SECOND EUROPEAN ROTORCRAFT AND POWERED LIFT AIRCRAFT FORUM

Paper No. 29

AN EXPERIMENTAL STUDY ON A COMBINED OUTSIDE WORLD/INSTRUMENT DISPLAY FOR HELICOPTER OPERATION AT NIGHT AND IN BAD WEATHER

R. Beyer

Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e.V.
33 Braunschweig-Flughafen

September 20 - 22, 1976

Bückeburg, Federal Republic of Germany

Deutsche Gesellschaft für Luft- und Raumfahrt e.V.
Postfach 510645, D-5000 Köln, Germany

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Dipl.-Ing. R. Beyer
Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e.V.
Institut für Flugführung
33 Braunschweig-Flughafen

1. Introduction

The introduction of electro-optical sensors as, for example, a low light level television camera or a forward looking infrared camera as part of a helicopter avionics system may extend the flexibility of helicopter operations at night and in bad weather. It has been shown, however, that a mere addition of an image of the outside world presented on a monitor screen to the conventional instrument panel does not satisfy the pilot's information requirements [1]. The objectives of a joint study between the GAF Helicopter Transport Wing 64 and the DFVLR, therefore, were to investigate in a Bell UH-1D helicopter which instrument displays should be combined with the outside world image and which display format should be chosen to make most efficient use of a combined outside world and instrument display.

2. State of technology

Low light level television or infrared cameras and associated monitors are readily available as well as electronic symbol generators to generate instrument displays on a TV-monitor. Means are available to superimpose both pictures on a monitor screen. Further technological advances as, for example, an augmentation of the perception angle of an infrared camera or an uniform raster format for different electro-optical sensors and electronic symbol generators are still desirable, of course. But it is felt that an appropriate balance between technology and application oriented studies should exist to support advances in both fields. Now that the basic technology of airborne electro-optical sensors exists, questions of the attainable flight performance, of a human engineered display format, of an efficient control of the sensor and the aspects of pilot training and flight safety are of increasing interest.

3. Objectives of the study

The objectives of the study were:

i) to investigate a human engineered instrument display format to be superimposed on the image of the outside world for helicopter operation at night and in bad weather,

ii) to investigate a human engineered control of the electro-optical sensor within given limits as far as the field of view, factor of magnification and line of sight are concerned.

Experiments were provided for various flight profiles and for different control modes of the sensor as, for example, the sensor being fixed to the axes of the helicopter, being pitch-stabilised or looking ahead including roll-stabilisation. For the sake of simplicity, however, the results of the basic experiment only will be presented here. The conditions of the basic experiment were:

> Flight at a demanded height above ground of 150 ft at 80 knots IAS under VMC using the conventional instruments and under simulated IMC using a combined outside world and instrument display only.

A more detailed description of this experiment may be found in [2] .

4. Design of the experiment

The independent variables of the experiment were - in short form -

i) VMC : Flight under VMC using the conventional instruments.

ii) IMC : Flight under simulated IMC using the combined outside world and instrument display only. The top, bottom, side and front windows on the experimental pilot's (left hand) seat were completely obscured while the safety pilot on the right hand seat had supervisory control.

iii) level terrain: Flight over level terrain.

iv) hilly terrain: Flight over hilly terrain.

v) known course : Repeated flights over a course well-known to the pilots from training flights.

vi) unknown course : Single flight over an unknown course. Flight preparation could be made in advance only by means of a map with a scale of 1:50000. During these flights the experimental pilot was assisted by an observer. During flights under simulated IMC identical information was available to the pilot and to the observer, i.e. the combined outside world and instrument display, the clock and the map.

After an adequate period of training 2 pilots made 6 flights per pilot over 2 different types of terrain (level/hilly) under VMC and simulated IMC respectively giving a total amount of 48 flights. The length of each course was approximately 25 kilometers representing approximately 10 minutes flight time. In addition each pilot made 2 flights over unknown courses of an average length of 40 kilometers.

