Simulator Studies of Methods of Computing and Displaying the Velocity Vector in a Head-up Display for Low Speed Flight Path Control

LENNART NORDSTRÖM and HÅKAN ARNE
Saab Aktiebolag, Linköping, Sweden

SUMMARY

A new head-up display presenting the flight situation indicates the desired flight path by a perspective pole-track and the actual flight path by a velocity vector symbol. Specific display-control problems for low speed flight depend on flight dynamics and large angles of attack. In a simulator experiment, pilot performance and rating were about twice as good with a dynamically correct velocity vector than with one locked to the aircraft laterally assuming zero sideslip. This experiment and other studies concerning velocity vector versus attitude information and quickening are part of a programme to develop the pole-track display for the 37 Viggen aircraft.

1. Introduction

The head-up display

The simulator studies reported in this paper are part of a programme to develop the pole-track display, a new type of head-up display for flight path control, especially for low altitude flight including landing. The 37 Viggen aircraft is equipped with such a display. The head-up display provides a means of displaying flight data information collimated in front of the pilot at eye level and superimposed on the outside world when this is visible. The possibilities of the head-up display of improving flight safety are worth mentioning. In spite of auto-throttle, stability augmented control systems, and other new aids most aeroplanes still require a good deal of pilot skill to be safely controlled in a landing approach. Also when the flying qualities are supposed to be acceptable the pilot work load can be very high in a category 2 landing with a decision height of 100 feet and 1200 feet runway visual range. With proper information displayed in a proper and accurate way the head-up display has the potential of improving handling qualities and accuracy of flight path control, and of reducing pilot work load in instrument flight, visual flight, and transition between these flight modes.

The pole-track display

Before we turn to the specific studies of this paper it seems appropriate to describe briefly the basic principles of the pole-track display[1]. The flight situation is presented in an integrated way by means of a few easily interpreted symbol configurations. The desired flight path is indicated by a space stabilised perspective pole-track and the actual flight path by a velocity vector symbol, Fig. 1. The pole-track consisting of six vertical poles and an aiming dot constitutes a model of the outside world in a natural angular scale 1:1. The velocity vector is displayed in the same scale and is thus pointing in the flight path direction. The vertical poles in combination with a pair of reference height poles adjacent to the outermost height poles and representing 100 metres supply height information in relation to the desired flight path and in relation to the ground, the latter represented by the bottom level of the poles. The perspective of the pole-track depends upon the height situation.

Figures 1–5 illustrate the principles. In Fig. 1, the aircraft is flying straight and level and at the top level of the poles indicating in this example a desired height of 200 metres. There is no lateral change of perspective of the pole-track. The distance between the poles is one degree. Figure 2 shows the aircraft below the desired height and climbing at 1·5°. Present altitude indicated by the intersections of the horizon line with the height poles is 150 metres. In Fig. 3, the aircraft is above the desired flight path and diving at 3°. Present altitude is 300 metres. Azimuth flight path errors are indicated as in Fig. 4. The desired flight path is 2° to the right of the actual one. So far the pole-track has been described as horizontal with the aiming dot on the horizon line. Applications are used for navigational flight modes. For landing approaches the same basic display principles can be used, the only alteration being that the pole-track has been moved to about 3° below the horizon line in order to indicate the desired glide path (Fig. 5).

This display has an important similarity to some landing displays in a research programme proposed by R. Baxter to be carried out by the Blind Landing Experimental Unit of the Royal Aircraft Establishment at Bedford. Basic features in common are a space stabilised outside world model and a

