Nationaal Lucht- en Ruimtevaartlaboratorium

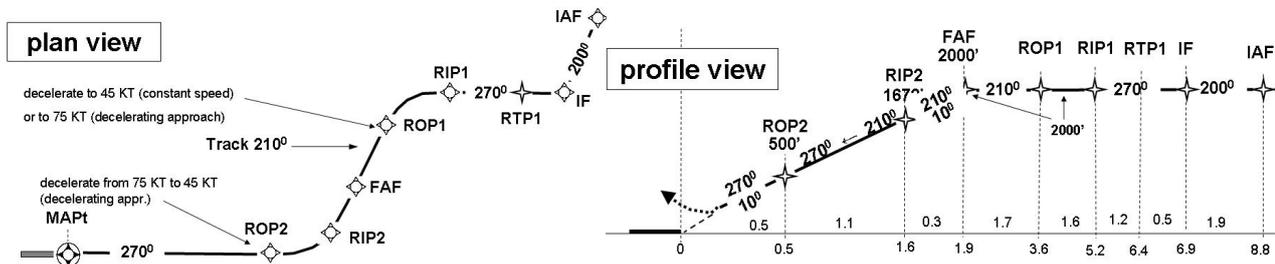National Aerospace Laboratory NLR

Executive summary

Design and execution of piloted simulation tests of steep segmented and curved rotorcraft IFR procedures at NLR

Problem area

In the EU-project OPTIMAL (Optimised Procedures and Techniques for the Improvement of Approach and Landing) a series of rotorcraft steep IFR procedures are being developed. These may be segmented or contain curved segments in order to make use of the specific features and performance of rotorcraft. Just how well these segmented and curved procedures will be acceptable is not quite well known.

Description of work

An experiment was designed and then executed in the helicopter simulator 'HPS' (Helicopter Pilot Station) at NLR in order to test 6 steep rotorcraft IFR procedures (2 straight procedures, one segmented and one curved), next to a baseline 6° straight procedure. Six pilots participate in the evaluation.

Results and conclusions

The class of straight-in steep procedures was well accepted by the pilots, with good performance achieved in manual flight, despite the sometimes steep glideslope of 9°-10°. The segmented and curved procedures required near maximum allowable pilot workload. Required performance could be achieved only with the use of a flight director. The crosswind at landing had quite a strong impact on the pilot workload and performance as well.

Applicability

The experience and knowledge gained will be used in the design of a special rotorcraft procedure, which will enable a simultaneous non-interfering (SNI) flight procedure of a rotorcraft on a busy main airport (e.g. Schiphol). Test of this procedure is foreseen for next year in an integrated ATC environment

This report is based on a presentation held at the European Rotorcraft Forum, Maastricht (the Netherlands), 12-14 September 2007.

Design and execution of piloted simulation tests of steep segmented and curved rotorcraft IFR procedures at NLR

.

NLR-TP-2007-610

Design and execution of piloted simulation tests of steep segmented and curved rotorcraft IFR procedures at NLR

H. Haverdings, J. van der Vorst and M. Gille[1]

[1] TUD

Customer	National Aerospace Laboratory NLR
Contract number	----
Owner	National Aerospace Laboratory NLR
Division	Aerospace Vehicles
Distribution	Unlimited
Classification of title	Unclassified
	July 2008

Approved by:

Author	Reviewer	Managing department
Hav 18/8/08	28/8/08	8/08
25/8/08		

Summary

In the European Commission Framework VI project **OPTIMAL** steep curved-segmented rotorcraft IFR approach procedures are being investigated in order to increase airport capacity, improve the efficiency and reduce the noise footprint. The two most striking features are 1) a final segment, starting at the final approach fix from where the 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 9º-10º. This allows the procedure to be oriented such that the rotary-wing traffic is kept separate from the fixed-wing IFR traffic, and to avoid noise-sensitive areas and obstacles. To evaluate the flyability, handling qualities and workload a number of such segmented (vertically and/or laterally) and curved steep procedures were evaluated using man-in-the-loop simulations. The maximum glideslope investigated was 10º.

Workload tended to be high for especially the curved procedure. The wind turned out to be a significant factor to be accounted for. Best way to fly the final approach segment is to fly it at a constant-speed, dictated by the glideslope angle and rate of descent limit of 800 fpm.

The results will be used to lay out a so-called Simultaneous Non-Interfering (SNI) procedure, whereby the rotorcraft can fly these approach procedures that do not interfere with other IFR traffic at a busy airport.

Contents

5

DESIGN AND EXECUTION OF PILOTED SIMULATION TESTS OF STEEP SEGMENTED AND CURVED ROTORCRAFT IFR PROCEDURES AT NLR

Henk Haverdings[1], Jasper v.d. Vorst[2], Michael Gille[3]

[1]National Aerospace Laboratory NLR
Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands
e-mail: haverdi@nlr.nl

[2]National Aerospace Laboratory NLR
Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands
e-mail: vorst@nlr.nl

[3]National Aerospace Laboratory NLR
Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands
e-mail; gillem@nlr.nl

Abstract. In the European Commission Framework VI project **OPTIMAL** steep curved-segmented rotorcraft IFR approach procedures are being investigated in order to increase airport capacity, improve the efficiency and reduce the noise footprint. The two most striking features are 1) a final segment, starting at the final approach fix from where the 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 9º-10º. This allows the procedure to be oriented such that the rotary-wing traffic is kept separate from the fixed-wing IFR traffic, and to avoid noise-sensitive areas and obstacles. To evaluate the flyability, handling qualities and workload a number of such segmented (vertically and/or laterally) and curved steep procedures were evaluated using man-in-the-loop simulations. The maximum glideslope investigated was 10º.

Workload tended to be high for especially the curved procedure. The wind turned out to be a significant factor to be accounted for. Best way to fly the final approach segment is to fly it at a constant-speed, dictated by the glideslope angle and rate of descent limit of 800 fpm.

The results will be used to lay out a so-called Simultaneous Non-Interfering (SNI) procedure, whereby the rotorcraft can fly these approach procedures that do not interfere with other IFR traffic at a busy airport.

NOMENCLATURE

DA/H	Decision Altitude/Height
FAS	Final Approach Segment
FD	Flight Director
FDP	Final Deceleration Point
FTP	Final Turning Point
GBAS	Ground-Based Augmentation System
GPA	Glide Path Angle
HPS	Helicopter Pilot Station
IAS	Initial Approach Segment
IS	Intermediate Segment
k	Von Karman constant
MCH	Modified Cooper-Harper
RFMS	Research Flight Management System
RNP	Required Navigational Performance
ROD	Rate Of Descent [fpm]
RTP	RNP Transition Point
SBAS	Space-Based Augmentation System
SNI	Simultaneous Non-Interfering
V	ground speed
V_w	wind speed
V_{w*}	friction velocity
VPA	Vertical Path Angle
z	height
z_0	roughness length

1   INTRODUCTION

In the European-funded 6th Frame Work OPTIMAL project the goals are to design new, or novel optimal procedures that offer better capacity, safety and environmental impact than the procedures used up to now. Although much focus is on fixed-wing technology, for rotorcraft a special work package is related to the design of rotorcraft-specific IFR procedures. With their unique capabilities, compared to fixed-wing, the new optimal rotorcraft procedures are likely steeper than conventional ones, and may contain segments or curves to allow more flexibility in circumnavigating restricted areas, obstacles, as well as to reduce the noise footprint with the steep glideslopes.

The procedures themselves are characterized by the presence of various waypoints defining segments which have different glideslopes and/or tracks. In some cases the glideslope may be successively built up from level to a steep angle if required. The maximum glideslope angle to be tested was 10º. A value of 12º has been contemplated.

Basically 3 different types of procedures were considered for evaluation, viz. 1) the class of *straight* procedures, with either a *single*-slope or a *dual*-slope descending segment, 2) a (laterally) *segmented* final approach procedure (with a descending turn past a fly-by waypoint on the final segment), and 3) a *curved* final approach procedure (with a descending curve of a prescribed radius on the final segment).

Other issues to be evaluated were the speed concept during the approach (i.e. constant-speed or decelerating final approach) and the landing crosswind condition (calm or limiting). A short discussion will be given on the design criteria involved in designing the procedures tested.

7

With each approach procedure 2 missed approaches (one per speed concept) were to be carried out. The purpose is to gather information about the height loss that occurs when going around on a steep approach. This parameter is of importance in determining the obstacle clearances that come with these steep procedures. Since the parameters of influence are the glideslope angle and the speed at the moment of going around these are the parameters that were included in the experimental design.

2 GUIDANCE CONCEPTS AND DISPLAYS

2.1 General

Besides the procedures there were also aspects of piloting, handling qualities and guidance to be evaluated, varying from manual flight to flight director-assisted flight, the final approach speed concept and two 'vertical guidance concepts' in the cockpit. For guidance the standard ILS-type of display was to be used, so ILS-deviations (in dots) were displayed to the pilot in the normal way. In the case of the simulations they were displayed on the HSI (Horizontal Situation Indicator), i.e. head-down and below the ADI (Attitude Director Indicator).
These guidance concepts were aimed at assisting the pilot especially in manual flight to perform the vertical and lateral navigational task within the required performance levels and to improve situational awareness.

2.2 ILS-squared display concept

For the trials NLR developed the so-called "ILS-squared" symbology. In Figure 1 this guidance concept is shown. With the "ILS-squared" concept the pilot is given a "double" set of localizer/lateral and glideslope/vertical deviations (i.e. both in track/course and in altitude): the solid set of symbols present deviations with respect to the *present* track/segment of the approach, and the dotted/dashed lines or symbols are the deviations with respect to the *next*
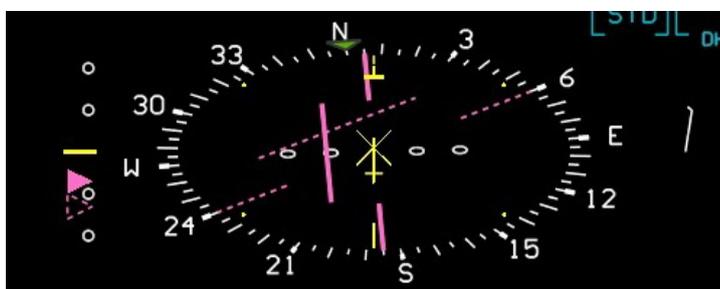
Figure 1 ILS-squared symbology

track/segment. It is expected that especially with segmented procedures this type of display will be beneficial to the situational awareness of the pilot. In the example given the rotorcraft is almost 1 dot above both the present glideslope as well as about 1.5 dots above the next

glideslope (or the extension of it). In case the present or next track is a curved segment then a point 10 seconds ahead on the curve is taken as the "next" point. This was done especially in order to help guide the pilot through the curve.

2.3 Square-roots display symbology

Another (vertical) experimental guidance concept, developed by Eurocopter, is the so-called "square-roots" symbology, as indicated in Figure 2.
It portrays, see the blue symbol in the form of a "square root" (hence the name square-roots symbology), the required altitude

Figure 2 Square-roots

by the horizontal line on the altitude tape, and the required vertical speed to arrive from the present position to the correct altitude at the next waypoint of the flight path. The combined symbol is the square-roots symbol. In the example given the aircraft is about 90 ft too high, and the sink rate of 700 fpm should be increased to more than 1500 fpm. When approaching a waypoint the required vertical speed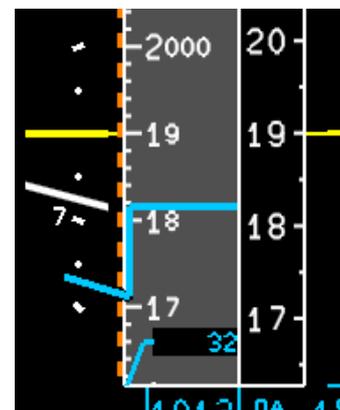 may become very sensitive due to the distance to the waypoint becoming "small". A minimum distance equal to the turn anticipation distance was used in the algorithm to prevent the required vertical speed from becoming too erratic.

3   DISCUSSION OF PROCEDURES

3.1   General

There were a number of types of procedures that warranted further probing, these being:
a)   The straight procedure, with a single glideslope of 9º, including a baseline procedure with a slope of 6º.
b)   The straight procedure, but with a dual glideslope, viz. an intermediate segment with a slope of 3º, and a final segment with a slope of 9º. Aim was to be able to investigate whether a single-slope would be a better option than a dual-slope, since both have their advantages and disadvantages.
c)   A segmented procedure. Although "segmented" refers first of all to the final approach segment, also a level turn past a so-called fly-by waypoint was included in the intermediate segment, in order to be able to compare the level fly-by turn against the descending fly-by turn.
d)   A curved procedure. Also here not only the final approach segment had a (descending) curve, but there was also a level curve on the intermediate segment, for the same comparison reasons.