Most of the dependent variables are self-explanatory exept the three parameters following:

$\Delta v_{z,RMS}$ - relative measure representing the average roughness of the terrain (see appendix)

r^2_{φ,ω_z} - the squared product-moment-coefficient of correlation between bank angle φ and yaw rate ω_z representing the proportion of "coordinated flying", i.e. the proportion of the variance of ω_z which is directly correlated with a variation of φ

$\omega^2_{x,RMS}$, $\omega^2_{y,RMS}$, $\omega^2_{z,RMS}$ - relative measure representing pilot strain to control the helicopter in its axes (see appendix)

The analysis of the data sometimes showed statistically significant differences between the two pilots which, however, were operationally insignificant. Therefore the data obtained for each pilot were treated as being samples of a common population. Five data sets were formed characterized by the following variables:

1. known course, level terrain, VMC
2. known course, hilly terrain, VMC
3. known course, level terrain, IMC
4. known course, hilly terrain, IMC
5. unknown course, IMC

and the following comparisons were made:

a) VMC/simulated IMC : Data sets 1+2/3+4
b) level/hilly terrain : Data sets 1+3/2+4
c) known/unknown course: Data sets 3+4/5

The analysis of the difference of means was made on the basis of the H_o - hypothesis (two-tail test).

Subjective data was gathered by pilot interviews and by means of questionnaires to support the interpretation of the objective data.

5. Layout of the display

The layout of the display for the basic experiment, i.e. low level cruise flight under simulated IMC, is shown in fig. 1. The layout of the instrument display was not determined by any limitation of the electronic symbol generator but was designed only according to operational requirements and to human engineering considerations. The outside world sensor was simulated by an ordinary TV camera because the objective of the study was to investigate the appropriate combination of the outside world and instrument displays but not to concentrate on particular sensor characteristics. The product of the field of view (in angular terms) and the factor of magnification of the camera was 14 in azimuth and 11 in elevation and the factor of magnification could be varied between 0.36 and 1.8.

Within these limits the pilots found an optimum condition with a field of view of 28° in azimuth and 22° in elevation and a factor of magnification of 0.5. A factor of 0.5 means that an outside world object is seen by the pilots half as large (in angular terms) on the display as the object being seen directly through the windscreen. The line of sight of the camera was aligned with the longitudinal axis of the helicopter in azimuth but had a depression angle of -6° against the cabin floor of the helicopter which was found to be optimum for a flight condition characterized by $v = 80$ kn IAS, $\vartheta = -2^\circ$ and $h_R = 200$ ft. A TV-system with 625 lines was used and the size of the monitor screen was 17 cm x 13 cm. The luminance of the instrument displays was 800 cd/m^2 at maximum but a value of 600 cd/m^2 was chosen by the pilots. 12 shades of gray were discernible. The instrument displays were presented then with a luminance of 600 cd/m^2 while the maximum luminance of the image of the outside world was one shade of gray below this value.

6. Test results

6.1 Comparison of flights under VMC and simulated IMC

Table 1 presents a comparison of parameters obtained from flights under VMC and simulated IMC regardless of the type of the terrain (level or hilly).

Emphasizing the guidance of the helicopter it can be seen, that under simulated IMC the pilots did not reduce average airspeed compared to VMC flights as it is anticipated sometimes but increased height above ground by 26 %. This may be due to safety requirements as well as to the fact that objects of the outside world are moving more slowly on the screen and therefore for a longer period of time are available for identification and orientation. The increased safety requirements of the pilots flying under simulated IMC may be recognized also by an increase of the minimum height above ground by 26 % and by a decrease of the minimum indicated airspeed by 11 %.