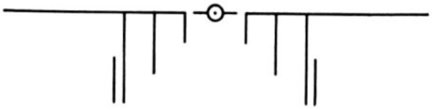

FIG. 1 — Level flight on desired flight path and height 200 m

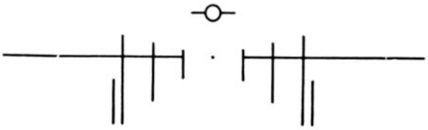

FIG. 2 — Below desired flight path and climbing at 1·5°.
Present altitude 150 m

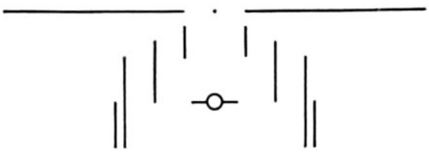

FIG. 3 — Above desired flight path and diving at 3°.
Present altitude 300 m

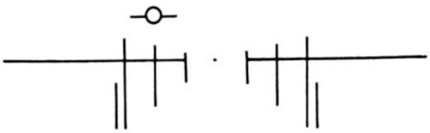

FIG. 4 — Azimuth flight path error 2°, otherwise
same as Fig. 2

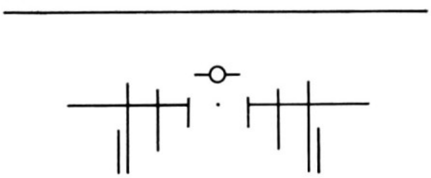

FIG. 5 — Landing mode of the pole-track display

velocity vector in natural angular scale 1:1 to indicate the flight situation, but in other respects there are differences.

Man–machine problems regarding the pole-track display

A great number of various man–machine problems have been included in the research and development of the pole-track display concerning all the components in a closed-loop system, the display, the pilot, the controls, and the aircraft. Examples are the effect of pilot work load, accuracy of sensors and computing devices, wind turbulence, cross-wind, and flight dynamics. The problems discussed in this paper concern the velocity vector and low speed flight path control of an aircraft with a large angle of attack. A correct and a simplified method of computing and displaying the velocity vector are compared. It is also discussed whether the true velocity vector is an optimum directional information for low speed flight path control, comparison being made with flight attitude and quickened velocity vector information.

Specific velocity vector problems

The height poles and the velocity vector provide a very efficient combination of positional and directional information regarding the vertical flight situation. In the lateral plane there is no positional information, though this can be obtained by varying the pole-track perspective laterally. However, this information has been considered to be of little importance. Another reason for keeping the pole-track symmetric is to achieve simplicity regarding symbol generation and legibility.

If the directional information of the velocity vector is divided into components it may be argued that the vertical component is more important than the lateral one. At a certain stage in the development of the display it was discussed whether a simplification neglecting sideslip could be introduced in the lateral direction in order to reduce control law complexity.

The space stabilised pole-track can be positioned in the display field of view by signals from a gyro platform representing the attitude angles θ, ψ, and ϕ (Fig. 6). There are also other methods. It is more complex to produce the velocity vector symbol, V, as the sensing and computing of the angle of attack, α, and the angle of sideslip, β, is required. The computing has to include noise filtering because of wind turbulence and compensation for the lag introduced by the filter. Because of the sensing and computing problems a simplification that neglects the angle of sideslip was desirable. A simulator experiment was carried out in order to answer the following question.

Question 1: What is the advantage of displaying a dynamically correct velocity vector compared to one locked to the aircraft laterally assuming zero sideslip?

Further discussions on methods for low speed flight path control led to experiments regarding the following questions.

Question 2: What is the advantage of displaying a dynamically correct velocity vector compared to an attitude symbol fixed to the aircraft and depressed by the trimmed angle of attack?

Question 3: What is the optimum directional information in the pole-track display for low speed flight path control?

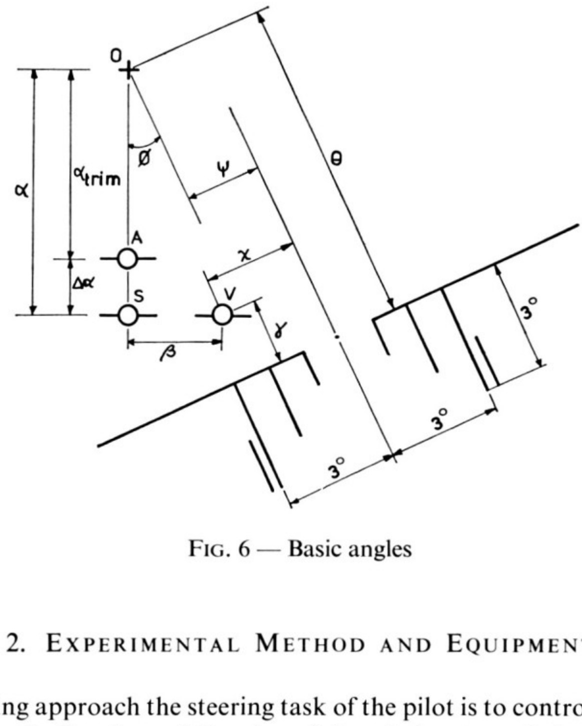

FIG. 6 — Basic angles

2. Experimental Method and Equipment

In a landing approach the steering task of the pilot is to control the position and flight path direction of the aircraft in relation to a desired glide path. Instead of studying a landing approach and this type of combined control task, an experimental layout was used that simplified the simulator equipment and made it possible to study the effect of display methods on different steering tasks. Thus the flight missions used in the experiments were composed of the following subtasks to be mainly performed in horizontal flight.

