overall one can see the (weak) main effect of turn type, tending to increase the workload from the ‘fly-by’ value of “demanding” to close to halfway “demanding” and “very demanding” for the ‘curve’ turn type. Also the flight director



reduced the workload overall, irrespective of turn type or speed concept. Overall the standard error (variation) in the workload is fairly large, except for the ‘fly-by’ turn type in manual flight and decelerating approach, when compared to the flight director. No explanation can be given for that other than

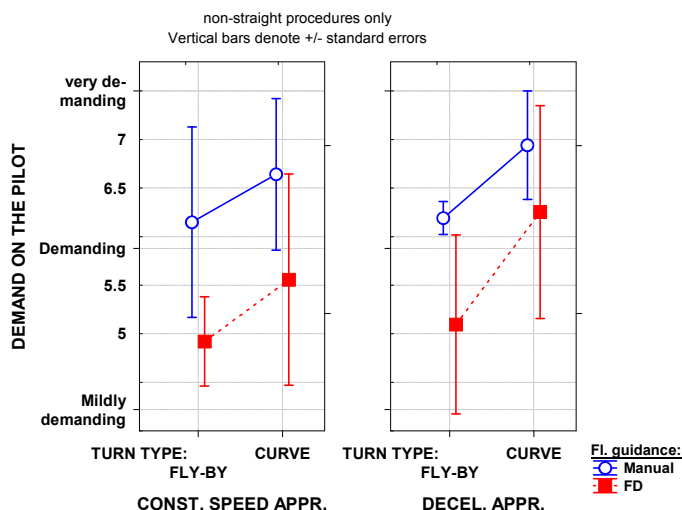


Figure 18 Turn type x Fl. guidance x speed concept interaction effect on pilot's demand

perhaps to say that the use of the flight director by the pilots was not always easy. Some pilots needed a longer transition to the use of it than other pilots did, and also some pilots “flew through” the flight director indicators (bars) saying that, because of the SISO loop design (e.g. speed error to the pitch cue only, and glide path error to the collective cue only), the indications should not always immediately be followed up.

7.5 Effects on pilot control activities

7.5.1 Manual flight

The control activity itself is made up of the rms values of the various controls (lateral,

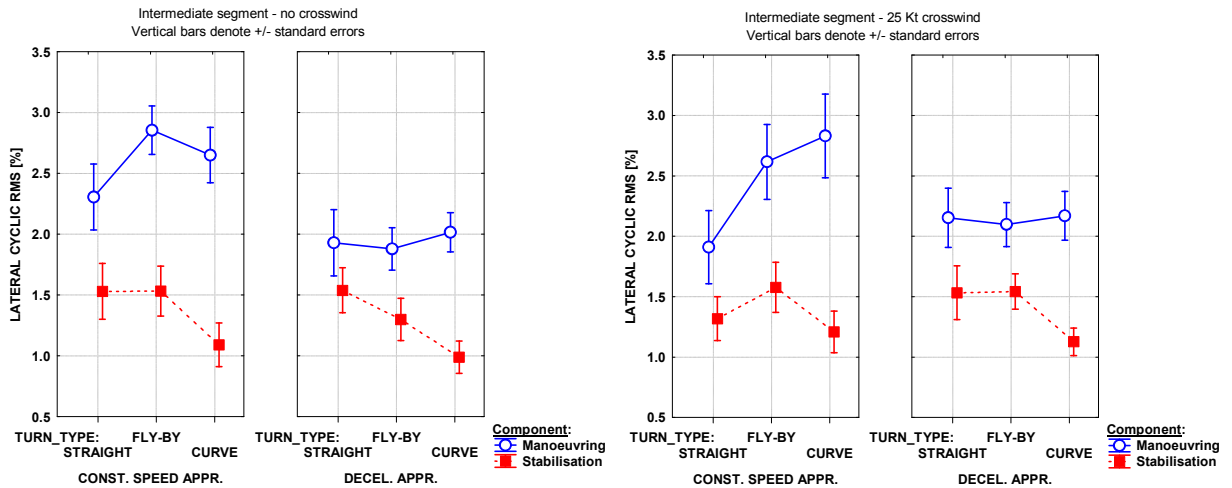
longitudinal, collective and pedal) for 2 segments, viz. the intermediate segment and the final segment.

For the first ANOVA the effect of the experimental factors is evaluated on the lateral control activity, in terms of the manoeuvre rms and stabilisation rms, as explained in para. 6.5.2. This has been further subdivided into the 2 approach segments to be considered. A 3 (turn type) x 2 (speed concept) x 2 (wind speeds), grouped by 2 (segments) repeated measures ANOVA was carried out. In fact a multi-variate ANOVA was carried out since the manoeuvre and stability component of the lateral cyclic were taken together, resulting in a so-called Multiple ANOVA or MANOVA. The multi-variate equivalent of the univariate F-test is the Wilks Lambda function to test for significance of effects.

Many factors and interactions turned out to be significant ($p < 0.05$). The turn type x speed concept x wind x segment interaction is shown in Figure 19a) thru d).