An increase of $\omega^2_{x,RMS}$ by a factor of 29 and an increase of $\omega^2_{y,RMS}$ by 25 % indicate much higher pilot strain when flying under simulated IMC. This may be because a qualitative assessment of pitch and roll and their variation is much easier for the pilots under VMC than it is by means of the display. Increased pilot strain is also indicated by the measure of "coordinated flying" r^2_{φ,ω_z} which drops from 52 % under VMC to 39 % under simulated IMC. A major cause may be the higher and more unsteady activity in roll ($\omega^2_{x,RMS}$) under simulated IMC just mentioned. It is interesting to note that the pilots also allowed an increase of the average bank angle φ_o by 80 % when flying under simulated IMC. The later addition of a slip indicator to the display, however, gave some improvement in this respect.

A significant difference of means for $\omega^2_{z,RMS}$ and $\Delta v_{z,RMS}$ (roughness of the terrain) could not be expected from this analysis because the data sets for level and hilly terrain were combined.

6.2 Comparison of flights over level and hilly terrain

Table 2 presents a comparison of parameters obtained from flights over level and hilly terrain regardless of the flight conditions, i.e. VMC or simulated IMC.

From this table it can be seen that for the flights over hilly terrain there is only a moderate increase of height above ground by 14 % which may be caused by the greater difficulty of the task and by increased safety demands as compared to the flights over level terrain. An increase of $\omega^2_{z,RMS}$ by 41 % and $\omega^2_{y,RMS}$ by 13 % reflects higher pilot strain caused by much more turns to be flown and by the varying slope of the terrain. The different types of terrain are marked by a significant difference of $\Delta v_{z,RMS}$ obtained from flights over both courses.

6.3 Comparison of flights over known and unknown courses

Table 3 presents a comparison of parameters obtained from flights under simulated IMC over well-known and unknown courses.

The pilots responded to the new task of flying over unknown courses in comparison to flights over a well-known course by a reduction of indicated airspeed by 14 % and by a major increase of height above ground which, however, was statistically not significant because of the relatively large variability of height. To a major degree this variability is caused by the somewhat conflicting demands to maintain a certain height:

i) Safety aspects (high altitude)

ii) The need to discern relatively small objects on the ground for navigation (low altitude)

iii) The need for a general view and perspective in the case of a loss of orientation (high altitude)

The greater safety requirements of the pilot are reflected furthermore by an increase of minimum height above ground $h_{R,Min}$ by 56 % and by the reduction of minimum airspeed v_{Min} by 33 %.

An increase of $\omega^2_{z,RMS}$ by a factor of 2,6 marks higher pilot strain because of the much more turns required on the unknown courses. While the magnitude of $\omega^2_{x,RMS}$ dropped by a factor of 43 r^2_{φ,ω_z} reached a maximum of 0.54 compared to all other flights, i.e. an increase of 38 % compared to flights under simulated IMC over a well-known course. This demonstrates that the pilots flew coordinated with respect to roll and yaw but in gentle turns only. This may be due the fact that for a larger than the relatively low indicated airspeed of 36 m/s (70 knots) compared to a demanded airspeed of 80 knots and for rapid yaw movements the danger to lose orientation is much greater than on a well-known course which in each case would stop the experiment.

7. Pilot Training

A special training will be required for pilots once a combined display will be introduced for helicopter operations as discussed here. The following experiences may be of interest in this respect:

In order to achieve safe and uniform flight manoevres under simulated IMC which could be well reproduced approximately 5 hours of flight training were required for each of the two pilots having helicopter flight experience of about 1500 and 3300 flying hours with 10 % of it under IFR. Later in the course of the experiments each pilot flew approximately 30 hours under simulated IMC using the combined display only. After a break of about 5 months 10 training flights with a total flight time of 1.5 hours per pilot were required to re-establish the state of training as it was before the break. Furthermore experiences have shown that a major change of the experimental conditions, i.e. a replacement of the fixed sensor by a steerable sensor or a change from cruise flight to landing approach, an additional training in the order of the refresh training is required.