Subtask *A*: To control height and azimuth flight path angle.
Subtask *B*: To control height in horizontal turns.
Subtask *C*: To control vertical and azimuth flight path angles.

The altitude range was between 75 and 150 metres and the height commands did not exceed 25 metres. Directional commands were within 3 and 5° for the vertical and azimuth flight path angles, respectively.

The main components of the simulator equipment are shown in a block diagram (Fig. 7). They are briefly described below.

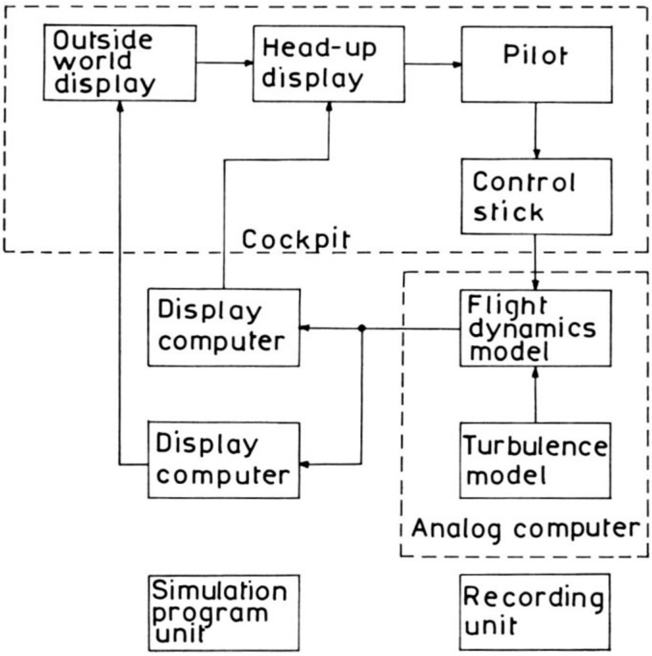

FIG. 7 — Block diagram of flight simulator

Flight dynamics

The flight dynamics model used represents a high performance aircraft flying at low altitude and constant speed. Two versions of the model can represent either a difficult system, *D*, or a moderate one, *M*. The classification concerns handling qualities. Some characteristic data are summarised in Table 1 for two of the flight speeds investigated, $M=0{\cdot}16$ and $M=0{\cdot}20$. The most significant differences between the two systems are as follows, the comparison being made at the flight speed $M=0{\cdot}16$. In pitch the short period undamped natural frequency is 0·2 and 0·3 c.p.s., and the short period damping ratio 0·5 and 0·6 for the difficult and moderate systems, respectively. The Dutch-roll damping ratio is 0·12 and 0·35 for the two systems.

TABLE 1.

SOME CHARACTERISTIC DATA OF THE FLIGHT DYNAMICS MODEL

Parameter	*Dimension*	*System D*	*System M*	
		$M=0{\cdot}16$	$M=0{\cdot}16$	$M=0{\cdot}20$
Trimmed angle of attack	degrees	18	18	11
Short period undamped natural frequency, pitch	cps	0·2	0·3	0·4
Short period damping ratio, pitch		0·5	0·6	0·6
Short period lead time constant, pitch	sec	2	2	1·8
Dutch-roll undamped natural angular frequency	rad/sec	2	2	2
Dutch-roll damping ratio		0·12	0·35	0·40
Roll to equivalent side velocity ratio at Dutch-roll frequency	rad/m/sec	0·044	0·035	0·035
Aileron exitation of sideslip $(\omega_\phi/\omega_d)^2$		0·40	~1	~1
Roll-subsidence time constant	sec	1·2	0·7	0·7
Spiral-mode time constant	sec	15	15	18

Wind turbulence

Wind turbulence was introduced as increments to the angle of attack and the angle of sideslip by two independent signals from white noise generators shaped by filters having the following transfer function.

$$Y=\frac{sT}{1+sT}\cdot\frac{k}{1+sT}$$

where $T=5$ sec and k is a constant.