All procedures were set to have a decision altitude/height DA/H of 200 ft.
A particular aspect of the rotorcraft procedure is the much steeper slope than is normally the case. In the OPTIMAL project the glideslopes considered feasible are 10º; a glideslope of 12º has been contemplated, however, the speed associated with the 800 fpm Rate Of Descent (ROD) limit would be quite low, viz. 37 kt. This was judged to be too low a speed for manually flying the SAS-equipped rotorcraft used in the simulation tests owing to reduced handling qualities and speed stability.

The baseline procedure is the "standard" against which the other procedures are to be compared. Since under visual conditions helicopters "normally" operate at about a 6º glideslope the (straight) baseline procedure was set to have a 6º glideslope.

3.2   Procedure design aspects

3.2.1   Straight procedures

The gradient and length of segments were determined by conditions of:
- Max. initial entry speed of 150 kt.
- A deceleration rate of 1.5 kt/s.

- A maximum allowable speed on the initial segment of 120 kt, and of 75 kt on the intermediate segment. The 75 kt is 5 kt more than the ICAO "standard", and was selected on the basis that then a still faster approach would be possible.
- A maximum speed on the final segment determined not by some value, like 70 kt from ICAO, but by a limiting maximum rate of descent value of 800 fpm. Because of the steep slopes involved the associated (ground) speed could be as low as 45 kt.
- A visual maneuvering segment length determined by a deceleration of 2 kt/s from the speed at the decision altitude/height (DA/H) to hover. The vertical path angle of the visual maneuvering segment is the same as of the preceding final approach segment. The ILS look-alike virtual antenna ("glideslope" and "localizer") positions were calculated to be 3600 m past the helispot, with a 2-dots width of 106.8 m at the "threshold" for the "localizer", and a helicopter hovering height of 10 ft above the helispot when on the glide path for the "glideslope" antenna.

A detailed description of all the generic straight procedures is given in the experimental design & test plan document that is proprietary to the OPTIMAL project. Here a sketch of the steep (i.e. 9°) dual-slope procedure is given, see Figure 3.
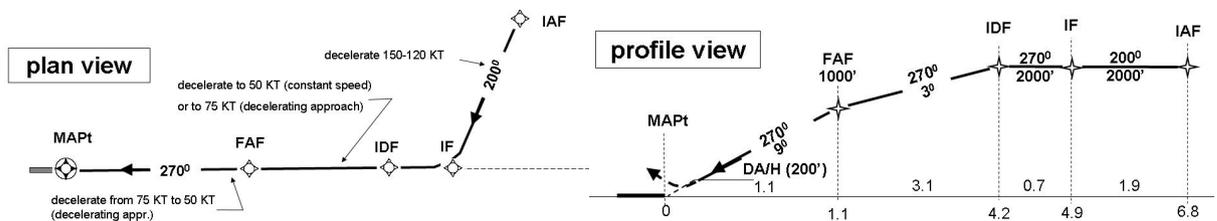
Figure 3 Sketch of dual-slope straight procedure

3.2.2 Segmented procedure

This procedure is characterized by:
- Two fly-by waypoints, one on a level (intermediate) segment and one on the descending final segment.
- A glideslope of 10°.
- The anticipation distance per fly-by waypoint is based on either the max. airspeed of 120 kt per (intermediate) segment or on the maximum rate of descent of 800 fpm, with the groundspeed following from the glideslope angle through the relationship:

$$V(kt) = 0.009875 ROD(fpm)/\tan(GPA) \tag{1}$$

A sketch of the generic segmented procedure is given in Figure 4, including the airspeeds per segment. In case of (cross)winds the pilot was allowed to add 5 kt maximum to these values in order to reduce the crab angle and increase the ground speed (which otherwise could drop to as low as 35 kt).

Figure 4 Sketch of generic segmented procedure

There are quite a number of waypoints. Besides the "standard" ones like IAF, FAF, etc., there are so-called RTPs, or RNP Transition Points, where the applicable RNP, to which the "ILS" sensitivity scaling is linked, changes (linearly) from one value to another, lower value, see also 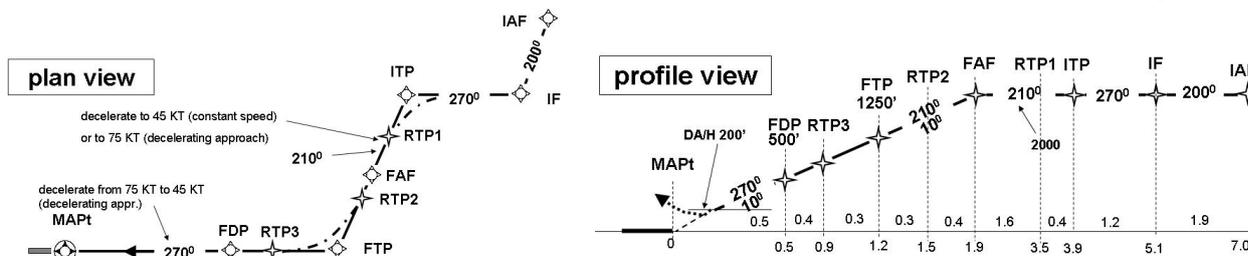§3.3. Maximum gradient of change in RNP is 0.58 NM per NM. The ITP is the Initial Turning Point, and the FTP is the Final Turning Point. The FDP is the Final Deceleration Point from where, in case of a decelerating approach, the deceleration is to start. It is located at a challenging 500 ft altitude.

3.2.3 Curved procedure

Similar to the segmented procedure, the curved procedure is characterized by the following:
- Two curves, one on the level, intermediate segment, one on the descending final segment. The radius of the curve is based on a turn rate of 0.5 times the standard value, i.e. on 1.5°/s, and a speed as described by a max. speed of 120 kt on the intermediate segment, and a rate of descent limiting value of 800 fpm for the final, descending segment.
- A glideslope of 10º.

An example of a steep, curved final approach procedure is given in Figure 5, where both the level curve on the intermediate segment and the descending curve on the final segment are shown (in the figure 'RIP' stands for "Roll-In Point", 'ROP' for "Roll-Out Point" and 'RTP' stands for "RNP Transition Point").
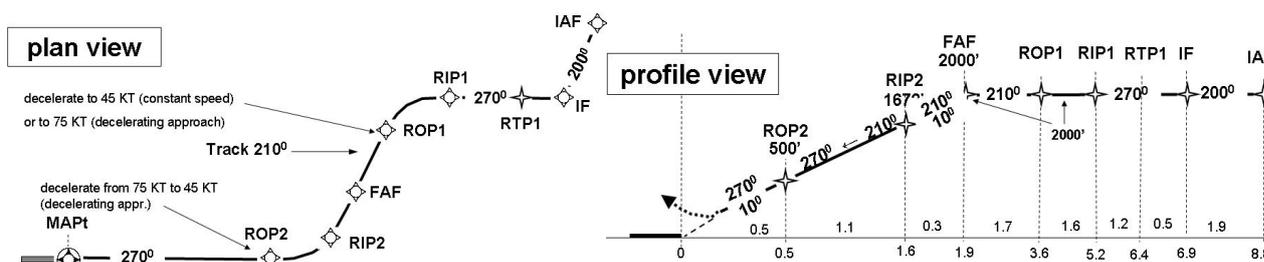
Figure 5 Sketch of steep curved final approach procedure

3.3 Guidance display sensitivity scaling

For guidance information to the pilot the typical "standard" deviation indications were provided in the cockpit. This was one of the requirements of the OPTIMAL project in that the guidance for these new procedures should be as much conventional as possible. The relevant deviations are computed by the (Research) Flight Management System RFMS that was installed in the

11

simulator. Deviations in nautical miles are converted to dots by making use of a varying ILS display sensitivity scaling, which is related to the Required Navigational Performance, or RNP. For the initial approach segment the generally allowable/required performance is RNP 1.0 NM, for the intermediate segment it is RNP 0.3-0.5NM and for the final segment it is set equal to the ILS-equivalent sensitivities. Accurate GNSS guidance, to give ILS-like performance, is tentatively delivered by either a Ground-Based Augmentation System, or "GBAS", or a Satellite-Based Augmentation System "SBAS". The procedures are so-called 'APV' procedures, standing for "(precision) **A**pproach **P**rocedure (with localizer Precision from SBAS or GBAS) with **V**ertical guidance" (from the FMS). This is the approach procedure category considered in the OPTIMAL project.

In the procedures the sensitivity scales are linked to the RNP such that one dot lateral or vertical deviation equals 1 RNP (laterally or vertically). These values were changed at specific RTP waypoints, if necessary. The maximum change in sensitivity was such that an equivalent gradient of change of 0.58 NM in RNP per nautical mile (58% or a "slope" of 30º) was allowed. This could mean that, when at 1 dot deviation and trying to correct for it by steering at a 30º intercept angle, the deviation would still remain at 1 dot as long as the transition is in effect.

For the segmented procedure the problem with guidance of this sort is that, by actually cutting off the "corner" when passing past a fly-by waypoint a shorter path results than according to the lengths of the segments. This implies that during the fly-by turn the required rate of descent should increase to more than estimated from the constant glideslope of the procedure. In order to "compensate" for the increase in lateral deviation that must occur during the fly-by, the sensitivity scaling was temporarily desensitized by increasing the allowable deviation by 0.1 NM, this being the maximum deviation for a 60º track change. For the curved procedure this problem did not exist.

As an example of how the lateral and vertical scaling was adapted the scaling for the curved procedure is given below in Figure 6.
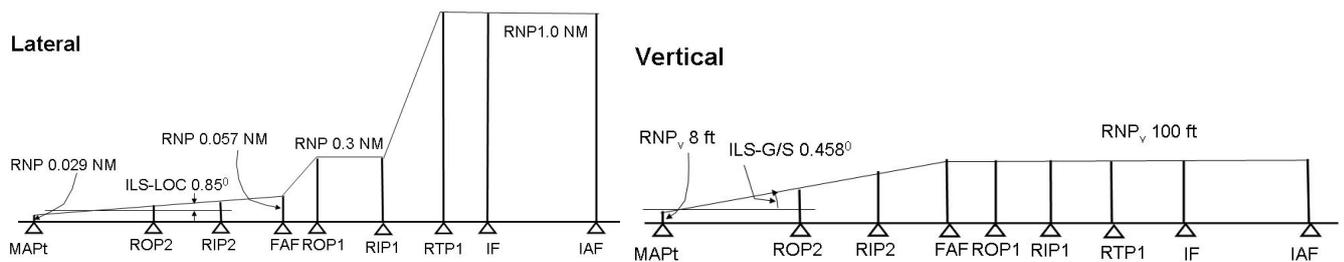
Figure 6 Lateral and vertical scaling of ILS deviation (varying with RNP) for the curved procedure

It is assumed that accurate (lateral and vertical) guidance signals are available for the entire final segment. In the simulator this "high accuracy" signal can always be delivered. However, the present S(G)BAS equipment under development is not able to deliver these accurate signals for other than a straight (final) segment, according to the ILS look-alike concept. So, the reality implies that for the near-future the vertical guidance, and protection of the turn/curves on the final segment before the last straight part, is taken care of by the FMS, with its inherently less accurate (vertical guidance) signal than delivered by the S(G)BAS. A further development might be to adapt this S(G)BAS system to deliver accurate signals also for segmented or curved final segments.

4 EXPERIMENTAL DESIGN

4.1 Objectives of the tests

The objectives were derived from the research questions, and are among others the following:
- To investigate the flyability of the steep, segmented or curved steep procedures.
- To determine whether it is more advantageous to have a dual-slope than a single-slope straight procedure. In case of a dual-slope there are two descending segments, the first one having a small glideslope angle of 3º, while the second one, starting where the first has ended, has a much steeper glideslope of 9º. With this dual-slope concept the change in flight path angle is tentatively "broken down" into two smaller changes in flight path of 3º and 6º respectively. This is supposed to be better manageable by the pilot.
- To determine the handling qualities and workload levels associated with the procedures and the guidance display concepts.
- To determine whether or not decelerating final approaches are preferable to constant-speed final approaches.
- To determine the influence of (cross)wind on piloting aspects of the steep procedures.
- To find if there is a performance improvement using one or the other vertical guidance display concept, compared to the standard ILS display.

Another objective was to look at the influence of the use of a flight director. It was expected that the novel segmented/curved procedures would be quite demanding, which could require the use of a flight director.

4.2 Experimental factors

4.2.1 Speed concept

One of the questions raised was whether or not a decelerating final approach is feasible. To answer this question all procedures were flown both with a constant-speed final approach and with a decelerating final approach. In the latter case it was assumed that, for the design of the procedure, the deceleration would occur at a rate of 1.5 kt/s.