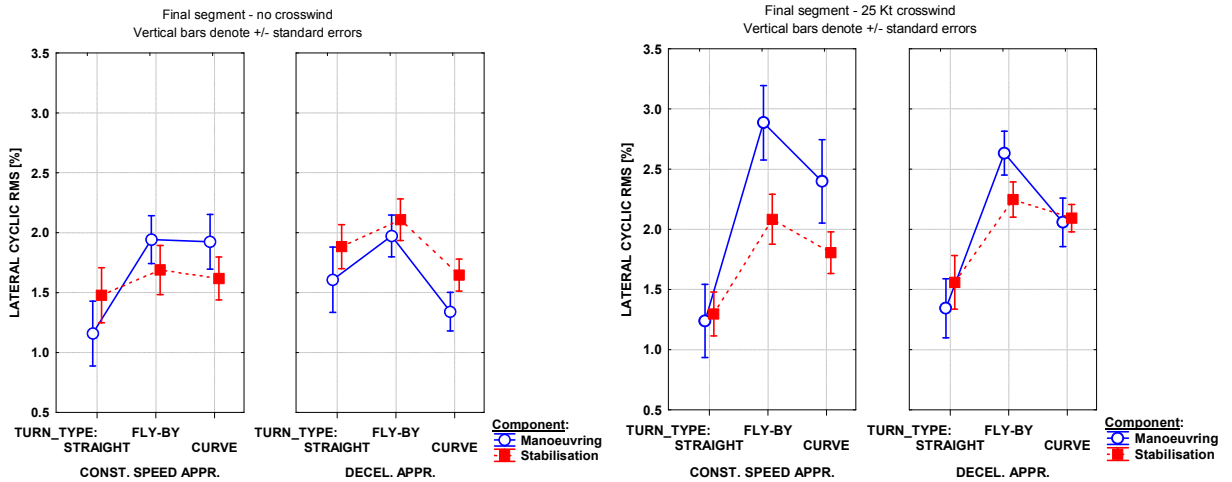
On the intermediate segment the manoeuvre rms is in general larger than the stabilisation rms. For the final segment they are much closer to one another, except perhaps for the constant-speed approaches and non-straight procedures. The ‘straight’ turn type in general had less rms than for the other turn types, something that was expected. Only in case of no crosswind for the final segment the manoeuvre and stabilisation components are closest to one another. Although significant it seems that crosswind on the lateral control rms had less effect on the intermediate segment than on the final segment.

The (significant) main effect of *speed concept* ($F(1,10)=6.22, p=0.0318$) was to especially



a) Intermediate segment – no wind

b) intermediate segment – 25 Kt crosswind



c) Final segment – no wind

d) Final segment – 25 Kt crosswind

Figure 19 Four-way interaction of lateral cyclic activity (rms)

reduce the manoeuvre rms, rather than the stabilisation component (see especially Figure 19a). Apparently the average higher airspeed involved in the decelerating approaches, although requiring a higher workload, was enough to improve the lateral control response such that the manoeuvring component became less, with the stabilisation component remaining the same.

Looking at the final segment there is a tendency for the manoeuvre rms to be larger for the ‘fly-by’ turn than for the other turn types. This tendency is intensified with crosswind. The reason is because the ‘fly-by’ turns require more manoeuvring input than with the curves

due to the greater turn rates. On the final segment in case of no crosswind the stabilisation rms is even larger than the manoeuvring rms.

7.5.2 Non-straight procedures

In case of non-straight procedure a 2 (turn type) x 2 (Fl. guidance) x 2 (speed concept) x 2 (wind) repeated measures, grouped by 2 (segment) MANOVA was performed on the combination of the manoeuvre and stabilisation RMS of the lateral control. Many factors and interactions reached significance. Perhaps the most revealing way of showing the various

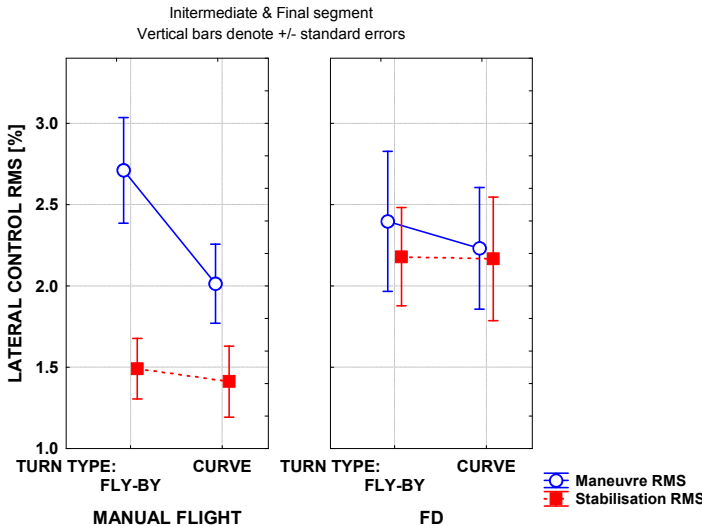


Figure 20 Turn type x Fl. guidance interaction on lateral control RMS; non-straight procedures

effects is to show the turn type x fl. guidance interaction for the two components, as done in Figure 20.

For manual flight the effect of turn type is significant for the lateral cyclic manoeuvre RMS, $F(1,8)=212.87, p=.0000$, and also for the stabilisation RMS, $F(1,8)=247.3, p=.0000$. The 'curve' requires significantly less manoeuvre rms than the 'fly-by' turn, as expected, since flying the curve is more like closed-loop error tracking, for which smaller control inputs are needed, also due to the lower turn rates involved with the 'curve'.

For the FD guidance case this is not so. The FD has the (significant) effect, $F(1,8)=22.38, p=.00148$, of increasing the stabilisation RMS, while only slightly modifying the manoeuvre RMS. With the FD there is in fact no difference anymore between the 'fly-by' and the 'curve' control RMS.

So the function of the flight director is in fact to increase the small-amplitude, high(er)

frequency lateral cyclic inputs to keep flight path errors small.

7.6 Effects on procedure acceptance

7.6.1 Manual flight

In fact 'procedure' is identical to 'turn type', since that determines the procedure tested (only one procedure applies for one turn type).