The low pass filter represents the turbulence model, the high pass filter has the purpose of cutting off very low frequencies to avoid zero drift problems. The turbulence level was adjusted to 1·5 m/sec, which has a probability of occurrence of about 10 %.

Cockpit

The fixed cockpit was equipped with a head-up display system including a display unit at eye level of the pilot and, at the same level, an outside world display unit. The latter can generate symbolic patterns representing the outside world. The pictures from the two displays are observed superimposed at an infinite distance. In these experiments the outside world display was simple, a horizon line and two lines representing a long straight road displayed in a correct perspective. The only control for the pilot was a spring loaded control stick for pitch and banking manoeuvres.

Recording equipment and simulation programme unit

By means of special recording equipment variables of interest were measured and recorded in a digital form suitable for further treatment in digital computers. Analog recorders were also used for monitoring purposes. A digital simulation programme unit was used to control the experiment, including the pilot's flight missions and subtasks, recordings, etc.

Procedure

Six test pilots participated as subjects in the experiments. Each pilot had to perform a five-minute flight mission for each of the configurations investigated. The different configurations, introduced in random order, were grouped into series lasting about 45 minutes. Before such a series the pilot had one hour of training and instruction, when also actual problems were introduced.

The five-minute flight mission was composed of ten 30-second periods. In the last nine periods the three subtasks were introduced, three times each at random order. Height and directional commands were introduced in the beginning of a period. Also in subtask *B* there were commands to make horizontal turns, introduced as azimuth flight path commands, three times in a period. The type and size of the subtask was indicated by the display, but the subjects were not informed of the configurations introduced.

During the last 8 seconds of each period the absolute mean values of the following variables were measured.

Δh height error of the aircraft
$\Delta \chi$ azimuth flight path error of the aircraft
$\Delta \gamma$ vertical flight path error of the aircraft
$\dot{\chi}$ rate of change of azimuth flight path angle
$\dot{\gamma}$ rate of change of vertical flight path angle
α angle of attack (in experiment 2 and 3)
β angle of sideslip (in experiment 2 and 3).

In order to get a relative measure of the steering difficulties experienced by the subjects, the pilots were instructed to estimate, after each flight mission, the total difficulty of the task in relation to the difficulty of a standard configuration, presented first in a series of configurations and also every five times. The difficulty of the standard was marked 10. Mark 20 was to be used when the actual configuration was twice as difficult as the standard, mark 5 when it was half as difficult, and so on.

3. Results and Discussions

Some results of the simulator experiments are summarised in Figs. 8–12, presenting measured positional and directional errors of the aircraft in relation to the desired flight path in two of the subtasks, *A* and *C*, and pilot ratings, reflecting the difficulties experienced by the subjects. Mean values of the performance variables and ratings are presented — as columns — and standard errors of the means. There are 18 observations behind each mean except for the pilot ratings, where there are 6. More complete data from the experiments including the rate of changes of the flight path angles, $\dot{\gamma}$ and $\dot{\chi}$, the angle of attack, α, and the angle of sideslip, β, are presented in Table 2.

Experiment 1

In the first experiment the true velocity vector and the simplified one locked to the aircraft laterally neglecting sideslip were compared for three combinations of flight dynamics and flight speed, namely the difficult and moderate systems at $M=0{\cdot}16$ and the moderate system at $M=0{\cdot}20$. Typical results are those for the difficult system and $M=0{\cdot}16$ in Fig. 8. There is a very significant difference between the results for the true and the simplified velocity vector to the advantage of the true one. The difference is similar for the other system and flight speed investigated (Figs. 9 and 10). In all three cases the average effect of the simplification of the velocity vector is that height errors and directional flight path errors have doubled and steering difficulties indicated by pilot ratings have trebled.

The results of the first experiment clearly indicate that the proposed simplification cannot be accepted. The velocity vector should be computed and displayed correctly for the pole-track head-up display in order to provide a suitable means for low speed flight path control.

The reason for the different results obtained for the true and the simplified velocity vector is a difference in dynamical behaviour in banking manoeuvres. When the aircraft is banked it rotates about a principal axis, which is close to the reference axis of the angle of attack, point *O* in Fig. 6. At first the aircraft, due to inertia, tends to maintain the flight path direction indicated by the true velocity vector, *V*. This causes a sideslip. If the aircraft could be banked instantaneously with an angle ϕ the angle of sideslip would be $\beta=\alpha\,.\,\sin\phi$, where α is the angle of attack. Gradually, of course, the sideslip angle is reduced to zero. This means that in steady state conditions there is no difference between the two display methods.