4.2.2 Flight assistance mode

All procedures were to be flown manually, however, for the segmented and the curved (generic) procedure the workload could be so high that a flight director might be warranted. Initially, for comparison reasons, also the straight procedures were intended to be flown with the flight director; however, the available time did not permit this. The flight director was a 3-cue FD, giving roll, pitch (green) and collective (white) cues. A "standard" display format for the flight director was used, see Figure 7. In the figure shown the flight director commands a pitch up, roll right and collective-up control input.
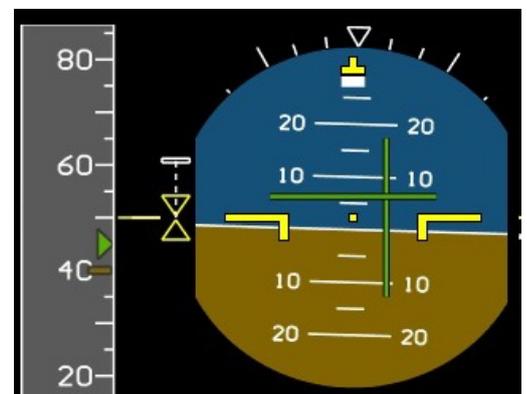

Figure 7 Flight director display

4.2.3 Wind speed

In order to evaluate the "sensitivity" of the procedures to environmental matters 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 90º (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:

$$V_w(z) = \frac{V_{w*}}{k} \ln\left(\frac{z}{z_0}\right) \qquad (2)$$

Here z_0 is the roughness length, V_{w*} is the "friction velocity", and k is the Von Karman constant; $k = 0.4$. With a tower-reported wind, i.e. measured at 10 m height above a mown lawn (then z_0=1.0 mm, see Ref.[1]) of 25 kt the friction velocity V_{w*} can be computed to be 1.0857 kt. This resulted in a wind speed of 36 kt at 2000 ft altitude, i.e. an increase of 11 kt. Also the wind direction was set to veer 30º from 10 m to 2000 ft in a linear fashion.

4.2.4 Weather limits (above or below landing limits)

The "weather" was simulated in the visual scenery of the simulator. This variability was meant to drive the pilot into making a go-around on several occasions. Goal was to determine the height loss during the go-around under controlled circumstances. Since it was expected that the largest height loss would occur with the max. crosswind, go-arounds were "designed" to be made with this wind, for both constant-speed and decelerating final approaches.

4.2.5 Guidance symbology

Because of its interesting aspects a comparison of the two vertical guidance display concepts, discussed in §2, seemed especially interesting for the dual-slope straight procedure, where on the intermediate, descending segment the difference in guidance information could play a role. For comparison reasons also a "normal ILS" display type was used during the trials. The conditions tested were for a constant-speed final approach, where the whole speed change from intermediate to the final approach speed is made on this intermediate segment.

4.3 Test matrix

The piloted simulation experiment took place from February to March of 2006. In total 6 pilots participated in the tests. Their flying experience ranged from 1500 to 7200 flight hours. All pilots were IFR-rated, 2 were from the Royal Netherlands Air Force and the others were civilians.

Putting all variables together and their level of variation has been done in the test matrix, see Table 1. The scope of the tests amounted to 32 measurement runs per pilot, which took an average of 2 days of testing (including training runs).

Table 1 Experimental test matrix

Exp. factor: Procedure	Flight assistance mode	Speed concept	Wind speed	Vertical guidance concept	Meas. runs	Tests (see §7.1)
Baseline (6º)	M	CS, D	0, 25 kt	ILS[2]	4	1,4
Straight (9º) *Single*-slope	M	CS, D	0, 25 kt	ILS[2]	4	1,4
Straight (3º/9º) *Dual-slope*	M	CS, D	0, 25 kt	ILS[2]	4	1,3.4
Straight (3º/9º) *Dual-slope*	M	CS	0, 25 kt	Square-roots	2	1,3
Straight (3º/9º) *Dual-slope*	M	CS	0, 25 kt	std ILS	2	1,3,4
Segmented (10º)	M, FD	CS, D	0, 25 kt	ILS[2]	8	1,2,4
Curved (10º)	M, FD	CS, D	0, 25 kt	ILS[2]	8	1,2,4
				Total:	32	

M = Manual Flight; FD = Flight Director
CS = Constant-speed approach, D = Decelerating approach

The effect of the experimental variables on e.g. performance will be analyzed using ANalysis Of VAriance (ANOVA). In fact a repeated measures ANOVA is used, whereby within each subject (i.e. pilot) a test is repeated with one parameter varied in a systematic manner. More information on ANOVAs can be found in Ref.[2].

5   SIMULATOR SET-UP AND MODELS

5.1   Helicopter pilot station

NLR's Helicopter Pilot Station HPS is a fixed-base simulator, consisting of a digital control loadings block, upon which is mounted the seating and cockpit panel, made from hardboard. Only a right-hand seat is available. Three overhead projectors project a CGI on 3 white-painted panels. Overall the visual range offered by this facility is 135º horizontal x 33.5º vertical (i.e. 11.5º up, and 22º down).

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

The rotorcraft flight mechanical model is driven by the FLIGHTLAB real-time simulation tool/model.
An artist impression of the HPS is given in Figure 8.

Figure 8 Artist impression of the Helicopter Pilot Station

5.2   Rotorcraft model

The rotorcraft model implemented in FLIGHTLAB was a Eurocopter AS365N Dauphin medium-class helicopter, at 4.3 tons of mass. The modeling 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-centering 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, and was therefore lowered to 25 kt.

5.3   Research Flight Management System

A Flight Management System functionality was provided by NLR's Research Flight Management System RFMS. It was implemented using a touch-sensitive panel, mounted on the pedestal left of the pilot. It mimics a "normal" FMS. The routes to be flown are selectable by the pilot. The FMS calculates the deviations that occur by comparing present position against the flight-planned route or procedure.

5.4   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 colored spots with equal brightness as the other spots of the same or different color.
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.

6   DATA GATHERING & PROCESSING

6.1   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. The questions asked related to such matters like handling qualities, workload and procedure-related questions like acceptance of the procedure or speed concept, preferred combinations of procedure and speed concept, etc.

All questionnaire data were stored into a file that could be processed by the statistical package STATISTICA™ (version 7.1), see Ref.[2].

6.2   Performance data

From the FLIGHTLAB simulation environment various kinds of flight data were recorded for later analysis. Data recorded were the time histories of flight path deviations (lateral/vertical) converted into dots, speeds, attitudes, attitude rates, control activities, etc., at a sampling rate of 10 Hz. Also the conditions at the procedure's waypoints passage were recorded. Flight path deviations were post-processed into RMS values for each approach segment (i.e. initial, intermediate and final segment). Other statistics computed per segment were the minimum, mean and maximum value of the above parameters, as well as the 25th and 75th percentile values.

Levels of *desired* performance were set at 0.5 dots laterally/vertically for the deviations from the flight path, or 1 dot for *adequate* performance. In term of speeds 5 kt deviation from target speed was the desired performance level, and 10 kt for the adequate performance level.

7   RESULTS OF EXPERIMENTATION

7.1   General

The data obtained in the repeated measures experiment was "grouped" into 4 tests, as follows:
- Test 1: effect of procedure, speed concept, wind influence, under conditions of ILS-squared display and manual flight only.
- Test 2: effect of flight director, wind, speed concept for segmented and curved procedures only, under conditions of ILS-squared display only.
- Test 3: effect of guidance display concept, speed concept, under conditions of manual flight, no-wind conditions, and for the straight dual-slope procedure only.
- Test 4: determination of minimum height loss in the go-around, from missed approaches made, under conditions of 25 kt crosswind, manual flight, and ILS-squared guidance display only.

The sequence of runs and procedures was randomized over the pilots in order to alleviate learning effects as much as possible. Since it was a repeated measures experiment the pilot went through many repeats of cases, with the result that due to learning effects the results could be biased when, for example, the same procedure is always flown first or last. This was circumvented by suitable randomization of the sequencing of runs offered to the pilot. Before starting the "measurement runs" all pilots went through about half a day of training in order to become familiar with both the procedures and the simulator environment, including the rotorcraft's flight-dynamic behavior.

7.2   Subjective performance

7.2.1   Procedure acceptance ratings

The question of how well the procedures were accepted was asked per run (in the in-cockpit questionnaire) as well as afterwards (debriefing questionnaire), after all runs per procedure had been flown.

Straight procedure's acceptance

Concerning the single-slope or dual-slope procedure the pilot's acceptance from the debriefing questionnaire is given in Figure 9. All the straight procedures were accepted when operating with the constant-speed concept. For decelerating approaches the results were more diffuse: there was a shift from "accepted" to "neutral" on average, and the difference in acceptance rating for the decelerating approach cases was significantly ($p<0.05$) different from the constant-speed approaches. Because of the pilot's familiarity with the baseline procedure this one was accepted as the best one.
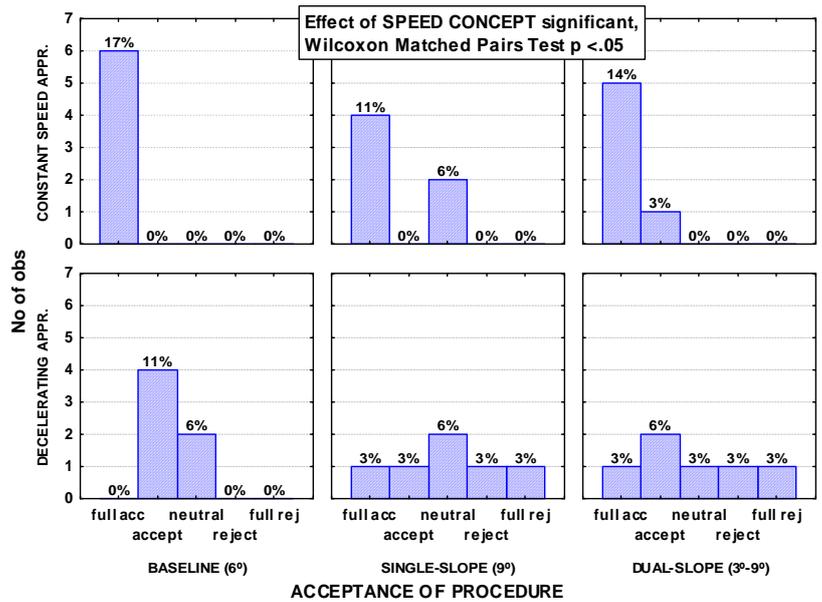

Figure 9 Acceptance of straight procedures

Segmented procedure's acceptance

The segmented procedure was much less accepted in general, see the histogram in Figure 10. There is a weakly significant ($p<0.1$) difference between the constant-speed and decelerating approaches (Wilcoxon matched pairs test, $p=0.075$), with the latter concept being less accepted. Only 17 percent of the constant-speed approaches was *rejected* (1 pilot), whereas 17 % of the decelerating approaches was *accepted* (1 pilot).
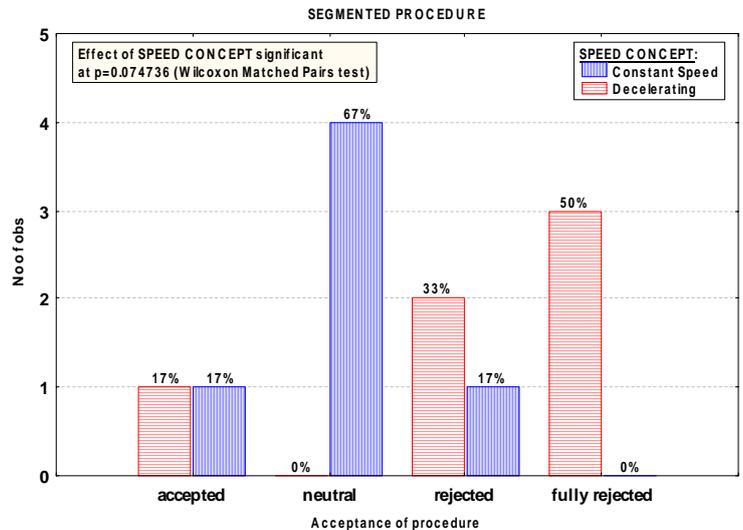

Figure 10 Acceptance of segmented procedure

How the speed concept was accepted is shown in Figure 11. The constant-speed approach concept was neutrally accepted at least, whereas for the decelerating approach concept the best acceptance rating was "neutral". Again here there was a significant (p<.05) difference in acceptance of the speed concept.
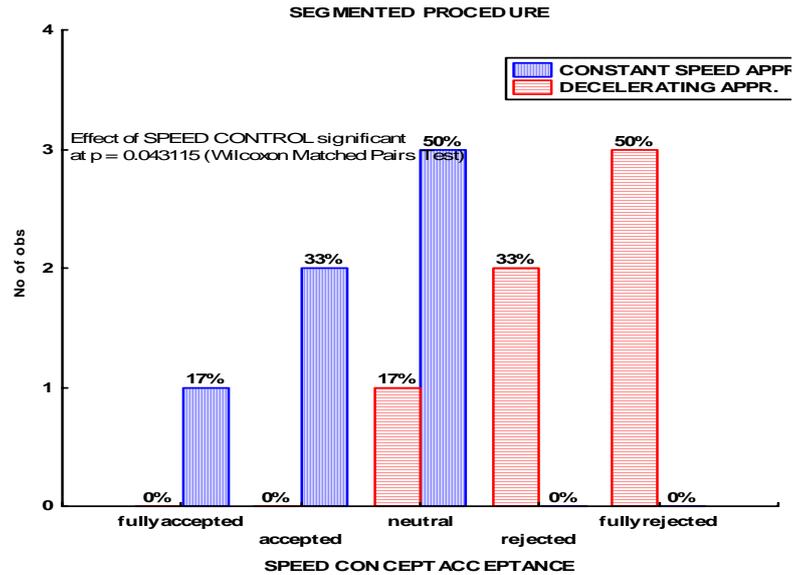