Ratings about acceptability could be obtained from the questionnaires, both the in-cockpit as well as the debriefing questionnaire. With the subset of experimental runs in the adapted test matrix the relevant data in this case was taken from the in-cockpit questionnaire. The most important effect on procedure acceptance is obviously the factor of turn type. The histogram given in Figure 21 emerged for the acceptance when plotted versus turn type and speed concept.

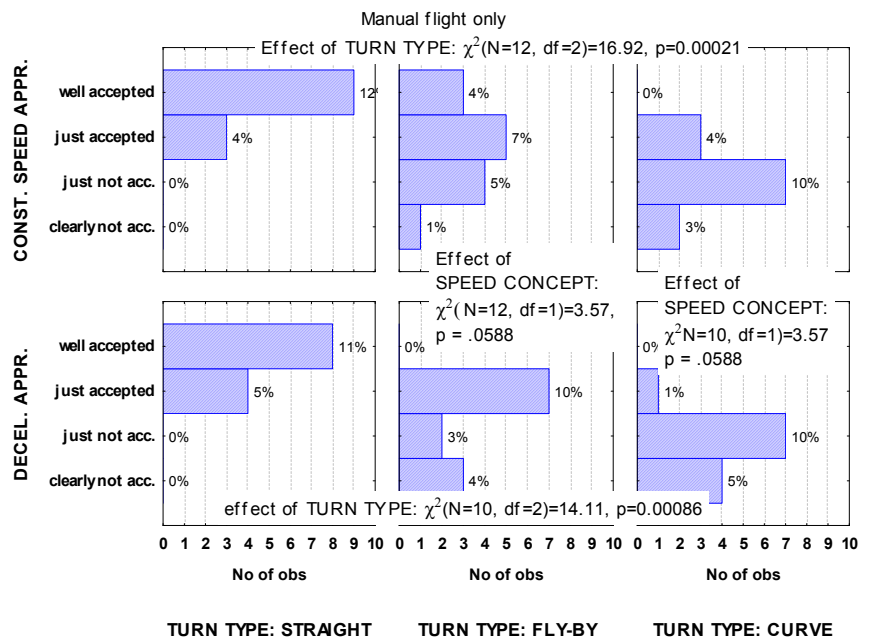


Figure 21 Pilot's acceptance of type-of-turn vs speed concept; manual flight

The effect of **turn type**, regardless of the speed concept, is a reduced acceptance for the 'fly-by' turn type, witnessing more cases of lower acceptance ratings, and still more lower (i.e. worse) acceptance ratings for the 'curve' turn type. The Friedman's ANOVA on ranks test for



the constant-speed approaches shows the effect of turn type to be highly significant, $\chi^2(N=12, df=2)=16.92, p=0.00021$, as well as for decelerating approaches, $\chi^2(N=10, df=2)=14.11, p=0.00086$.

Speed concept did not affect the turn type acceptance for ‘straight’ turn types. Only in case of the ‘fly-by’ and ‘curve’ turn types did the speed concept (almost) significantly ($p<.05$) affect the acceptance rating: constant-speed approaches were more accepted for these procedures than decelerating approaches.

Primary reasons the pilots gave for not accepting the turn type ‘fly-by’, for example, ranged from ‘*too manoeuvring*’, ‘*time pressure*’, ‘*high workload*’, ‘*track changes*’, etc. From the results of the handling qualities and workload data it is clear why pilots did not accept these non-straight procedures so well.

7.6.2 Non-straight procedures

The main question about the procedure (i.e. turn type) acceptance in case of flying with a flight director is whether or not the addition of a flight director, with it associated improvement in performance and workload, may also affect the acceptance rating. To this end the questionnaire data was re-ordered as a 2 (Fl. guidance) x 2 (turn type) repeated measures ANOVA on

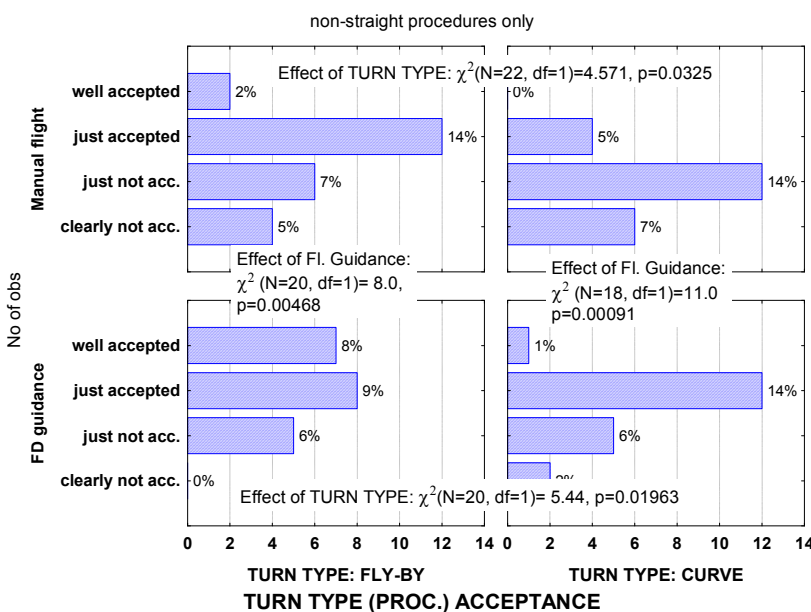
ranks, grouped per speed concept, wind and pilots. A histogram with the results is given in Figure 22.