The true velocity vector indicates the flight path direction correctly, also in a banking manoeuvre. The simplified velocity vector on the other hand, neglects sideslip and will therefore falsely indicate an initial change of the

TABLE 2A. MEAN VALUES (divide all values by 100 except ratings)

		Exp. 1; Fig. 8 $M=0\cdot16$; *system D*				*Exp. 1*; Fig. 9 $M=0\cdot16$; *system M*				*Exp. 1*; Fig. 10 $M=0\cdot20$; *system M*				*Exp. 2*; Fig. 11 $M=0\cdot18$; *system M*				*Exp. 3*; Fig. 12 $M=0\cdot18$; *system M, D*			
Display		*V*	*S*	*V*	*S*	*V*	*S*	*V*	*S*	*V*	*S*	*V*	*S*	*V*	*A*	*V*	*A*	*V*	*Q*	*V*	*Q*
Turbulence		0	0	1·5	1·5	0	0	1·5	1·5	0	0	1·5	1·5	0	0	1·5	1·5	0	0	0	0
	Subtask																				
Δh m	*A*	193	492	229	623	316	612	405	638	412	342	370	429	349	425	330	540	239	255	398	253
$\Delta\chi^{\circ}$	*A*	55	94	72	198	35	91	53	119	32	60	48	118	20	32	42	39	13	14	31	35
$\dot{\gamma}$ deg/sec	*A*	13	18	29	30	6	8	22	23	7	8	25	28	11	10	30	29	9	9	61	44
$\dot{\chi}$ deg/sec	*A*	17	28	29	50	13	28	26	39	13	27	25	44	28	25	43	37	19	21	25	35
α°	*A*													20	17	86	52	14	15	81	78
β°	*A*													46	46	106	116	31	35	52	85
Δh m	*B*	287	358	427	358	308	491	362	468	319	384	398	534	283	424	361	640	185	275	392	448
$\Delta\gamma^{\circ}$	*C*	14	33	34	50	11	28	38	53	5	14	47	63	10	21	27	16	9	7	44	27
Rating	*A–C*	4	16	17	34	3	15	10	29	4	10	10	18	5	6	10	12	5	5	24	13
Standard	*A–C*	same as in Fig. 9						×				×				×		same as in Fig. 11			

TABLE 2B. STANDARD ERRORS OF THE MEANS (divide all values by 100)

		Exp. 1; Fig. 8 $M=0\cdot16$; *system D*				*Exp. 1*; Fig. 9 $M=0\cdot16$; *system M*				*Exp. 1*; Fig. 10 $M=0\cdot20$; *system M*				*Exp. 2*; Fig. 11 $M=0\cdot18$; *system M*				*Exp. 3*; Fig. 12 $M=0\cdot18$; *system M, D*			
Display		*V*	*S*	*V*	*S*	*V*	*S*	*V*	*S*	*V*	*S*	*V*	*S*	*V*	*A*	*V*	*A*	*V*	*Q*	*V*	*Q*
Turbulence		0	0	1·5	1·5	0	0	1·5	1·5	0	0	1·5	1·5	0	0	1·5	1·5	0	0	0	0
	Subtask																				
Δh m	*A*	32	106	37	133	95	147	53	119	66	66	36	40	53	69	32	76	45	55	64	76
$\Delta\chi^{\circ}$	*A*	13	17	11	12	10	16	4	14	3	8	4	12	3	9	5	9	2	2	4	6
$\dot{\gamma}$ deg/sec	*A*	2	4	2	4	1	1	1	2	1	1	1	2	2	1	1	2	1	2	7	10
$\dot{\chi}$ deg/sec	*A*	2	6	3	5	2	5	1	3	1	4	2	5	3	3	3	4	2	2	2	6
α°	*A*													3	3	6	6	2	3	12	17
β°	*A*													6	5	8	2	2	3	5	16
Δh m	*B*	44	53	81	57	61	109	30	80	44	62	45	71	43	57	35	85	35	43	50	97
$\Delta\gamma^{\circ}$	*C*	2	10	2	7	2	6	2	8	1	4	7	11	1	12	2	1	2	1	6	5
Rating	*A–C*	39	508	199	985	172	410	0	995	72	434	0	434	146	183	0	428	167	207	327	378
Rating	*A–C*	36	384	176	765	109	319	0	743	60	299	0	350	115	141	0	313	131	144	282	285