Figure 11 Acceptance of speed concept with the segmented procedure

Curved procedure's acceptance

The pilot's acceptance ratings for the curved procedures are given in a histogram, shown in Figure 12. As can be seen overall the curved procedure was marginally accepted in case of the constant-speed approach, and not accepted at all in case of decelerating approaches. The difference is statistically significant, p< 0.05 (Wilcoxon matched pairs test, p=0.0277). From pilot comments it was obvious that the deceleration on the final approach segment, after the descending curve and starting at about 500 ft (while still in IMC), was too much to ask, inducing too high a workload.
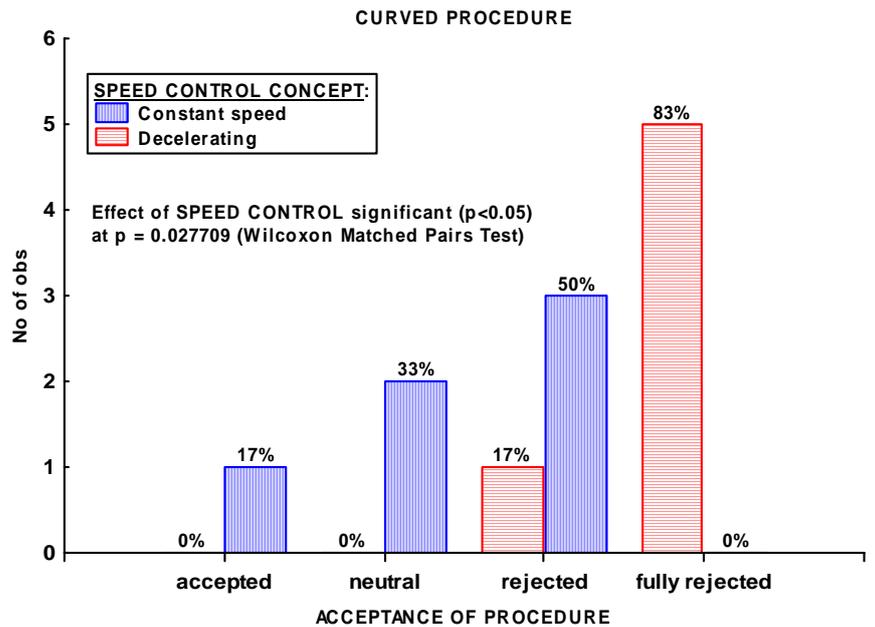

Figure 12 Acceptance of the curved procedure

How the speed concept was accepted for the curved procedure is shown in the histogram in Figure 13. In this case an even stronger 'no' was expressed against the decelerating approach, since all decelerating approaches were rejected. It is obvious that a decelerating approach technique on a curved procedure here, with the deceleration to be made starting from 500 ft, was not acceptable at all. Pilots preferred to have a situation where all approach parameters (e.g. speed and heading) would be stabilized at 1000 ft, or 500 ft at the latest.
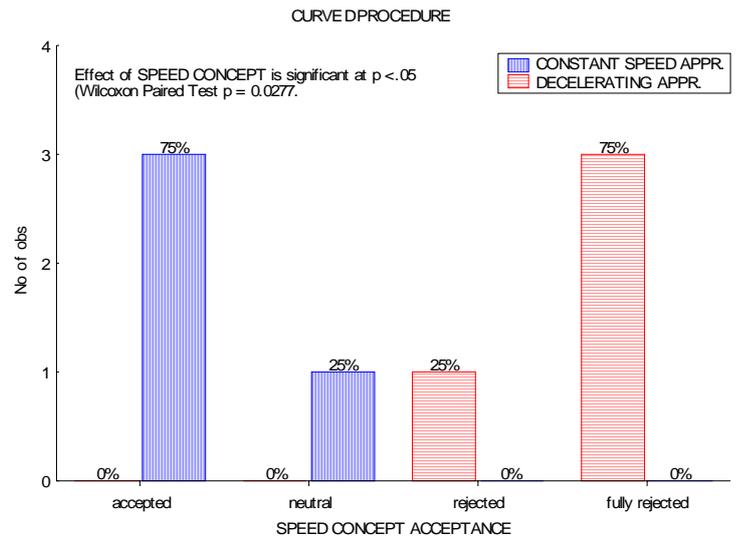

Figure 13 Acceptance of speed concept for the curved procedure

7.2.2 Situational awareness

With all the heading and track changes an important aspect of safe flight is situational awareness. Situational awareness is near to impossible to quantify in measurable terms and can only be "determined" subjectively using questionnaires.
For the segmented and the curved procedure such a question was included in the debriefing questionnaire.

Segmented procedure
One interesting aspect of situational awareness (SA) is whether or not there was a difference in SA between the level and descending turn. For the segmented procedure the resulting histogram is shown in Figure 14. For level turns the situational awareness was rated to be at least weakly significantly better, p<0.1, than in the descending turn (Wilcoxon Matched pairs test, p=0.068).
Apparently, due to the high workload, the pilot had less situational awareness as he was making a fly-by turn on the final approach segment.
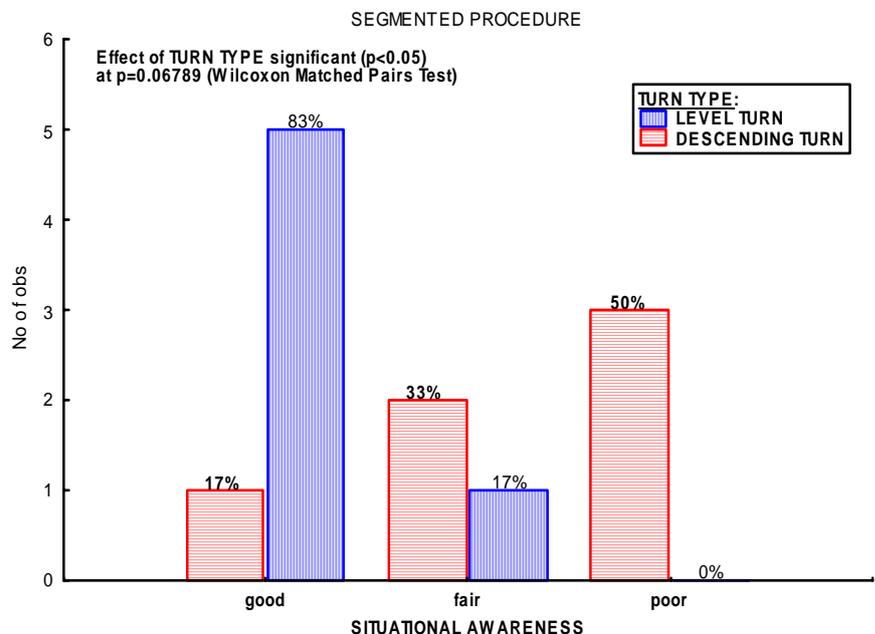

Figure 14 Situational awareness for the segmented procedure during level and descending turns

Curved procedure

With the curved procedure a similar question about situational awareness was asked, in that here also both a level and a descending turn (i.e. curve) were made. The resulting histogram of the questionnaire is shown in Figure 15. It is obvious that also here the situational awareness during the level curve was rated significantly (p<0.05) better than for the descending curve (Wilcoxon matched pairs test, p=0.0278). It is suspected that this is due to the higher workload during the descending curve, with the pilot having less time to scan around for situational awareness.
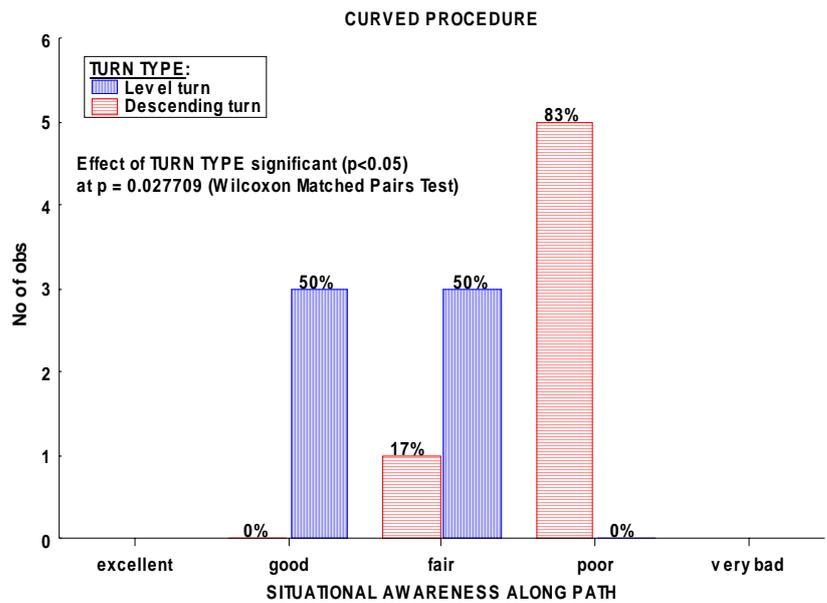
Figure 15 Situational awareness with the curved procedure's level and descending curves

7.2.3 Pilot's workload

Correlation between demand and Modified Cooper-Harper workload scales

An important aspect of flyability of the procedures is pilot workload. It was "obtained" from the pilot's questionnaire, where two scales had to be filled out, viz. the McDonnell's "demand" scale (Ref.[3]), and the Modified Cooper-Harper scale (MCH), see Ref.[4]. Both ratings correlated reasonably well with one another, see Figure 16. Both a linear fit and a cubit fit between the data were determined. The cubic fit in fact is very close to the linear fit especially for the "lower end" of the "demand" scale, showing also that at the higher end of the demand scale the MCH is more sensitive to changes in condition than the demand scale is. It is remarked though that th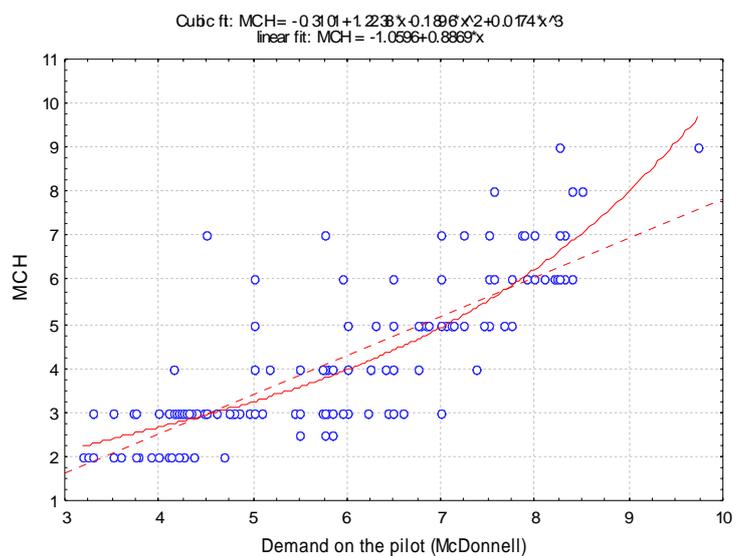e demand scale is an interval scale whereas the MCH scale is an ordinal scale. It is emphatically stated that this MCH scale does not rate handling qualities but workload only, even though a similar

Figure 16 Correlation between demand and MCH

21

choice-box structure in the scale is followed as is the case with the handling qualities rating scale from Cooper-Harper.

Effect of procedure, speed concept, winds from Test 1

The effect of procedure, wind speed and speed concept (from Test 1) on pilot workload is shown in Figure 17, in case of manual flight.

As the figure shows the workload for the first three procedures fell more or less into the same category, whereas the workload for the segmented and curved procedures was, as a group, significantly ($p<0.05$) higher, $F(1,2) = 32.02$, $p=0.0298$. Looking at the more challenging procedures, the workload of the curved procedure was (almost) significantly ($p<0.05$) higher than that for the segmented procedure, $F(1,2)=12.0$, $p=0.0741$. Pilots reported that tracking the lateral path in the curve

Figure 17 Workload as function of procedure, speed concept and crosswind – manual flight

was much like continuously intercepting a track, a task that required continuous attention. With the segmented procedure the turns past the fly-by waypoints were flown in an "open loop" sense, requiring much less attention, and hence less workload. Overall the workload for the higher-workload procedures is a solid Level 2, becoming close to "completely demanding", and running close to the Level 3 region of the MCH scale. This indicates a serious workload issue that should be addressed. Note: Level 3 implies that errors made are no longer "small and inconsequential" and where a "system redesign is strongly recommended". Level 2 workload is a workload where the "mental workload is high and should be reduced". The Level 2 and Level 3 boundaries were drawn using the linear fit data from Figure 16.