8. Flight Safety

For some parameters table 4 presents the average limiting values which are arithmetic means of the extreme values measured for each flight. For the same parameters table 5 presents the absolute extreme values. Larger or smaller values than those shown in table 5 did not occur in the course of the 48 flights of the experiment reported here. The results show that all flights were well within safety limits.

9. Summary

The introduction of electro-optical sensors together with a combination of an image of the outside world and the instrument displays shows promise to assist helicopter operations at night and in bad weather. For this purpose a human engineered layout of the instrument displays and of some sensor parameters was investigated. The results of the flight tests have demonstrated that on the whole the pilots were able to fly the helicopter equally well under simulated IMC using the combined display only as under VMC after adequate but not excessive training. Problems of flight safety did not arise. In detail, however, a variation of piloting technique, increased pilot strain and the influence of certain course characteristics could be determined quantitatively by means of significant variations of parameters measured during flights under simulated IMC compared to flights under VMC.

10. Acknowledgement

Special thanks are in order to the staff at DFVLR, in particular to Ing. grad. E. Kohnen (flight test management) and Dipl.-Ing. H.-D. Schenk (data management) and Dipl.-Psych. F.V. Schick of the Technical University of Braunschweig (pilot interviews) as well as to the GAF Helicopter Transport Wing 64 who assigned a helicopter and pilots to the experiment.

11. References

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2. R. Beyer, Untersuchung einer kombinierten Darstellung von Umweltbild und Instrumentenanzeigen in einem Hubschrauber Bell UH-1D. DFVLR IB 153-76-11 (1976).