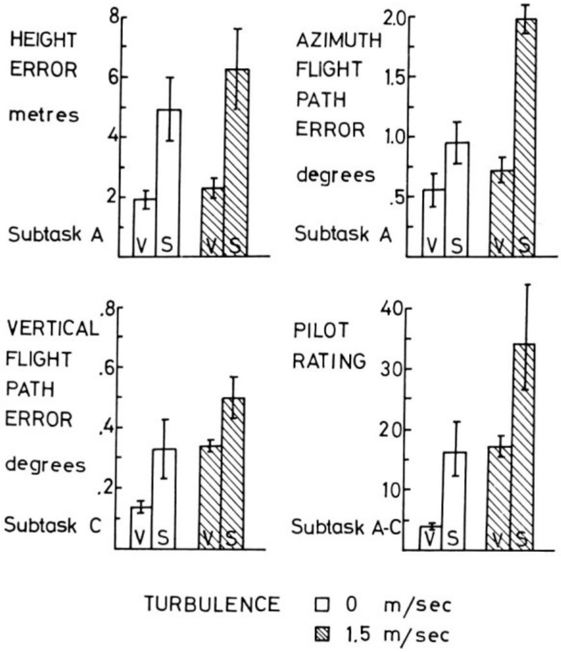

FIG. 8 — $M = 0{\cdot}16$; system D
Exp. 1. True velocity vector (V) and simplified (S)

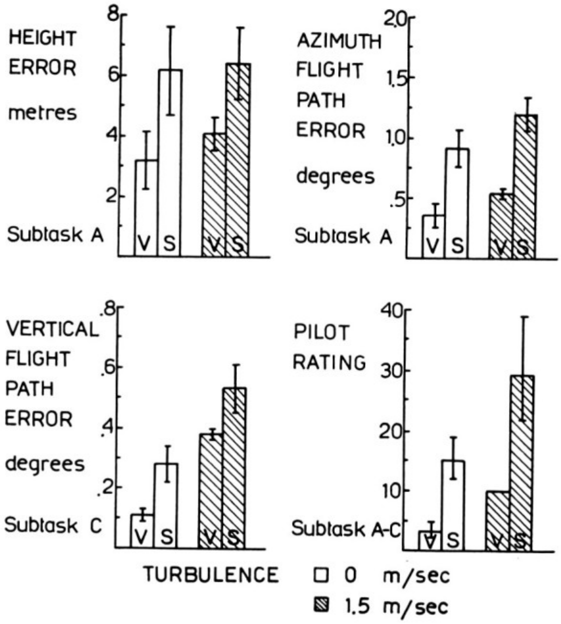

FIG. 9 — $M = 0{\cdot}16$; system M
Exp. 1. True velocity vector (V) and simplified (S)

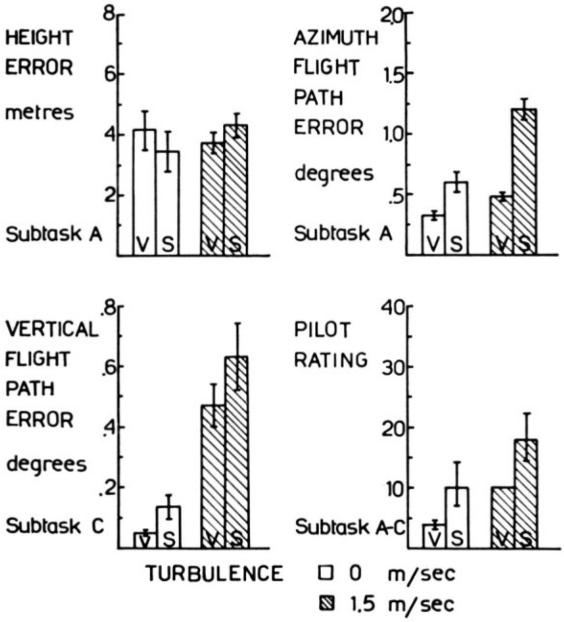

FIG. 10 — $M = 0{\cdot}20$; system M
Exp. 1. True velocity vector (V) and simplified (S)

lateral flight path direction to the left when the pilot is banking to the right in order to turn right. Typical angles of sideslip due to this effect in the simulator experiment are one and two degrees for the flight conditions studied with trimmed angles of attack equal to 11 and 18 degrees. The false and unstabilising information about the lateral flight path direction has increased the steering difficulties not only in the lateral direction but also in the vertical plane, as the results of the simulator experiment indicate.