It turned out that for each category of Fl. guidance the **turn type** had a significant effect on the procedure’s acceptance ($p<.03$), based on Friedman’s ANOVA on ranks. For the ‘curve’ turn type the acceptance was less than for the ‘fly-by’ turn type. It is possible that this may have to do with the pilots being acquainted with the fly-by waypoint concept in navigation, but that flying a curve is rather unusual. Also, flying the curve required more workload (see Figure 22), and hence rendered the ‘curve’ turn type less accepted. The effect of **flight guidance** was also highly significant ($p<.004$) for both categories of turn type. With the FD the acceptance rating improved, compared to manual flight. It could be a mixture of improved performance and reduced workload that made the curved procedure better acceptable when flown with a flight director.

8 Correlations among various handling quality ratings

8.1 General

According to its definition the HQR must depend on performance, since several of the decision moments in the decision tree of the CHR scale contain phrases such as “desired performance” or “adequate performance”. In the experiment desired performance was to keep the lateral and vertical deviations less than 0.5 dots, whereas the level of adequate performance was to keep flight path deviations to less than 1 dot. Furthermore, in one of the decision tree blocks, reference is made to “tolerable workload”. All HQRs less than 7 have tolerable workload or less, whereas for $HQR \geq 7$ this no longer holds. The question is of course how this “tolerable” workload relates to the adjectives on the Demand scale.



8.2 Correlation between HQR and Demand-on-the-pilot

From results in paras. 7.2.1 and 7.4 it became clear that the HQR depended upon turn type and crosswind, while the demand-on-the-pilot

Figure 22 Procedure acceptance vs turn type and Fl. guidance; non-straight procedures only



depended only on turn type. They did, surprisingly, not depend on the speed concept. Therefore, in case of manual flight only (i.e. no FD), the correlation between HQR and Demand is shown per turn type and wind speed in Figure 23. Also shown are the 95% percentile prediction regression bands.

For all conditions except 2 the correlation coefficient could be determined with statistical significance ($p < .05$) (in bold-case). The exceptions are the 'straight' and the 'curve' turn types with no crosswind.

Note that in some cases very high values

workload, which can then be associated with pilot's demand values between "very demanding" and "completely demanding" using the regression line.

The correlation coefficient varied from $r=0.59$ to $r=0.72$. Especially for the 'curve' turn type with no crosswind the correlation between HQR and Demand was low ($r=0.26$), but also not significant. With wind, however, it increased to $r=0.69$, and also the 95% regression predictive band was much "narrower". The simulation experiment was not intended to find a correlation between HQR and pilot's demand, therefore the spread in workload or HQR was

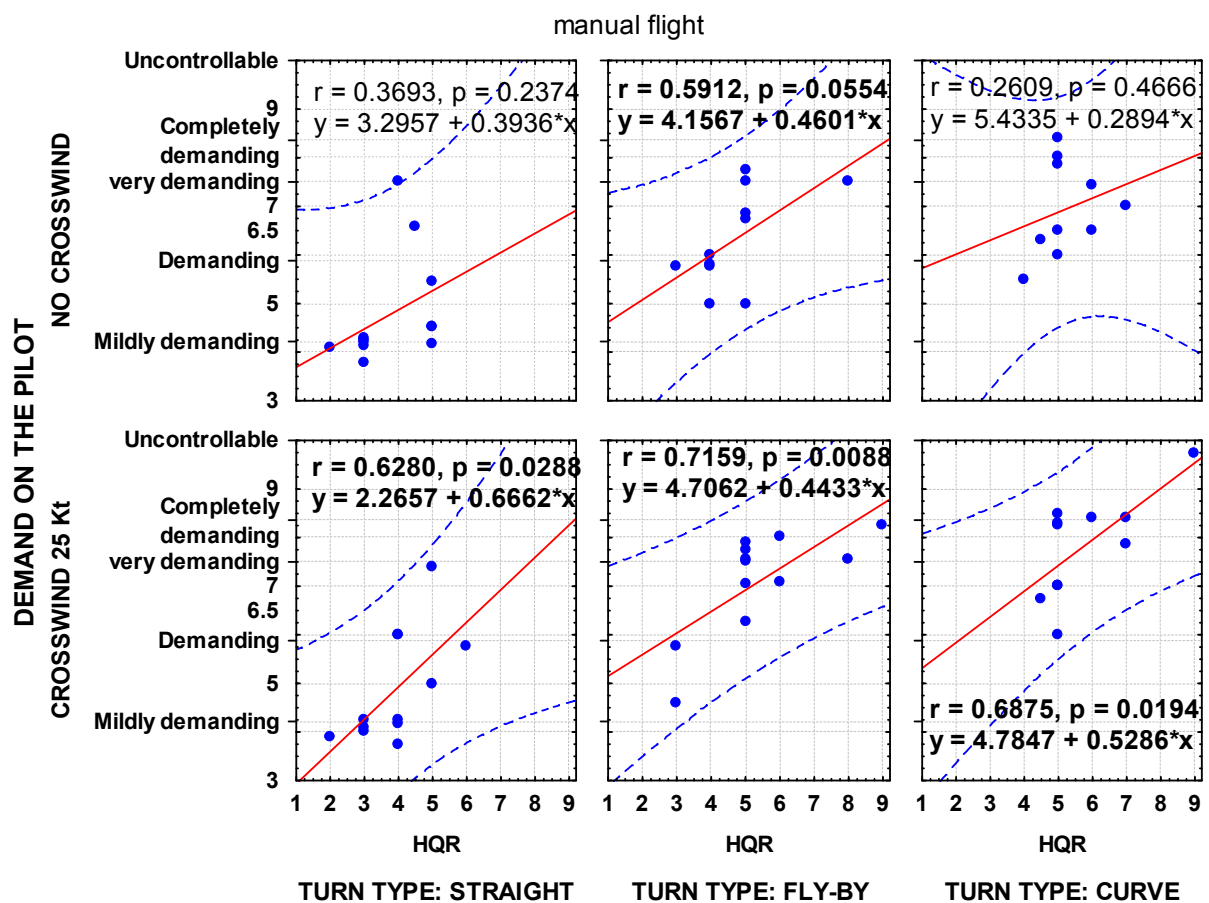


Figure 23 Correlation between HQR and pilot demand; manual flight

occurred for demand as well as HQR, viz. "completely demanding" and HQR=9 ('adequate performance was not attainable with a tolerable workload'; 'major deficiencies'; 'intense pilot compensation required to retain control'). If intolerable workload is associated with $HQR \geq 7$ then the 'fly-by' turn type with and without crosswind and the 'curve' turn type with crosswind had cases of intolerable

not large enough sometimes to cover an adequate range and provide a meaningful correlation coefficient. The above indications may be enough to suggest a correlation between HQR and the demand-on-the-pilot.