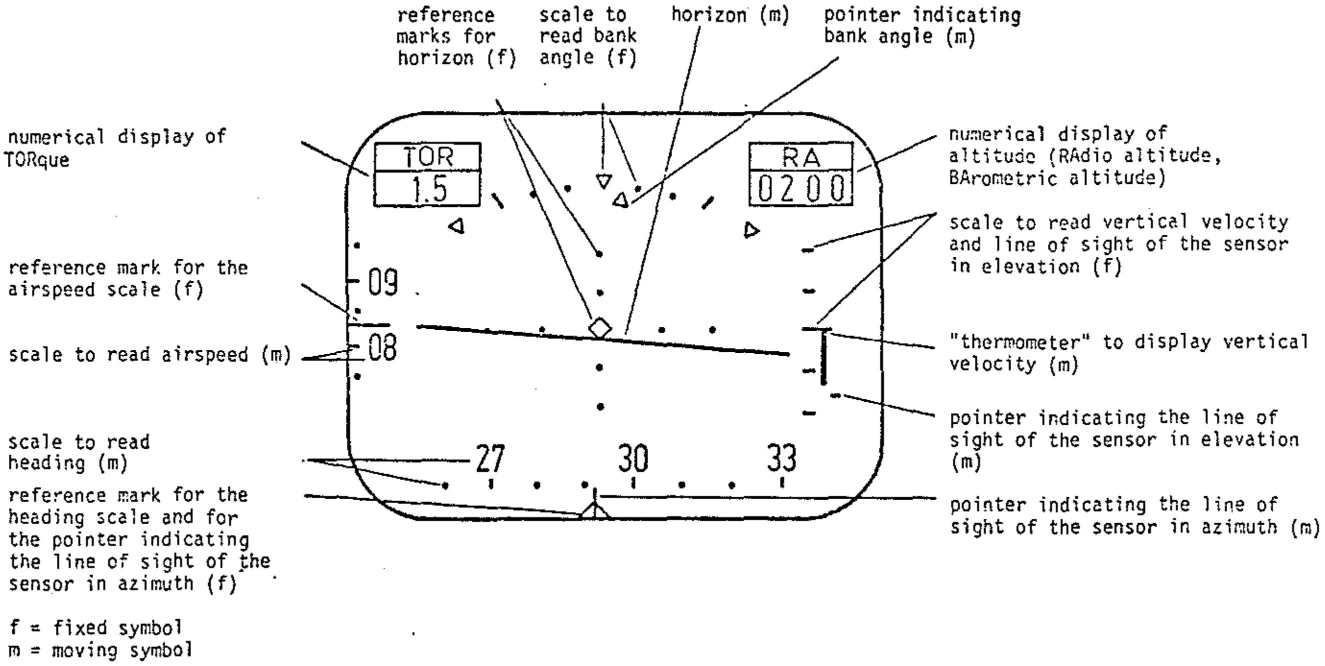


Figure 1: Instrument displays

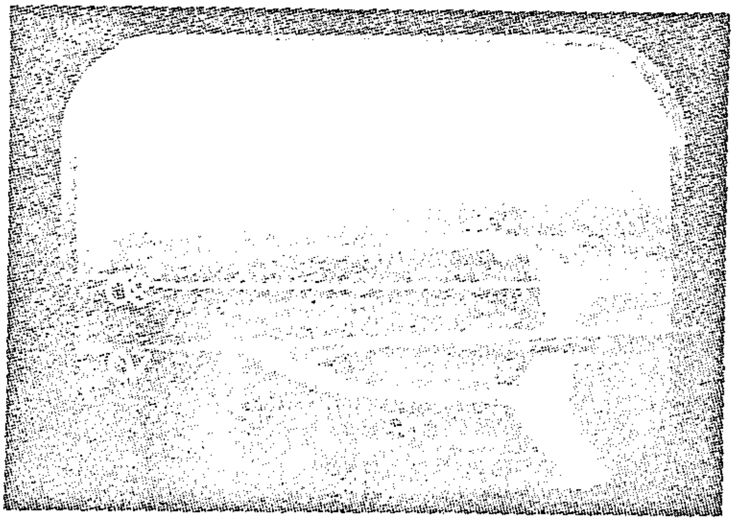
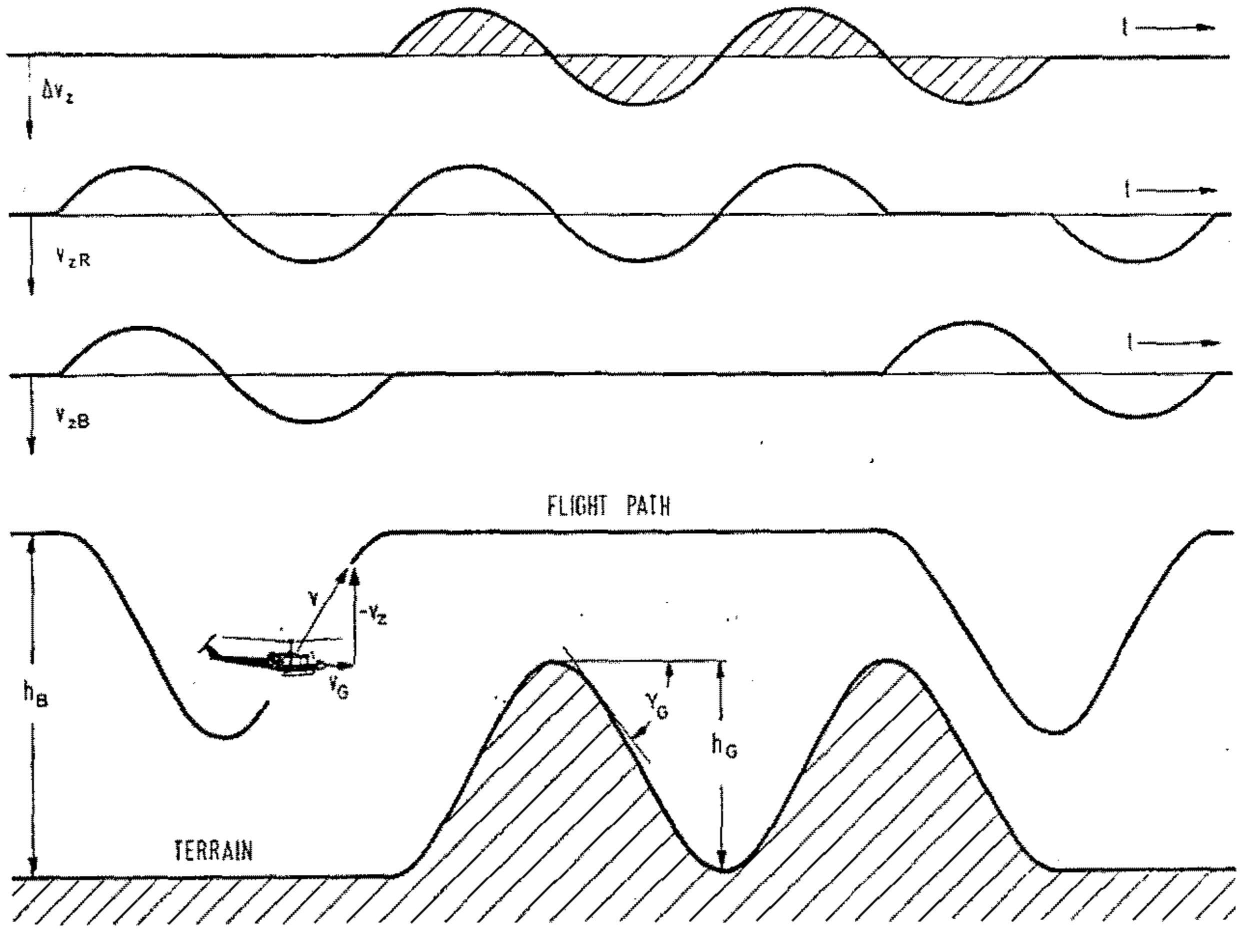