Experiment 2

In the second simulator experiment the true velocity vector was compared with an attitude symbol fixed to the aircraft not only laterally but also vertically in a direction depressed by the trimmed angle of attack. In steady state conditions this attitude symbol will indicate the true flight path direction like the velocity vector but in manoeuvres there are transient dynamical differences. The question to study in this experiment was whether the differences mentioned are advantageous to the velocity vector or to the attitude information.

The experiment was carried out for one combination of flight dynamics, the moderate system, and flight speed, $M = 0{\cdot}18$. The results, Fig. 11, are slightly better for the velocity vector for most of the performance measured and for the pilot ratings. Only two of the differences are statistically significant. To the advantage of the attitude symbol it can be mentioned that the variation of the angle of attack is smaller, Table 2A, indicating that pitch

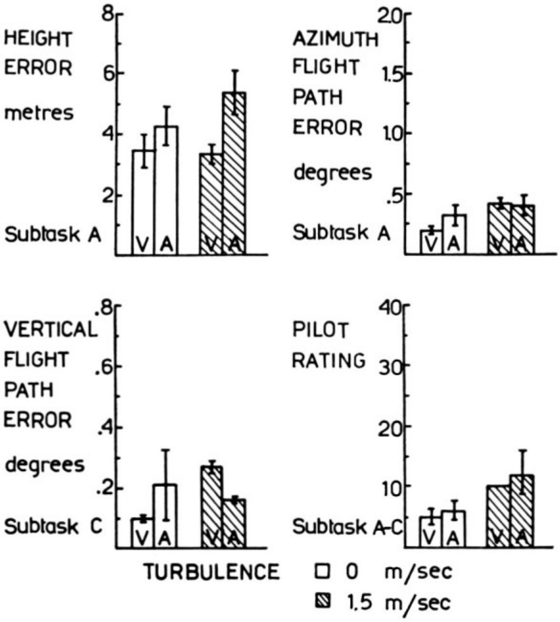

FIG. 11 — $M = 0{\cdot}18$; system M
Exp. 2. True velocity vector (V) and attitude symbol (A)

manoeuvres are better damped with the attitude symbol than with the velocity vector.

A comment on pitch control should be made in this context. It seems likely that pitch attitude information is important for pitch control. Such information is also provided by the pole-track head-up display when there is no specific attitude symbol. The horizon and the space stabilised pole-track constitute an outside world reference for the pilot, as in visual flight, and makes it possible to observe changes of the pitch attitude angle as movements of the nose of the fuselage or window frames in relation to the reference. This information helps the pilot to damp oscillations in pitch. The cockpit of the flight simulator used in the experiment was probably too simple to give a good attitude information of this type. Furthermore the simulator was fixed. In real flying the information about changes in pitch attitude is reinforced by motion cues. Because of this the difference regarding pitch damping mentioned above between the velocity vector and attitude symbol may be a simulator result that is not representative for real flight.

The attitude symbol has the disadvantage of transient errors in relation to the true flight path direction. In the manoeuvres required to follow the commands in the simulator experiment the average maximum transient errors were 0·9° and 1·6° without and with wind turbulence. When the aircraft has a poor flight path response the true velocity vector has the disadvantage of indicating the same poor behaviour of the aircraft. Thus there are pros and cons for the velocity vector as well as for the attitude symbol regarding the vertical flight situation. In the lateral direction there is no doubt that the velocity vector is superior to the attitude symbol, which does not provide any meaningful information.