8.3 Correlation between HQR and lateral performance

A breakdown of the correlation between the lateral deviation rms and the HQR is given in Figure 24 for both approach segments together, in case of manual flight.

It turned out there was only little correlation – at the most – between these two parameters.

Apparently the HQR is not so much driven by the lateral performance, or else more performance indices need to be taken into account (e.g. vertical deviations, rates of deviation, etc.), certainly for the non-straight procedures.

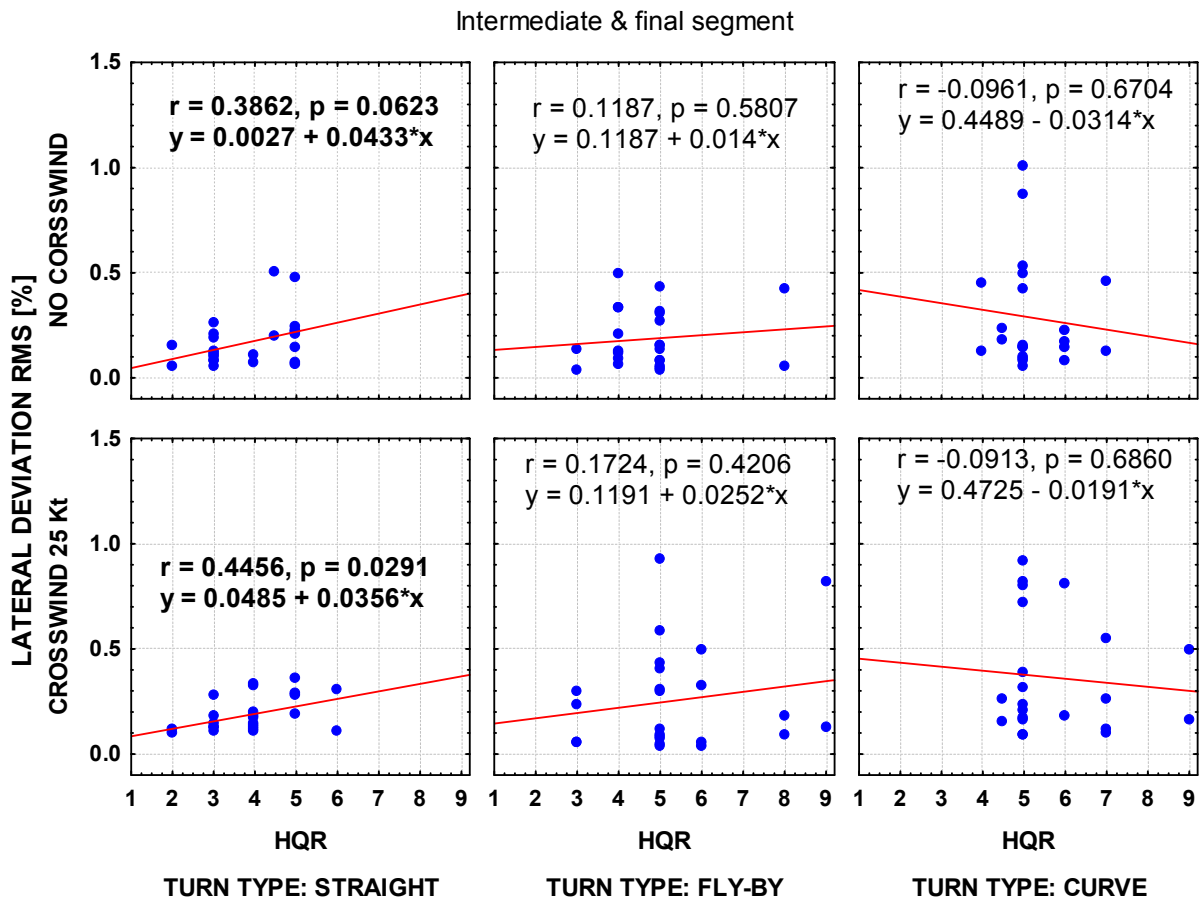


Figure 24 Turn type x crosswind interaction effect on lateral deviation rms for 2 segments; manual flight

Only for the ‘straight’ turn type a significant ($p < .05$) correlation could be found, with $r = 0.39$ - 0.44 , between lateral deviation and HQR. For the other turn types no such significance could be found.