Figure 2: Combined outside world/instrument displays



$$\Delta v_z = v_{zR} - v_{zB} = \left(\frac{dh_B}{dt} - \frac{dh_G}{dt}\right) - \frac{dh_B}{dt} = -\frac{dh_G}{dt}$$

$$\gamma_G = \text{arc tan } \left(\frac{\Delta v_z}{v_G}\right)$$

h_B, v_{zB} - barometric altitude and barometric altitude derived vertical velocity

h_R, v_{zR} - radio altitude and radio altitude derived vertical velocity

h_G - height of rising grounds with reference to the initial point of a course

γ_G - slope of the terrain

Figure 3: Measurement of the roughness of the terrain on the basis of the difference of barometric altitude and radio altitude derived vertical velocities

		known course		
parameter	dim.	VMC (level, hilly terrain)	Simulated IMC (level, hilly terrain)	error probability
v	m/s	43.6 (2.6)	41.9 (1.8)	< 2 o/o
h_R	m	53.8 (5.4)	67.9 (12.7)	< 1 o/oo
φ	deg	- 1.5 (0.4)	- 2.7 (0.5)	< 1 o/oo
$\omega^2_{x,RMS}$	$(deg/s)^2$	0.06 (0.02)	1.72 (1.7)	< 1 o/oo
$\omega^2_{y,RMS}$	$(deg/s)^2$	0.73 (0.2)	0.91 (0.1)	< 1 o/oo
$\omega^2_{z,RMS}$	$(deg/s)^2$	1.02 (0.49)	1.17 (0.29)	
v_{Min}	m/s	35.0 (2.9)	31.3 (3.8)	< 1 o/oo
$h_{R,Min}$	m	24.7 (5.0)	31.1 (6.6)	< 1 o/oo
r^2_{φ,ω_z}	-	0.52 (0.09)	0.39 (0.09)	< 1 o/oo
$\Delta v_{z,RMS}$	m/s	2.76 (0.71)	2.62 (1.22)	