Experiment 3

The previous discussion leads naturally to the question on optimum directional information for low speed flight path control. The third experiment was a first step to study this problem. Different combinations of velocity vector and attitude information were investigated, in all cases with the true flight path direction laterally. Such combined information can also be considered as a quickened velocity vector. A sample of results from the experiment is reported in this paper (Fig. 12). It shows a comparison between the

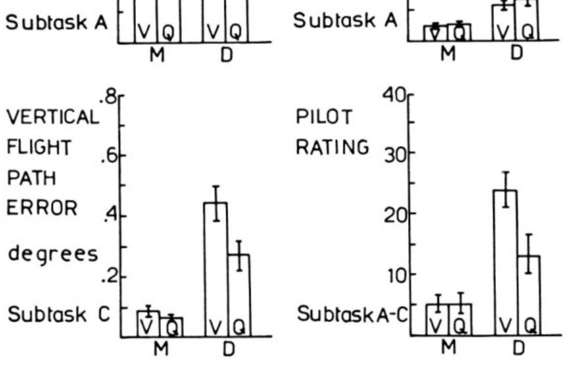

FIG. 12 — $M=0{\cdot}18$; system M, D
Exp. 3. True velocity vector (V) and quickened (Q)
No wind turbulence

true velocity vector and one that has been quickened by a term depending upon the angle of attack, α, in the following way:

$$\gamma_{\text{displayed}} = \gamma_{\text{true}} + k \,.\, sT/(1+sT).\, \alpha \qquad \text{(valid for } \phi=0\text{)}$$

where γ is vertical flight path angle

$k=0{\cdot}25$

$T=0{\cdot}50$.

The comparison was carried out for the moderate and difficult systems at a flight speed of $M=0{\cdot}18$ and without wind turbulence. Standard configuration for pilot ratings is the velocity vector with turbulence. The results indicate a significant improvement by quickening for the difficult system, *D*, but no effect for the moderate system, *M*. In the first case height errors and vertical flight path errors were reduced by 40% and steering difficulties or pilot ratings to one half. The average maximum transient error relative to the true velocity vector caused by the quickening term was $0{\cdot}7^\circ$ for the difficult system.

The reason for studying this specific type of quickening is that the quickening term is easy to compute. Other methods are also being investigated, among those the following which involve more complex computing and sensing devices.

$$\gamma_{\text{displayed}} = \gamma_{\text{true}} + k \,.\, \dot{\gamma}$$

$$\gamma_{\text{displayed}} = \gamma_{\text{true}} + k(\alpha - \alpha_{\text{trim}}) \qquad \text{(valid for } \phi=0\text{)}$$

where k is a constant.

The second method includes the true velocity vector ($k=0$) and the aircraft fixed attitude symbol depressed by the trimmed angle of attack ($k=1$). By varying the constant between zero and one it is thus possible to obtain any combination of velocity vector and attitude information. In the lateral direction similar quickening methods are being studied.

The results of experiment 3 and preliminary investigations regarding the quickening methods mentioned leads to the following tentative answer to the question on optimum directional information for the pole-track head-up display. The true velocity vector is the optimum information for low speed flight path control of an aircraft having good handling qualities. For an aircraft with poor handling qualities the optimum information is a velocity vector that has been artificially quickened. Type and size of the quickening should be carefully selected considering the dynamical characteristics of the aircraft, transient errors that can be tolerated in manoeuvres, and the effect of wind turbulence.

Further research on this problem is required. The experiments reported were made in 1965 and 1966. Among present and future work on the subject can be mentioned simulator studies of complete landing approaches, experiments in moving flight simulators to get the effect of motion cues, and verifying flight testing.

Reference

(1) Nordström, Lennart, 'Eye level flight information by a perspective pole-track,' Saab Technical Note TN 58, Jan. 1965.

Discussion

P. R. Williams (Norden, Division United Aircraft Corp., Norwalk, Conn., U.S.A.): According to some sources recent flight tests with head-up displays have shown that a 1:1 correspondence between the display symbols and the outside world results in excessive amounts of movement and jitter of the earth-stabilised symbols. This effect is apparently accentuated when the total field of view is small. It would be interesting to know if this effect has been found in your tests to date, and also if any tests are planned using scale factors other than 1:1.

L. Nordström and H. Arne: Our experiences from simulator and flight tests are favourable regarding the angular sensitivity 1 :1 when the control laws behind the symbols are properly optimised for aeroplane dynamics and effects of wind turbulence. Simulator tests regarding a landing approach have been carried out with an angular scaling of 1:2 as well as 1 :1 in the lateral direction. We did not find any significant differences between the performance measured or pilot opinions. Further simulator experiments might be performed with other scaling than 1:1 both vertically and laterally.