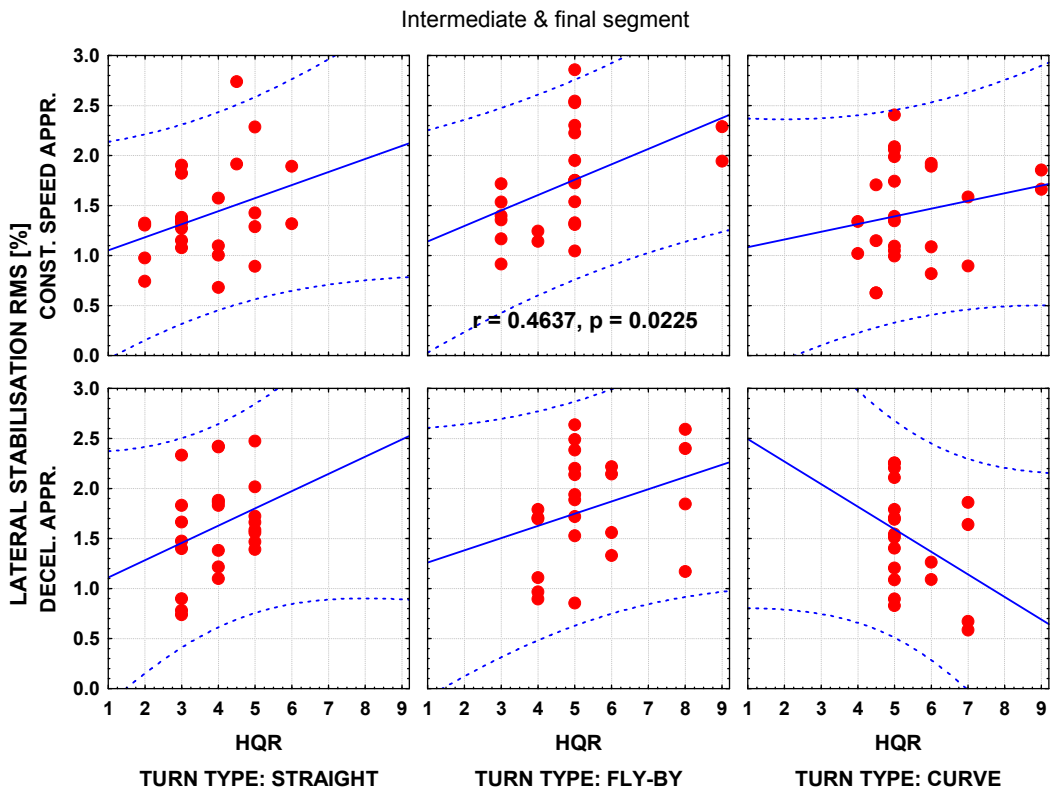
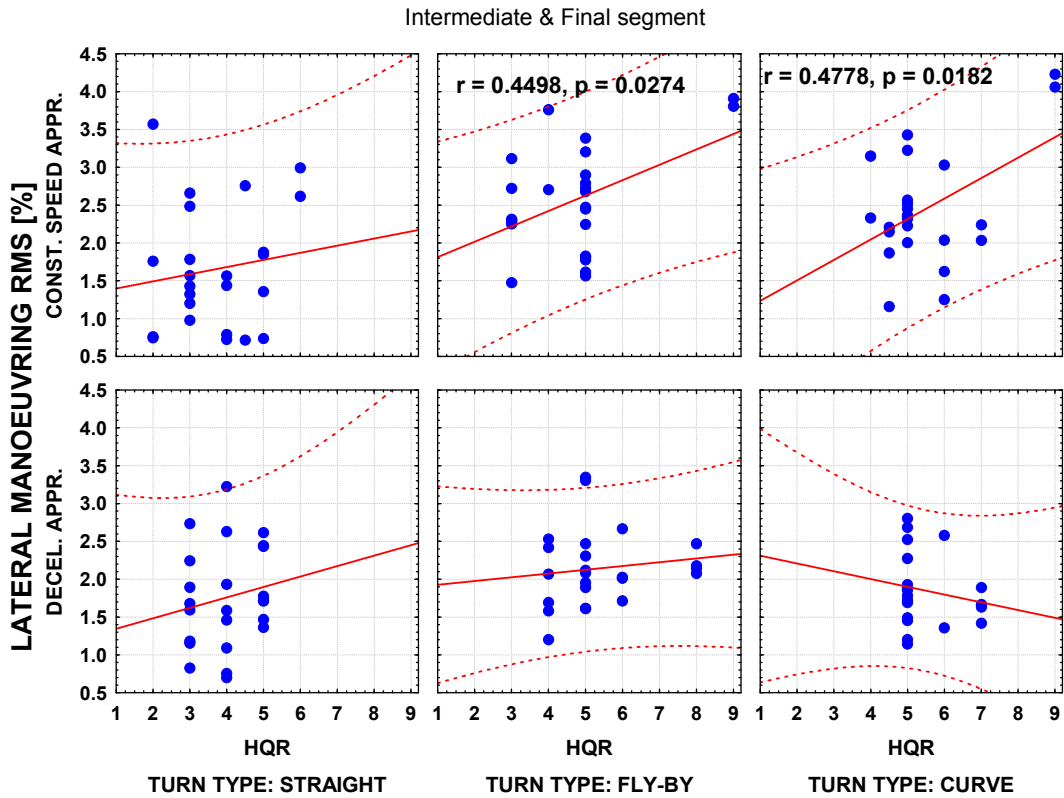


Figure 25 Turn type x speed concept interaction on lateral cyclic rms

8.4 Correlation between HQR and lateral control activities

A final interesting correlation that might exist is that between the HQR and the piloting lateral control activity, assuming that the inherited rotorcraft response characteristic will be reflected in the HQR, while the associated necessary control inputs for manoeuvring and stabilisation are reflected back in the lateral cyclic rms values.

Results from section.7.5 and Figure 19 indicate that the lateral control rms depended on the segment, as well as on turn type, speed concept and wind. Since the HQR depends “only” on turn type and wind these two parameters were taken to “break down” the correlation. The resulting scatter plot between HQR and the lateral cyclic rms is given in Figure 25, in part a) for the manoeuvring rms and in part b) for the stabilisation rms, for the 2 segments together.