Table 1: Comparison of parameter means obtained from flights under VMC and simulated IMC on a known course regardless of the type of the terrain. Number in parantheses: standard deviation

		known course				
parameter	dim.	level terrain (VMC, sim. IMC)		hilly terrain (VMC, sim. IMC)		error probability
v	m/s	43.0	(2.5)	42.5	(2.2)	
h_R	m	56.9	(11.2)	64.7	(11.8)	< 5 o/o
φ	deg	- 2.2	(0.7)	- 2.1	(0.8)	
$\omega^2_{x,RMS}$	$(deg/s)^2$	0.76	(1.2)	1.02	(1.6)	
$\omega^2_{y,RMS}$	$(deg/s)^2$	0.76	(0.19)	0.87	(0.16)	< 5 o/o
$\omega^2_{z,RMS}$	$(deg/s)^2$	0.91	(0.3)	1.28	(0.41)	< 2 o/oo
v_{Min}	m/s	33.8	(4.2)	32.5	(3.4)	
$h_{R,Min}$	m	28.6	(5.4)	27.2	(7.7)	
r^2_{φ,ω_z}	-	0.46	(0.12)	0.46	(0.11)	
$\Delta v_{z,RMS}$	m/s	2.18	(0.74)	3.19	(0.96)	< 1 o/oo

Table 2: Comparison of parameter means obtained from flights over level and hilly terrain on a known course regardless of the conditions of flight, i.e. VMC or simulated IMC. Number in parentheses: standard deviation

		simulated IMC				
parameter	dim.	known course		unknown course		error probability
v	m/s	41.9	(1.8)	36.0	(1.4)	< 5 %
h_R	m	67.9	(12.7)	103.5	(41.0)	
φ	deg	- 2.7	(0.55)	- 3.4	(0.7)	
$\omega^2_{x,RMS}$	$(deg/s)^2$	1.72	(1.7)	0.04	(0.01)	< 2 %
$\omega^2_{y,RMS}$	$(deg/s)^2$	0.91	(0.11)	1.06	(0.2)	
$\omega^2_{z,RMS}$	$(deg/s)^2$	1.17	(0.29)	3.10	(0.7)	< 2 %
v_{Min}	m/s	31.3	(3.85)	21.0	(3.8)	< 2 %
$h_{R,Min}$	m	31.1	(6.6)	48.5	(15.6)	< 5 %
r^2_{φ,ω_z}	-	0.39	(0.09)	0.54	(0.08)	< 5 %
$\Delta v_{z,RMS}$	m/s	2.62	(1.22)	2.26	(1.5)	

Table 3: Comparison of parameter means obtained from flights under simulated IMC over known and unknown courses. Number in parentheses: standard deviation

			average limiting values			
			level terrain		hilly terrain	
parameter	dim.	limit	VMC	sim. IMC	VMC	sim. IMC
v	m/s	lower	35.7	32.0	34.3	30.6
v	m/s	upper	47.0	48.0	49.7	47.3
h_R	m	lower	26.8	30.4	22.6	31.7
h_R	m	upper	88.1	107.0	119.1	143.4
ϑ	deg	lower	- 3.3	- 3.8	- 3.4	- 4.3
ϑ	deg	upper	5.9	5.3	5.3	5.8
φ	deg	lower	-17	- 16	- 24	- 21
φ	deg	upper	17	13	18	13
ω_z	deg/s	lower	- 3.2	- 3.8	- 5.6	- 4.7
ω_z	deg/s	upper	4.7	4.0	4.5	4.2

Table 4: Average limiting values of parameters obtained from flights on known courses under VMC and simulated IMC

extreme values			
parameter	dim.	extreme	magnitude
v	m/s	minimum	24.0
v	m/s	maximum	52.0
h_R	m	minimum	15.8
h_R	m	maximum	275.1
ϑ	deg	minimum	- 7.9
ϑ	deg	maximum	18.2
φ	deg	minimum	- 45
φ	deg	maximum	42
ω_z	deg/s	minimum	- 10.4
ω_z	deg/s	maximum	9.4