The speed concept did not have a significant main effect ($p>0.1$) at all, $F(1,8)=0.2216$, $p=0.684$, on the workload. This was a bit surprising, since a deceleration to be performed starting at about 500 ft was expected to cost more workload than for a constant-speed approach. Apparently the parameter(s) that "drove" the workload here was not the speed control issue (rotorcraft handling qualities was also one of the contributing factors).

Although the workload increased when there was a crosswind, the overall main effect of crosswind also was not significant ($p>0.1$), $F(1,8)=4.236$, $p=0.176$. For the straight procedures there was no effect of crosswind on the workload. For the segmented and curved procedure the crosswind increased the workload almost weakly significantly ($p<0.1$), $F(1,2) = 7.222$, $p=0.115$. The obvious reason is of course the track changes of the segmented or curved procedure, asking for a continuous adjustment of the pilot to the changing wind effect while on approach.
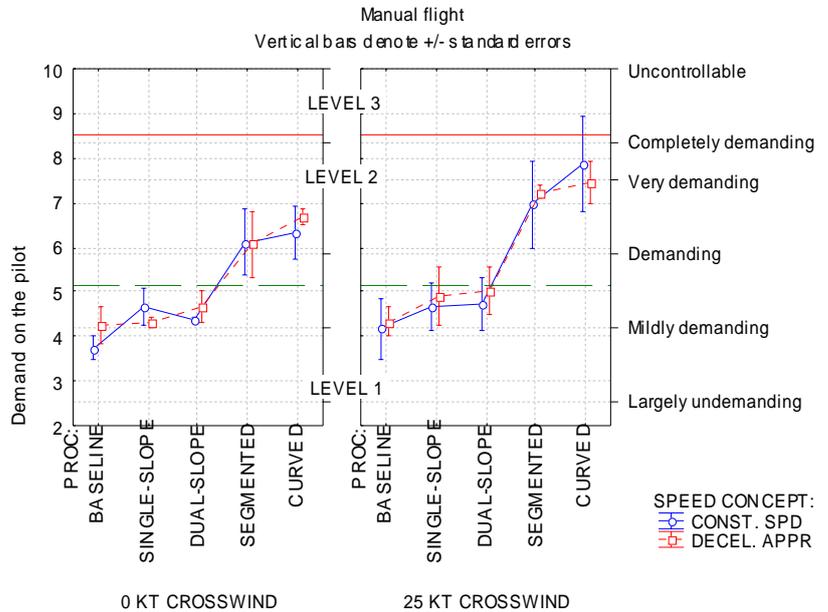
22

Effect of flight director (Test 2)

Taking data from Test 2, a comparison of workload between manual flight and flight director-assisted flight could be made for the segmented and curved procedures only. Results are shown in Figure 18.
The flight director had a weakly significant (p<0.1) main effect on pilot workload, $F(1,4)=5.169$, p=0.0854. With the FD the workload was lower than without, as expected.
For the curved procedure on average the workload was significantly (p<0.05) higher than for the segmented procedure, $F(1,4)= 11.34$,

Current effect: F(1, 4)= 11.776, p=.02649
Vertical bars denote +/- standard errors

Figure 18 Effect of flight director & crosswind on workload

p=0.0281. Pilots reported also that for the curved procedure the tracking of the curve was a higher workload task than making the "open-loop" turns in case of the segmented procedure.
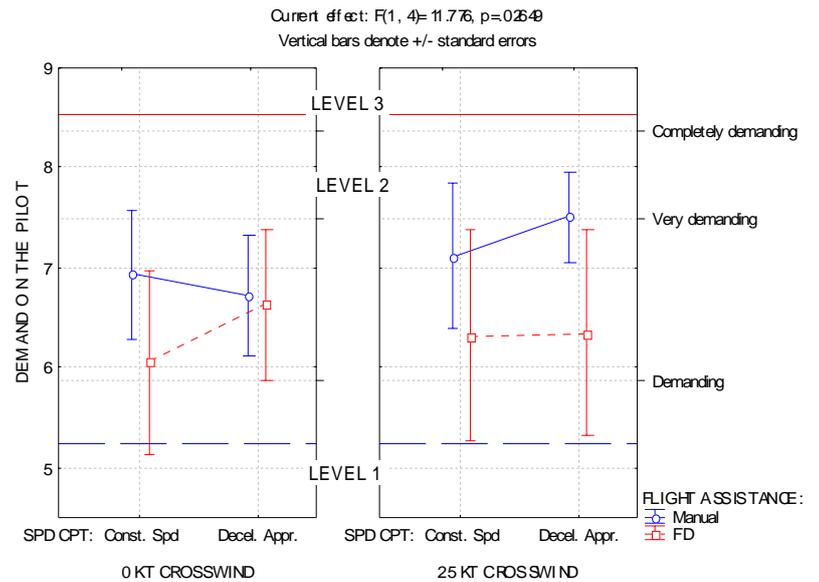
A significant interaction (p<0.05) existed between the crosswind and the flight assistance mode, $F(1,4)=11.78$, p=0.0264. This was because for the zero-wind case the FD workload for the curved procedure was higher than for the segmented procedure, see remark made earlier and the left-hand side of Figure 18; however, in case of a 25 kt crosswind the workload for both procedures was equal when flying with the flight director (see right-hand side). Only in case of manual flight could a small, non-significant difference be observed. The FD demanded still much attention during the procedure's curves or turns, and apparently with the higher-workload crosswind condition it didn't matter whether a constant-speed or decelerating approach was flown. It could be hypothesized that the speed concept has less effect on the pilot's workload since the flight director is taking care of it all. When following the FD commands the pilot doesn't really need to know if a deceleration is taking place or not, other than by setting the speed bug on the speed scale (this bug was set on verbal command from the pilot by the experiment leader/co-pilot).

Effect of vertical guidance display (Test 3)

For the case of comparing the effect of the vertical guidance display concepts on pilot workload, data were taken from Test 3.
The effect of the vertical guidance display and crosswind is shown in Figure 19. The type of display had no significant main effect (p>0.1) on pilot workload, $F(1,10) = 2.472$, p=0.134, although it was becoming weakly significant. Looking closer there was a significant effect (p<.05) of display type in case of a 25 kt crosswind, where the square-roots display scored a lower workload than the other two display types together, $F(1,5)= 8.872$, p=0.0308. In case of no wind there was a much more equal workload among the 3 display types. Why the crosswind made it "easier" for the square-roots display could be hypothesized to be attributable to the display of the required vertical speed in the square-roots display concept. In case of the other displays the required vertical speed to maintain the glide path had to be estimated in case of

wind, whereas with the
square-roots display there is a
clear indication, making it
easier for the pilot to set the
proper vertical speed.
However, inherent in this
type of display, the average
vertical deviation may likely
have a non-zero bias when
following the required
vertical speed indication too
much, and the resulting
vertical deviation RMS,
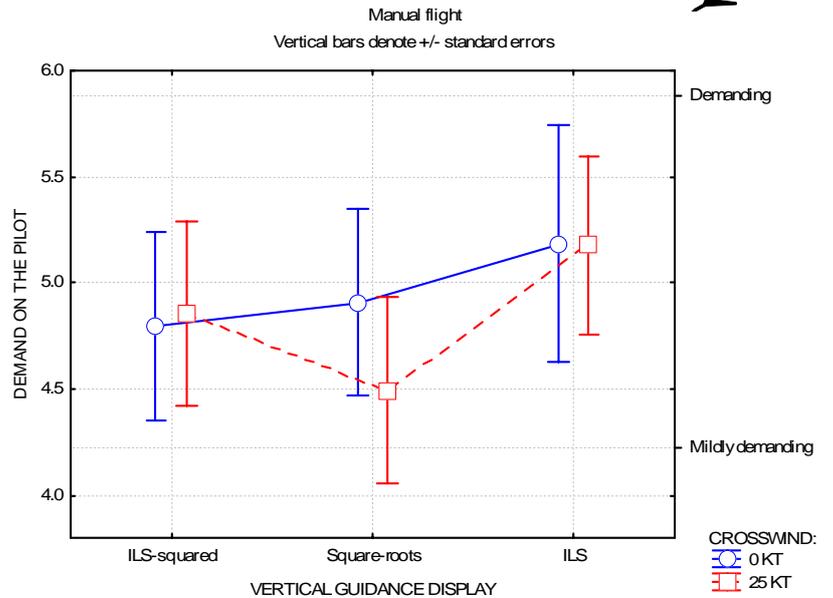shown later (§7.4.4),
confirmed this.

Manual flight
Vertical bars denote +/- standard errors

Figure 19 Effect of guidance display on pilot workload – manual flight

7.3   Summary of pilot comments about the procedures

For the baseline procedure the pilots had no real comments; it could be easily flown, and the glideslope was not too steep.
The dual-slope procedure was no problem either. This dual-slope issue could perhaps be combined with the other segmented or curved procedure. A slope of 9º was well acceptable.
The segmented procedure was a handful, and should not be flown with a decelerating final segment. Although difficult to fly, it was easier to fly than the curved procedure. Curves are a high workload task. For both these segmented/curved steep procedures the final deceleration at 500 ft is not done. Because of their steeper glideslope than of the others, the impact of wind is greater, and overall the workload is too high, requiring a flight director. With the flight director they can be "easily" flown.
Especially for the segmented and curved procedures pilots almost unanimously found the approach segment lengths to be on the short side; the waypoints were too close to another. There was hardly time or occasion to correct for flight-technical errors from the previous segment, which could lead to an accumulation of effects on the final approach segment.

7.4   Objective performance

A definitively more objective assessment of performance is derived from the "measured" flight path and associated derived variables. Considering the vertical and lateral maneuvering involved, important variables to look at are the vertical and lateral deviation from the required approach track. These parameters are assumed to have a zero-mean value (any non-zero mean value, or bias, should be corrected for in the guidance displays), and then a good indication of the performance as well as of the variability is the RMS value of these deviations. These RMS values were computed per approach segment, i.e. the *initial* approach segment, containing the 70º intercept, the *intermediate* segment, containing the level turn/curve for the segmented or curved procedures or the initial descending segment for the dual-slope procedure, and the *final* approach segment with the steep glideslope. For each of the 4 tests a discussion of the results on these RMS values is given in the next sections.

Concerning the design of the procedures a further interesting variable to evaluate is the deceleration rate. For the IFR-part of the procedure a standard deceleration rate of 1.5 kt/s was used for the procedure design, but in the execution of the speed changes it was found that actual deceleration rates were less. This sometimes led to problems in completing the speed changes by certain waypoints, a possible reason why the approach segment lengths were found to be too short in general. Since it is likely that the "deceleration rate behavior" is more pilot-dependent than procedure-dependent, the factor of 'procedure' has been replaced by the factor of 'pilot', and a grouped ANOVA (see Ref.[2]) was performed. More details are given in §7.4.6.

7.4.1   Flight path lateral deviations (Test 1)

For comparing the performance among the procedures the more important variable to look at is the lateral RMS of the flight path deviation, but also the vertical deviation will be evaluated. In this section the lateral deviation will be evaluated in the case of manual flight.
Regarding the first test, which, see §4.3, can be used to evaluate the difference among procedures, the speed concept and wind effect, a (repeated measures) analysis of variance of the lateral RMS was performed. In order to "remove" outlying values the data for the "worst" and "best" pilot's overall lateral RMS was disregarded from the analysis.
The ANOVA showed many variables and mutual interactions to be significant, in a statistical sense.
The operationally more interesting aspects to evaluate are how the lateral performance has been affected by the speed concept (constant-speed or decelerating approach) and what the effect of the crosswind would be, and also which approach segment is affected most.
Of course one can go into great depth at analyzing the various contributions, but it is perhaps best summed up in Figure 20, where for calm wind (part (a)) and 25 kt crosswind (part (b)) the RMS is shown for the 5 procedures as function of speed concept for the 3 approach segments.