In general one can say/conclude that there is hardly any correlation between the lateral control rms (manoeuvring or stabilisation) and the HQR, except perhaps for a few special conditions such as a constant-speed approaches on a ‘fly-by’ procedure. In the other cases the correlation coefficient could not be determined with sufficient statistical confidence ($p > 0.1$) due to the scatter.

9 Procedure design parameter validation

One of the major parameters for design of the procedure, certainly with regard to the lengths of the various segments, was the design deceleration rate, set at -1.5 Kt/s. From one of the questions of the questionnaire it was reported that the time pressure was too great. Early in the experiment the entry speed was reduced from 150 Kt to 120 Kt IAS because pilots complained that it was too difficult to achieve the speed targets.

In computing the deceleration from differentiating the airspeed, a threshold of -0.75 Kt/s was used, and the mean deceleration rate was computed with the values below the threshold taken into account (i.e. only decelerations would be taken into account, not accelerations). It was assumed that values below -0.75 Kt/s are associated with a deliberate deceleration, other than some small-amplitude airspeed corrections. The deceleration rate was analysed for the intermediate segment only, since there most of the decelerations took place. A breakdown of the mean deceleration rate across all the turn

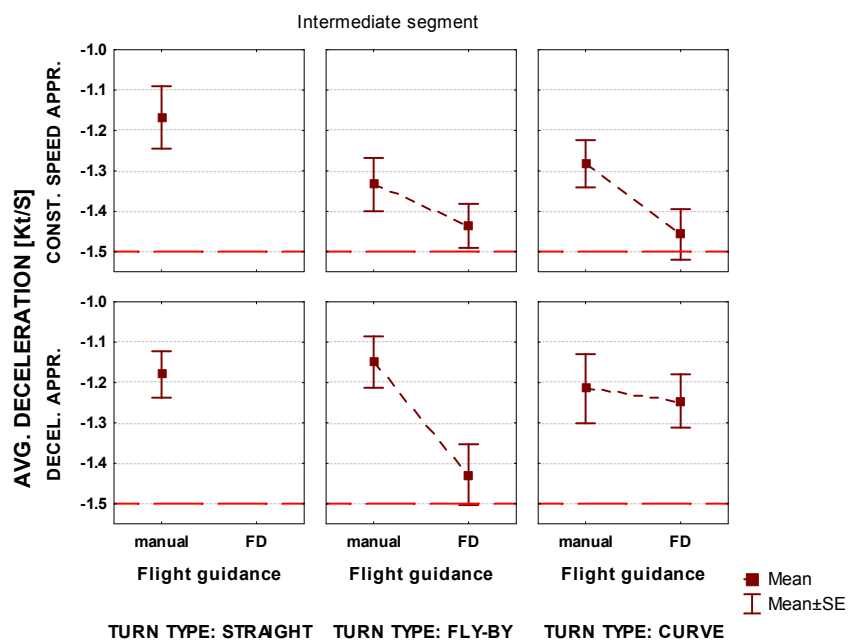


Figure 26 Average deceleration per turn type, Fl. guidance and speed concept; intermediate segment

types, flight guidance and speed concept is given in Figure 26.

For constant-speed approaches a speed change of 70-75 Kt (from 120 Kt to 45-50 Kt) should occur on the intermediate segment, while in case of a decelerating approach this speed change should be 45 Kt, i.e. from 120 Kt to 75 Kt.

Note that the target deceleration value is -1.5 Kt/s. The figure shows the highly significant effect of the flight guidance factor, according to the respective ANOVA ($F(1,9)=16.9, p=0.0029$). With the FD the target deceleration rate is approached much better than with manual flight, for obvious reasons: the FD



had a built-in deceleration program, activated by the pilot anytime the desired speed “bug” was set to a lower (or higher) value by way of the collective beep switch.

The speed concept also had a highly significant effect ($F(1,9)=11.52$, $p=0.0079$). With the decelerating approaches more of the deceleration occurs also on the final segment, and the deceleration on the intermediate segment is less (by about 0.1 Kt/s on average) than in case of a constant-speed approach, since the target speeds are higher. The results in Figure 26 confirm this.

It is obvious from this figure that the design deceleration rate of -1.5 Kt/s was not met, certainly for manual flight guidance. This in turn could lead to the rotorcraft passing the next waypoint after the deceleration still at too high a speed, which introduced an increase in workload, as the pilot was still busy decelerating while perhaps starting to descend.

Pilots were also reluctant to decelerate at -1.5 Kt/s under instrument flight conditions. The first comments pilots made when decelerating at this rate (on the intermediate segment, or earlier) was that the rotorcraft “almost went into autorotation”, an indication that the called-for deceleration rate of -1.5 Kt/s was perhaps over-specified. The resultant data indicate that a better deceleration rate value would be -1.0 Kt/s.

10 Concluding remarks and recommendations

Quite a comprehensive experiment has been carried out to assess the flyability and handling aspects of a number of IFR procedures, characterised by a steep glideslope of 9°-10°, and also with fly-by turns or curves present, both on the intermediate segment (in level flight) as well as on the final segment (descending flight). Simulation tests were carried out on a fixed-base simulator with a model AS365N helicopter with Level 2 handling qualities.

Conclusions and recommendations should be viewed in the light of the limitations and

peculiarities of the simulations performed, i.e. the use of (mostly) non-experimental test pilots, a fixed-base simulator, the specific navigational displays, etc.