Table 5: Extreme values of flight parameters obtained from 48 flights under VMC and simulated IMC over level and hilly terrain on a known course (2 pilots)

Notation

A - mechanical work
h_B - barometric altitude
h_G - height of rising grounds with reference to the initial point of a course
h_R - radio altitude
IAS - indicated airspeed
IMC - instrument meteorological conditions
m - mass
t - Torque
r - product-moment-coefficient of correlation, distance
t - time
T - duration of test
v - velocity
v_{Min} - minimum indicated airspeed
v_G - ground speed
v_{zB} - vertical velocity derived from barometric altitude
v_{zR} - vertical velocity derived from radio altitude
VMC - visual meteorological conditions
α - angle of rotation
γ_G - slope of terrain
ϑ - pitch angle
φ - roll angle
Θ - moment of inertia
ω - angular velocity
ω_x - roll rate
ω_y - pitch rate
ω_z - yaw rate

Appendix

1. Average roughness of the terrain

The average roughness of the terrain may be determined by (see fig. 3)

v_{zR} - vertical velocity derived from radio altitude
v_{zB} - vertical velocity derived from barometric altitude
h_B - barometric altitude
h_G - height of rising grounds with reference to the initial point of a course

Furthermore

$$-\frac{dh_G}{dt} = v_G \cdot \tan \gamma_G$$

v_G - ground speed
γ_G - slope of the terrain with reference to the horizontal plane

An effective slope of the terrain may be defined as

$$(\tan \gamma_G)_{eff} = \sqrt{\frac{1}{T} \int_0^T \left[\frac{-dh_G/dt}{v_G}\right]^2 dt} = \sqrt{\frac{1}{T} \int_0^T \tan^2 \gamma_G \, dt}$$

or

$$\gamma_{G,eff} = \text{arc tan} \sqrt{\frac{1}{T} \int_0^T \tan^2 \gamma_G \, dt}$$

As it was not possible to determine v_G

$$\Delta v_{z,RMS} = \sqrt{\frac{1}{T} \int_0^T \left[v_{zR} - v_{zB}\right]^2 dt} = \sqrt{\frac{1}{T} \int_0^T \left[-\frac{dh_G}{dt}\right]^2 dt}$$

was calculated which represents the effective rate of descent of the terrain. If v_G is maintained almost constant $\Delta v_{z,RMS}$ may serve as a measure for the average roughness of the terrain.

2. Control of the helicopter in its axes

In an unstabilised helicopter pilot strain may be regarded as directly related to the (mechanical) work A required for a rotation of the vehicle in its axes:

$A = M\alpha$
M - torque
α - angle of rotation

The total amount of work may be calculated as the sum of units of work dA:

$$dA = M\,d\alpha = m\,\frac{dv}{dt}\,r\,d\alpha$$

m - mass
v - tangential velocity at distance r from the center of rotation

$$\frac{d\alpha}{dt} = \omega \qquad dv = r \,.\, d\omega \qquad \Theta = mr^2$$

ω - angular velocity
Θ - moment of inertia

$$dA = mdvr\omega = mr^2\omega d\omega = d\,(mr^2\,\frac{\omega^2}{2}) = d\,(\frac{\Theta}{2}\,\omega^2)$$

For Θ = const. the average value of A may be calculated:

$$\bar{A} = \frac{\Theta}{2}\left[\frac{1}{T}\int_0^T \omega^2\,dt\right]$$

T - duration of test

And for

$$\omega^2_{RMS} = \frac{1}{T}\int_0^T \omega^2\,dt$$

it is

$$\bar{A} = \frac{\Theta}{2}\,\omega^2_{RMS}$$

For Θ = const. and for nearly constant friction loads (to be assumed for a nearly uniform progress of flights which can be examined by means of the flight parameters) and for $\bar{\omega} \approx 0$ the value of ω^2_{RMS} may be taken as a relative measure for pilot strain caused by the control of the work A required to control the helicopter in its axes.