Overall it is clear that the baseline procedure had the lowest lateral RMS, followed by the other straight procedures, as well as the segmented procedure. Without wind the decelerating approaches seemed to have a slightly better RMS performance, although the difference is not statistically significant (p>0.1), except again for the curved procedure.
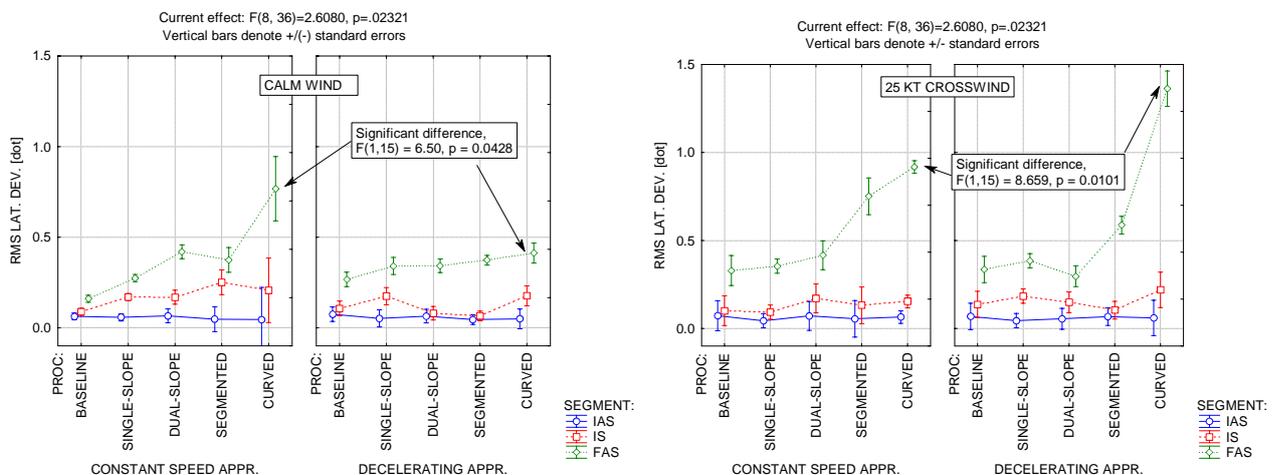
(a) calm wind   (b) 25 KT crosswind

Figure 20 Lateral RMS performance (Test 1) in manual flight

The type of <u>approach segment</u> (i.e. Initial Approach Segment, IAS, Intermediate Segment IS, or Final Approach Segment FAS) also had a highly significant (p<0.01) main effect, $F(2,15)=22.117$, p=.00003. It is obvious that the final approach segment had the largest lateral deviations. Even though lateral maneuvering took place mostly with the segmented and curved procedure these procedures did not have a lateral RMS larger than the other procedures had in zero-wind, except in the case of crosswind (this was evidenced by the interaction between procedures and wind speed being highly significant, $F(4,36)=8.0556$, p=0.000096). Without the "disturbing" crosswind it was apparently easier to track the final approach segment when it contains a curve than when flying past a fly-by waypoint, which, by itself, already introduced a lateral deviation.

The main effect of <u>crosswind</u> on the lateral RMS was highly significant (p<0.01) and quite strong, $F(1,9)=10.642$, p=.00980, especially for the segmented and curved procedures. For the crosswind case there is especially for the curved procedure a significant (p<0.05) increase in lateral RMS, from about 0.3 dots to about 0.6 dots on average. With the fairly low airspeeds in the order of 45 -50 kt (because of the rate of descent limit) the crosswind of 25-30 kt required wind correction angles that were in the order of 25-35 degrees.
The time to be aligned with the final approach course was much shorter than with the straight procedures, giving the pilot less time to be stabilized and estimate the crosswind effect. One of the other contributing factors was the shear in the crosswind. The wind boundary layer model in fact contains a built-in windshear effect, which was also observed to cause more lateral deviations and also increase the workload. Especially from about 500 ft and lower the shear became more evident. One can derive from Eq.(2) that the windshear, or gradient in windspeed with height z is:

$$\frac{dV_w}{dz} = \frac{V_{w*}/k}{z} \qquad \forall z > 0 \qquad (3)$$

This equation shows that the windshear increased inversely proportionally to the height above ground.

The <u>speed concept</u> did not affect the lateral RMS so much except for the curved procedure, where without wind the decelerating approach had less RMS than the constant-speed approach, but this reversed completely with crosswind, where the decelerating approach had a significantly larger lateral RMS than with the constant-speed approach. This is also evidenced by the interaction between speed concept and crosswind being significant (p<0.05), $F(1,15)=4.864$, p=0.0434. This means that the main effect of, say, speed concept, is modified by the wind effect for this procedure. Why this happened is at the moment uncertain.

Notice also that the mean lateral RMS for the curved procedure with crosswind was 1.3 dots, which puts it outside of the adequate performance limits. In operational practice a go-around would have had to be made most of the time. In the experiment, however, pilots were urged to continue the approach but to make mental note of the situation and report it in the questionnaire. This performance, with crosswind, is one of the reasons why a flight director is needed for assistance to improve performance. The FD results did indeed show a significant improvement, see §7.4.3.

7.4.2 Flight path vertical deviations (Test 1)

Besides lateral performance there is also the vertical performance to contend with. It is known that for the dual-slope procedure, for example, the vertical deviation on the intermediate segment may be affected by the vertical guidance display, and this will be evaluated in §7.4.4.

For this evaluation data was taken from Test 1, i.e. data flown with only one guidance display type, viz. the ILS-squared.

The effect of the speed concept is to increase the RMS on that segment where the speed changes are made, i.e. either the intermediate or the final segment. This can be seen in Figure 21, where the interaction between approach segment and speed concept is significant (p<0.05), i.e. for both the intermediate and the final approach 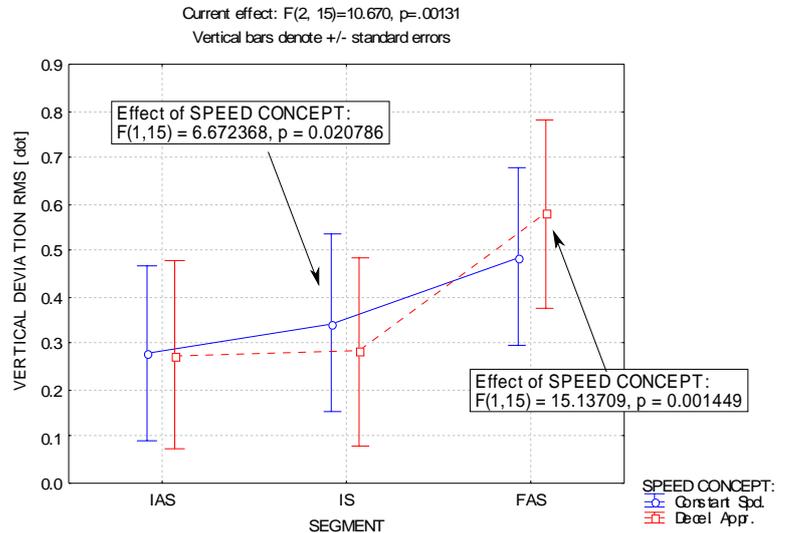segment there is an effect, but not for the initial segment. In case of a decelerating approach (dashed red line) the vertical RMS of the initial and intermediate segments are the same, and all the variation occurs on the final segment. The average effect of a decelerating approach compared to a constant-speed approach is to increase the vertical deviation RMS by about 0.05 dots.

So, if one wants an accurate vertical performance on the final segment it is better not to decelerate on the final segment. Mean vertical deviations (RMS) were in the order of 0.3 – 0.5 dots, which is within the desired performance level.

Figure 21 Vertical RMS as function of segment and speed concept

The main effect of crosswind is not significant; however, since it interacts with the speed concept & procedures it does have an effect, especially for the segmented and curved procedures, see Figure 22.

In case of constant-speed approaches (blue solid line) under no-wind there is no difference in vertical deviation RMS among the procedures; however, in case of a 25 kt crosswind it is especially the segmented and the curved procedures where the vertical RMS increases: the lowest RMS (0.25 dots) for the baseline, average (0.35 dots) for the straight single or dual-slope procedures, and largest (0.45 dots) for the segmented and
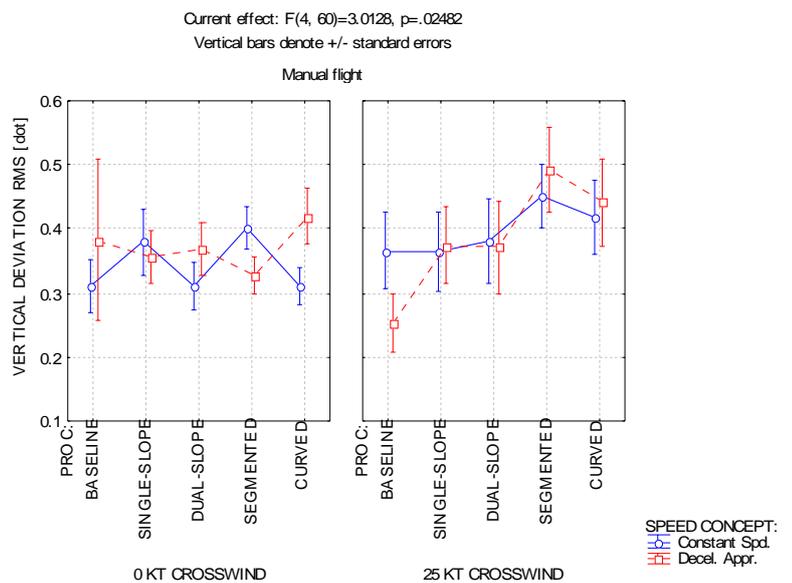

Figure 22 Vertical deviation RMS as function of crosswind per speed concept per procedure in manual flight

27

curved procedures. The crosswind, in combination with the changes in (final) approach track, either through a fly-by turn or a curve, made it much harder for the pilot to maintain the vertical path.

The reduction in vertical deviation RMS for the baseline procedure when having a crosswind, compared to no-wind, is not statistically significant (p>0.1), F(1,15)=1.5999, p=0.225. However, the fact that the vertical deviation RMS in case of 25 kt crosswind for the baseline procedure is lower for a decelerating approach than for a constant-speed approach (see right-hand side of Figure 22), F(1,15)=5.653, p=0.0312, can be explained by the increased airspeed (5 kt added) and the hardly reduced groundspeed on the final segment, making precision flying a little easier with this type of helicopter and associated stabilization equipment (a simple 3-axis SAS).

One could perhaps in general state: the steeper the approach angle (from 6º to 9º to 10º) the larger the RMS in vertical deviation that occurs.

There is a significant (p<0.05) difference between the vertical RMS of the segmented and curved procedures and that of the other procedures for the final approach segment, F(1,15)=24.066, p=0.0019, with the former group having a larger RMS, although the difference is small, operationally speaking. Results are shown in Figure 23. The "average" vertical RMS for the segmented procedure and curved procedures on the FAS is 0.67 dots and 0.64 dots respectively, while for the baseline procedure it is 0.44 dots, 0.47 dots for the straight single-slope procedure, and 0.44 dots for the dual-slope procedure. So these differences are very small indeed. For the straight procedures these values fall within desired performance (0.5 dots), while for the segmented and curved procedures they fall within adequate performance (1.0 dot).
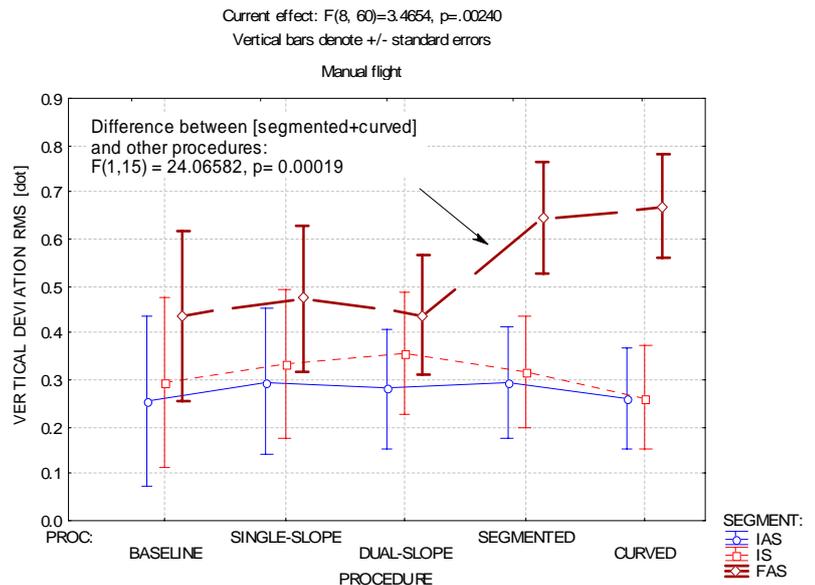

Figure 23 Distribution of vertical dev. RMS over approach segment and procedures – manual flight

7.4.3   Flight Director performance (Test 2)

One way to reduce pilot workload and/or to improve the performance is to provide the pilot with a flight director. For this purpose a FD from an existing rotorcraft was used, but the vertical control laws had to be adjusted in order to achieve satisfactory performance in intercepting the much steeper glideslopes than the FD had originally been designed for (3º). The flight director is a 3-cue FD, providing roll, pitch and collective cues in the sense of the "follow-me". This was contrary to the specification that came with the FD, or the specs for another FD in the S-76 for example. Especially the collective cue was "reversed" in sensing, in that e.g. a collective-*up* command is displayed by the small cueing bar moving *up*, see also Figure 7.

Only the segmented and curved procedures were (also) flown with the flight director.

The two flight performance variables to evaluate for the effect of the flight director are the lateral and vertical deviations (RMS), discussed in the next sections.

7.4.3.1 Effect of flight assist mode on lateral performance

From the ANOVA from Test 2 it turned out that many factors and interactions between factors were significant. The segmented procedure, for example, had smaller RMS deviations than the curved procedure did, although the difference was on average 0.05 dots. The approach segment of course also had a significant effect; most of the changes in the lateral deviation RMS occurred on the final approach segment, while between the initial and intermediate segments there were no significant differences. Adding crosswind increased the lateral deviation RMS on

Figure 24 Lateral RMS as function of flight assist mode for the segmented and curved procedures

average also by 0.05 dots. A perhaps best overview of the effects is given in Figure 24.