In view of the objectives and research questions asked the following can be concluded:

1. *flyability*:
 - a. Handling qualities: based on the original Level 2 HQs of the basic vehicle, the straight steep procedure was well flyable (HQR=Level 2 but close to Level 1). With the segmented or curved procedure the handling qualities degraded by about 0.5 HQR, but remained Level 2 on average. These procedures are therefore flyable, but improvement in the design or control system is warranted, however.
 - b. Performance: when considering the final segment of the approach, the segmented procedure showed worse lateral performance than the straight procedure; the curved procedure was worse than the segmented procedure. Overall, though, the average lateral deviation stayed within 1 dot, which means that the procedures were flyable from the performance point of view.
 - c. Pilot's demand: the pilot workload increased from “mildly demanding” for the straight procedure to “demanding” for the segmented procedure, and further to “very demanding” for the curved procedure. With “very demanding” being close, or equal to “intolerable” workload it is clear that the curved procedure is not tolerable/flyable without any further piloting aids to relieve his workload.
2. *type of track change*:
 - a. Handling qualities: there is no preference for one or the other type of track change.
 - b. Performance: the ‘fly-by’ turn clearly shows better performance for the pilot in manual flight. With the FD, however, the pilot had better performance on the curved turn type than on the fly-by turn type.
 - c. Pilot's demand: the ‘fly-by’ turn type has lower workload than the ‘curve’ turn type. So if a track change is to be made in a steep procedure, then the best preferred way of doing it is the ‘fly-by’ turn, based on pilot workload and lateral performance in manual flight.
3. *Speed concept*:



- a. Handling qualities: with decelerating approaches the handling qualities worsened, but by only a small amount (0.2 HQR) for the class of non-straight procedures.
 - b. Performance: the speed concept had no effect on the lateral performance.
 - c. Pilot's demand: the speed concept had no significant effect on pilot's workload.
- So from the handling qualities, performance and workload point of view there is no preference to flying a constant-speed or decelerating approach. However, since pilots accepted procedures flown with a decelerating approach less than with a constant-speed approach (see Figure 21 or 22) it is recommended to fly a steep final approach with constant speed.

4. *Crosswind effect*:

- a. Handling qualities: the HQs worsened significantly with crosswind. The change in HQR was about 0.7 HQR.
- b. Performance: the crosswind worsened the lateral performance.
- c. Pilot's demand: the crosswind had no significant effect on the pilot's workload, but it did increase the pilot's demand in case of the 'curve' turn type owing to more precise navigational requirements.

It is recommended for any piloted simulation where real applications are to be evaluated, that the influence of operational conditions such as (cross)wind be taken into account. A contributing factor were the steep glideslopes involved, which required fairly low airspeeds in order to keep the rate of descent within reasonable limits. In that case the effect of wind becomes relatively more important.

5. *effect of Flight Director*:

- a. Handling qualities: the rated HQRs improved significantly with the addition of the flight director. The average reduction in HQR was about 0.7 HQR.
- b. Performance: the lateral performance on final improved significantly with the addition of a flight director.
- c. Pilot's demand: the pilot's workload reduced weakly significantly with the addition of a flight director.

The question whether a flight director is needed can be answered positively for one of the

conditions in this experiment, i.e. flying a curved procedure with a Level 2 rotorcraft.

6. *correlation HQR-pilot controls*: this correlation could not be found. The HQRs apparently do depend on many more or on different parameters than just pilot lateral cyclic inputs.

The original experimental set-up had not been designed to determine any such trend (e.g. there was no gradual build-up of, or variations in, handling qualities, for example). More research is needed to accomplish such a goal.

7. *deceleration rate*. The procedures turned out to have been designed with too small a margin for variation in terms of deceleration rate. The design value of -1.5 Kt/s was not achieved, with as result that pilots "ran out of time" to reduce the speed properly. A better value to adopt for procedure design would be -1 Kt/s.

All of the above aspects influenced the **acceptability of the procedures** (or turn types). The 'straight' procedure was 'well accepted', the 'fly-by' turn procedure was 'just accepted', and the 'curve' in the procedure was 'just not accepted'. The constant-speed approaches were better accepted than the decelerating approaches, although for the 'straight' procedure this did not matter much. That is: the combination of decelerating approach and turning on the intermediate-final segments adversely affected the procedure acceptance. Pilots generally objected to flying lateral course changes below 500-1000 ft AGL.

11 Future outlook and application

As stated in chapter 1 and section 3.1 the results reported here are based on a first simulation experiment, where the HPS was used as a "stand-alone" simulator, in order to pre-define procedures to be used in an integrated simulation, where the HPS is coupled to an ATC simulator in order to evaluate the use of new helicopter procedures in an SNI concept within an ATC environment at a busy European major airport. The experience gained in this first experiment was used to improve the design of a

curved final approach IFR procedure that was tested within the (simulated) ATC environment of Schiphol airport. The basic handling qualities of the rotorcraft were also improved by installing an attitude-hold type of flight control system, with greatly improved response in all axes. Also the “tight” requirements in terms of timing and deceleration profile were relaxed, with as result an acceptable procedure that solicited a good pilot response. Results of the integrated HPS-ATC-simulations with this procedure have just recently been reported at the 34th European Rotorcraft Forum (Ref.[7]), held in Liverpool in September 2008.

12 Acknowledgement

The author would like to acknowledge the invaluable contribution made by the participating pilots from the Royal Netherlands Air Force, the Royal Netherlands Police Force, CHC Helicopter Corporation and private backgrounds, as well as Eurocopter for granting permission to use the AS365N Dauphin model as well as the use of related features, and the University of Liverpool for providing the AS365N FLIGHTLAB model. Furthermore the author would like to acknowledge the European Commission for sponsoring this project, under contract no. AIP3-CT-2004-502880. Also the partners in the European project OPTIMAL are acknowledged for granting permission to present these results.

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