The flight director can be seen to reduce the lateral RMS from more than 1 dot on the FAS in case of manual flight to about 0.1 dots with the flight director, quite a reduction in deviation for the curved procedure. When compared to the effect of the flight director on workload, see Figure 18, one may argue that the major contribution of the FD thus was in improving the lateral performance, although also the workload reduced from 'very demanding' to above 'demanding'.

7.4.3.2 Effect of flight assist mode on vertical performance

Similar to the previous section, here a similar evaluation is made of the vertical performance. It was already observed that the vertical performance stayed within the adequate performance range in case of manual flight. Interesting variables to evaluate are the speed concept and the wind, if applicable. It turned out that neither procedure, nor the wind nor the flight assist mode had any main effect (p>0.1) on the vertical deviation RMS. Only the speed concept had a significant (p<0.05) main effect on the vertical RMS, $F(1,12)=4.4051$, p=.05767.
To sum up best perhaps the various effects, the effects of flight assist mode and speed concept are shown in Figure 25. Only for the constant-speed approach did the flight assist mode have a significant (p<0.05) effect on the vertical RMS, $F(1,12) = 8.384$, p=0.01344. With the flight director the vertical deviation RMS reduced on average from 0.35 to 0.25 dots. For the decelerating approaches there was no improvement by the flight director. Again one may notice an increase in vertical deviation RMS when flying a decelerating approach instead of a

constant-speed approach, the increase in RMS being about 0.1 dots on average (from 0.3 dots for a constant-speed approach to 0.4 dots for a decelerating approach).
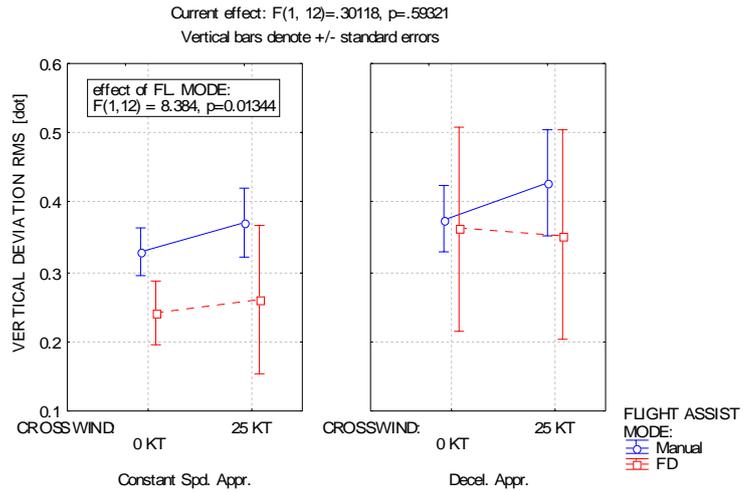
Current effect: F(1, 12)=.30118, p=.59321
Vertical bars denote +/- standard errors

effect of FL MODE:
F(1,12) = 8.384, p=0.01344

Figure 25 Effect of flight assist mode and speed concept on vertical deviation RMS

7.4.4 Guidance display concept effects on vertical deviations (Test 3)

The effect of the vertical guidance display concept on pilot workload has already been discussed in §7.2.3. Because of the function of the information displayed, the most interesting variable that will be affected primarily by this display concept is the vertical deviation RMS on the intermediate segment. The data for the ANOVA was selected from Test 4 data. Only runs with the constant-speed approaches were taken, as in this case the speed reduction is to be made on the intermediate segment.
Main results for the intermediate segment only are shown in Figure 26.

Intermediate segment only
Manual flight
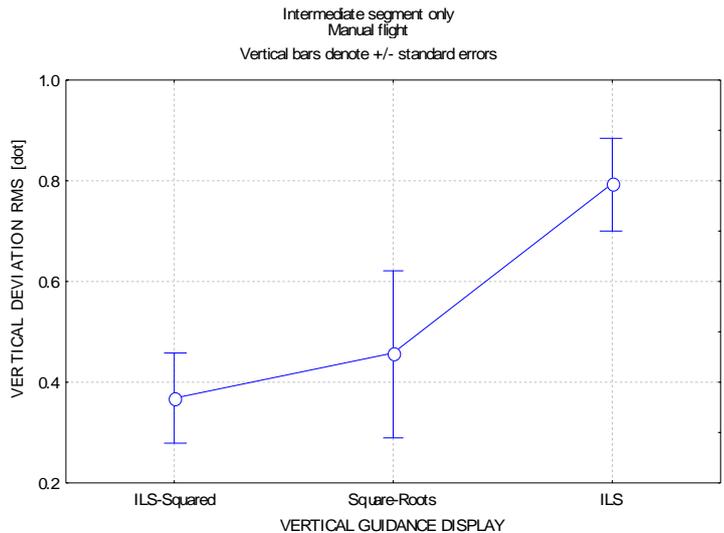Vertical bars denote +/- standard errors

Figure 26 Effect of guidance display on vertical dev. RMS on the intermediate segment, in manual flight

The guidance display type had a highly significant (p<0.01) main effect, $F_{(2,10)}=16.287$, p=.00071. The ILS-squared display had on average the lowest vertical RMS (0.38 dots), the square-roots display was a very good second (0.46 dots), and the ILS (conventional) display had the worst vertical RMS (0.79 dots).
The main effect was significant because it was the ILS display that had a vertical deviation RMS that was worse than the other two guidance display types together. It was obvious that the ILS had to be the worst, as in this case the only guidance the pilot had on the intermediate segment was a non-precision-like set-up, having to use the DME distance to the FAF waypoint to check altitude against tabulated values (in fact there was no guidance at all). The difference in vertical deviation RMS between the ILS-squared and the square-roots display was non-significant (p>0.1) for the intermediate segment, $F_{(1,5)}=0.801$, p=0.412.

30

7.4.5 Height loss in the missed approach (Test 4)

Statistics

A histogram of the distribution of the minimum height in the go-around, for the two classes of constant-speed and decelerating approaches, is shown in Figure *27*. The data was gathered from missed approaches, flown only with a 25 kt crosswind. The fitted normal distributions are also shown. The minimum height (5th percentile) overall was 145.6 ft for constant-speed approaches, and 124.7 ft for decelerating approaches. The corresponding 10^{-6} values (1-tailed) were computed to be 99.6 ft and 53.4 ft respectively.

Constant-Speed appr.: Height = 26*10*normal(x, 169.882, 14.8116)
Decelerating Appr.: Height = 29*10*normal(x, 162.397, 22.9254)

Figure 27 Min. height distribution per speed concept – manual flight

The two distributions, however, are (just) not statistically different from one another, p>0.1 (F(1,45)=2.395, p=.1287), although nearly weakly significantly so. Notice that in the decelerating approach class there were 2 cases that occurred at the very low end of the scale.
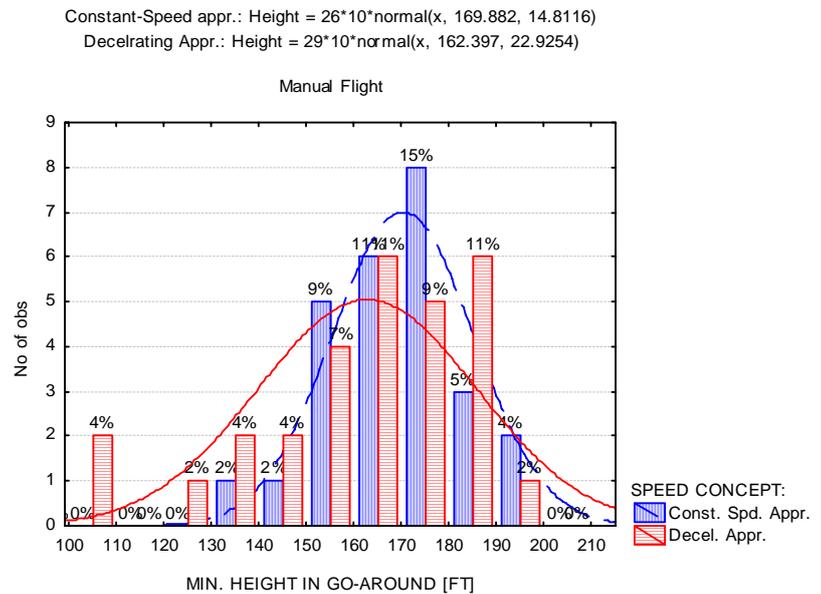
The minimum height in the go-around, or the height loss (= 200 ft – minimum height), was overall independent of the procedure flown, F(4,45)= 1.0449, p=.39478, although, looking in detail, the minimum height achieved with the dual-slope procedure was (almost) significantly less (about 25 ft) than that achieved with the other procedures, especially for decelerating approaches (p<0.05), see Figure 28. Why this is so is not (yet) understood, but likely it has to do with the much lower FAF altitude with this procedure (1000 ft) than with the other

Figure 28 Minimum height in the go-around as function of procedure & speed concept – manual flight

procedures (2000 ft). It was verified that neither the sink rate at the moment of go-around (i.e. at DA/H) nor the ground speed was the cause, so very likely it must have been the piloting control during the go-around maneuver itself.
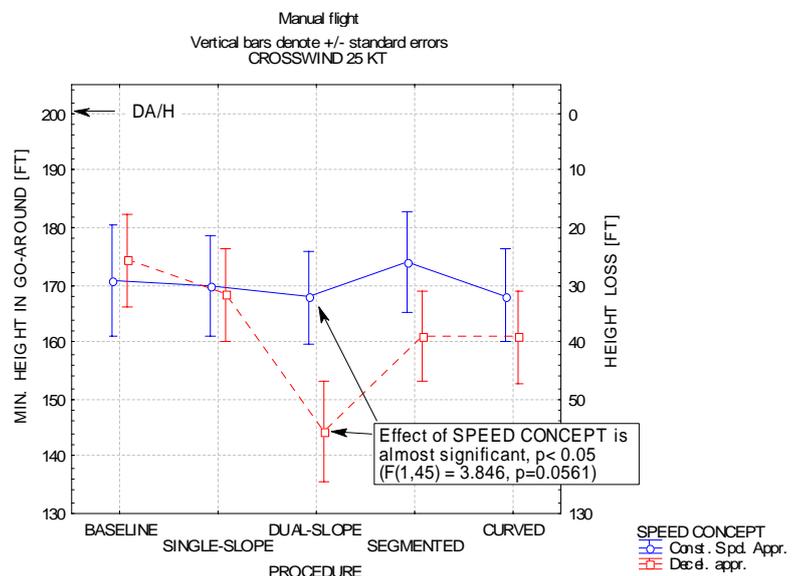
7.4.6 Deceleration rate on the approach

As mentioned in §7.4 the deceleration rate is a procedure design parameter, which will be compared against actual deceleration rates encountered.
For the first two pilots the approach entry airspeed was 150 kt, which had to be reduced to 120 kt on the initial segment. On the intermediate segment this speed had to be reduced further to the final approach speed or to 75 kt, depending upon the speed concept. Because of the first three pilots complaining about the aggressive level of deceleration required to meet the target speeds before the next waypoint, it was decided with the 3d pilot onwards to reduce the entry speed to 120 kt instead, and to also reduce the intermediate approach speed to 100 kt instead. Final approach speed remained as was put in the test plan, but with an additive of 5 kt in case of (cross)wind. The fact that pilots complained about the "high" speed and the "shortness" of the approach segments was already indicative of the aggressiveness in deceleration subjectively experienced. They apparently decelerated at a rate (much) lower than the 1.5 kt/s the procedure had been designed with. The analysis in this section will corroborate this.

The "flight" data has been organized such that per procedure segment the mean, minimum value, maximum value, standard deviation, 25th and 95th percentiles, etc., were obtained of all the parameters registered. As for the deceleration this means, since the deceleration did not occur exactly during one particular approach segment, that the mean value per segment will be less than the actual mean because of the shorter duration of the acceleration than obtained from the approach segment length.
The following 3 measures were taken as an estimate for the "true" mean deceleration value, viz:
- the minimum value. This is the peak negative deceleration on the segment, and is worse than the actual mean value;
- the 25th percentile value. This is the "lower" boundary (0.67-sigma) value of a non-zero mean normally distributed variable;
- the mean value per segment. It is known that this value will underestimate the actual mean deceleration.

The "true" mean deceleration on the segment lies somewhere between these measures, but is expected to be closest to the 25th percentile value.

A grouped ANOVA was performed with 'pilot', 'approach segment (i.e. IAS, IAS, etc.) and 'speed concept' as factors. The wind speed was hypothesized not to have an effect on how the pilot performs a deceleration; this also turned out to be the case. Also the flight director is a factor, in that the FD has a deceleration "program" of 1.5 kt/s built in. Therefore the data set was split up in those cases flown without a flight director and those cases with a flight director (i.e. only the
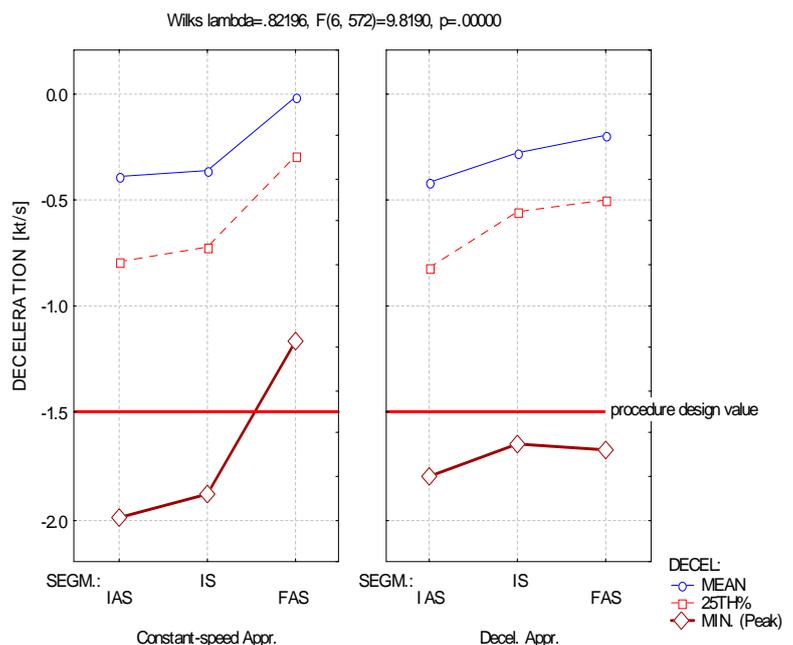

Figure 29 Estimate of deceleration on the approach – manual flight

segmented and curved procedure).

The ANOVA table for the no-FD cases showed many of these factors and interactions between factors to be statistically significant.

The "best overall" important result is shown in Figure 29, where the deceleration is shown as function of speed concept and approach segment for manual flight. There was a highly significant (p<0.01) interaction, F(6,572)=9.8190, p=.00000 between the approach segment and the speed concept, as expected, since the speed concept in fact determines on which segments decelerations take place.

The peak (i.e. minimum) deceleration per segment did indeed meet or exceed the procedure design limit, but this peak value is actually far more than the "average" mean value; that would be closer to the 25th percentile. The 25th percentile data here indicate that the average deceleration used by the pilots was much less (about 2/3) than the value of 1.5. kt/s used in the design of the procedures. Pilots also commented that decelerating at 1.5 kt/s was almost like "going into autorotation", indicating that this deceleration rate can be considered as too aggressive. The pilots' using a lower deceleration rate also explains why they felt in general that the approach segments were too short, since they had a harder time meeting the speed constraints set for the individual segments.

For flights with the FD the mean values were very similar, see Figure 30. The FD had a highly significant (p<0.01) effect of *in*creasing the deceleration, F(3,118)= 29.438, p=.00000, especially the minimum deceleration. It showed values less than or about equal to the procedure design value, more negative than in case of manual flight, while the 25th percentile values were closer to -1 kt/s, so in the end the decelerations with the FD were made a little "quicker" than in case of manual flight, but still at average rates below the procedure's design value.
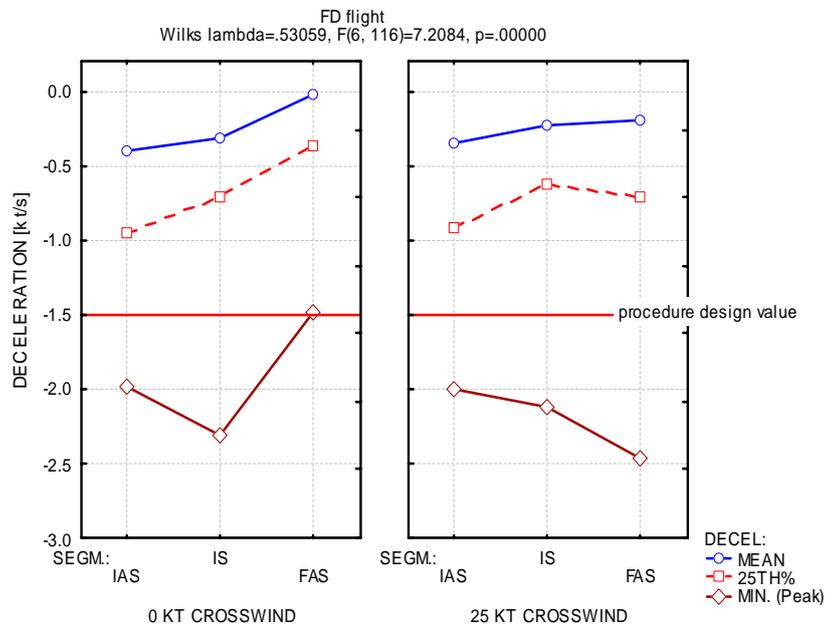

Figure 30 Estimate of deceleration on the approach– FD flight

7.4.7   Vertical deviation RMS as function of glideslope

One of the other interesting trends to determine is whether or not the vertical deviation RMS on the final segment is a function of the glideslope angle, windspeed and/or speed concept. There were 3 glideslope angles involved, viz. 6º for the baseline procedure, 9º for the straight single-slope and dual-slope procedures, and 10º for the segmented and curved procedures.

By re-ordering the data a grouped ANOVA was performed, with GPA (Glide Path Angle), windspeed and speed concept as factors. Only manual flight cases were considered (with the FD only the 10º GPA was tested) and only data for the final approach segment was evaluated.

The resulting ANOVA table showed the GPA to have a highly significant main effect on the vertical deviation RMS, $F_{(2,108)}=6.6586$, $p=.00188$. The values are given in Figure 31, together with a linear extrapolation of the results from 10º up to 12º GPA.

When using the normal distribution for the zero-mean vertical deviation, then when the vertical flight path deviation should stay within ±1 dot for 95 percent of the time (the 95th percentile 2-tailed distribution) the corresponding RMS can be computed to be 0.51 dots, see the line in the figure. This would mean that the 10º glideslope is already too steep to be acceptable for manual flight, and only the aid of a flight director will make this requirement feasible. It should be borne in mind though that the 10º glideslope was also accompanied by a segmented or curved final approach segment, rather than a straight segment, which may have deteriorated the performance.
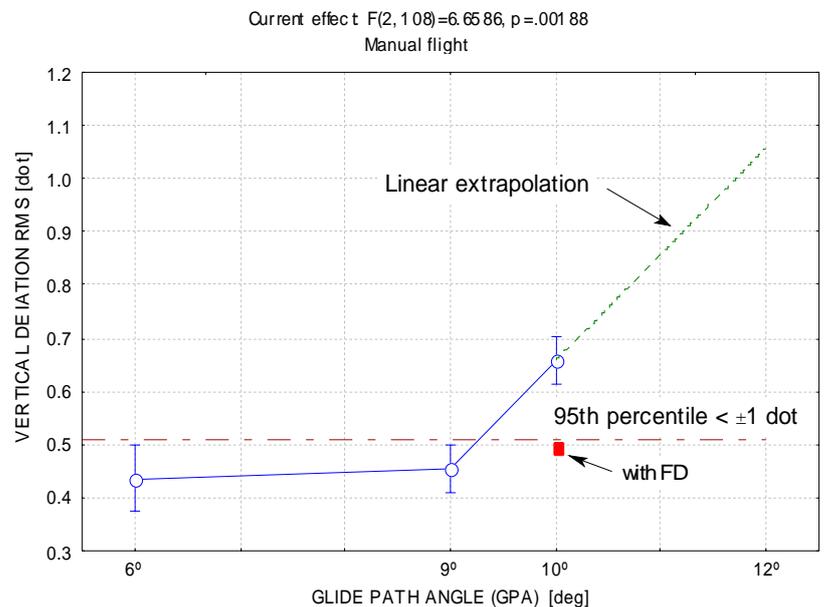

Figure 31 Vertical RMS as function of GPA – manual flight

For the data obtained the RMS values were within the adequate performance level, however, the 10º value exceeds it and extrapolation to 12º is likely to exceed that even further. This indicates a potential flight path accuracy problem when performing manually flown steep approaches with glideslopes of 10º-12º or more.

The speed concept turned out to have a weakly significant ($p<0.1$) main effect on the vertical deviation RMS, $F_{(1,108)}=2.918$, $p=.09047$. Overall the vertical deviation RMS increased from 0.46 dots average for the constant-speed approaches to 0.57 dots for decelerating final approaches, an increase of 0.11 dots. Crosswind had no significant influence at all.
The use of the flight director, which had a significant effect, was to reduce the vertical deviation RMS for GPA = 10º by 0.18 dots, i.e. it reduced this value from 0.66 dots to 0.48 dots. No trend can be drawn since no GPAs other than 10º were involved in the tests with the flight director.

8   CONCLUDING REMARKS AND OUTLOOK

A piloted simulation trial on a fixed-base simulator has been carried out at NLR to evaluate a number of novel, steep straight, segmented or curved rotorcraft IFR procedures. The procedures were laid out for the Schiphol airport. Parameters investigated were among others the speed concept to fly the procedures with, the winds, and also a few vertical guidance displays.
The conclusions are predicated on the limitations inherent in the experiment, i.e. in particular a helicopter model featuring only a rather simple 3-axis SAS, a fixed-base simulator and limitations in terms of displays (e.g. absence of power/torque indications).
In summary the following concluding remarks could be made:

- Curved or segmented procedures are feasible to be made, on the condition that the workload be reduced, e.g. by adding a FD or a level 1 AFCS.
- A vertical path angle (VPA) of 9º is feasible for manual flight, 10º or more is feasible only with a flight director, depending upon accuracy requirements. The maximum VPA limit in fact is determined by the ROD limit of 800 fpm, coupled to the "minimum IFR speed". With the present SAS modeled with the AS365N Dauphin the minimum IFR speed is about 40-45 kt (this would limit the VPA to a maximum of 11.4º). Below this speed the control of speed became quite difficult (due to the rotorcraft being operated in the so-called "second regime", or "backside of the power curve", a region where power required decreases with increasing speed), aggravated by deteriorating handling qualities (heading changes oversensitive to small bank angles) and the need for a heading-hold feature in the control system instead of a ball-centering" mechanism.
- The deceleration rate of 1.5 kt/s for the IFR segment was too high a value to use in designing the segment lengths of a procedure, when flown under manual control. A value of 1.0 kt/s is recommended. For the visual segment a value of 1.5 kt/s is recommended (instead of 2 kt/s).
- The generic curved and segmented procedures are of a different class than the other, straight procedures in terms of workload and performance. Because of more than one turn/curve involved they were more complex than an ultimately designed applicable curved or segmented procedure might be.
- Crosswind had a greater impact in terms of workload and performance, and especially on descent rate, on the segmented and/or curved procedures than on the straight procedures due to the fact that the final approach course was no longer constant but varying. This increased sensitivity needs to be taken into account when designing such procedures, e.g. for an SNI application.
- For the more complex segmented and curved procedures a flight director is required to reduce the workload to tolerable levels and/or to increase performance to adequate levels, certainly in case of (cross)winds.
- The best preferred speed concept is the constant-speed approach, regardless of the procedure.
- There was no clear best vertical guidance display; the standard ILS display scored the worst vertical performance on the intermediate segment, while the ILS-squared and the square-roots displays scored similarly good results. The ILS-squared display also gave additional lateral guidance cues, which was not the case with the square-roots display. Pilots expressed their desire to have both displays available.
- The minimum height loss in the go-around was independent of the type of procedure, and tended to depend on the speed concept: decelerating approaches with a low FAF tended to induce a greater height loss. The minimum height (5th percentile value) was in the order of 145.5 ft for constant-speed approaches, and 124.7 ft for decelerating approaches.

The results of this simulation exercise will be used to refine the design parameters and determine the limits for the application of a SNI procedure at a busy international airport, where these procedures will be embedded within the ATC environment. As a typical airport in case to check out the theoretical feasibility of these procedures, for the OPTIMAL project Schiphol airport has been selected, also because for real-time simulations a suitable ATC/TWR and visual scenery data base is available. Likely the glideslope angle may be reduced from 10º (to about 8º) to make the procedure less sensitive to varying wind directions when a curve is involved. This SNI procedure will be used in further tests scheduled for early 2007, where also ATC and control tower issues will be integrated in the tests to evaluate ATC-related interference issues.

9   ACKNOWLEDGEMENT

10   REFERENCES

[1] McIntosh, D.H., Thom, A.S.: "*Essentials of Meteorology*". Wykeham Publication (London) Ltd, 1969.

[2] Statistica, 1995: "*Volume IV: INDUSTRIAL STATISTICS. Chapter 3: Experimental design*". StatSoft Inc., 1995, ISBN 1-884233-16-3.

[3] McDonnell, J.D., 1968: "*Pilot rating techniques for the estimation and evaluation of handling qualities*". Air Force Flight Dynamics Laboratory Technical Report 68-76, 1968.

[4] Hoh, R. H., Smith, J. C., Hinton, D. A., 1987: "*The effects of display and autopilot functions on pilot workload for Single Pilot Instrument Flight Rule (SPIFR) operations*". NASA 4073, 1987.