Effect of Visual Threshold on Aircraft Control

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The resolution achieved when displaying such quantities as bank and pitch angle in a flight simulator is rarely as good as the corresponding resolution in flight. A flight simulator experiment was conducted to determine the influence on the closed loop control of an aircraft of poor resolution in bank and heading. Variations in the visual threshold of these quantities were made by varying the size of a dead-space to the pilot's display. The results show clearly that the control accuracy is degraded. Low-frequency limit cycles occur, of a character similar to those which can be observed in ground based simulators and, to a lesser extent, in flight. From these results it is concluded that the control situation is aggravated not only by threshold effects purposely inserted during the simulation, but also by the thresholds inherent in the pilot's own sensors. Thus in certain control situations, the inability of the pilot to detect attitude or position errors visually will result in control difficulties. The application of these results to the landing approach and flare is discussed.

Nomenclature

g = acceleration due to gravity, fps
h = height, ft
L_α = lift parameter 1/sec
p = rate of roll, deg/sec
q = rate of pitch, deg/sec
r = rate of yaw, deg/sec
s = Laplace operator
V = aircraft forward speed, fps
y = track position, ft
δ_a = aileron angle, deg
δ_e = elevator angle, deg
ϕ = bank angle, deg
ψ = heading, deg
ω_n = longitudinal s.p. frequency, rad/sec
ζ_n = longitudinal s.p. damping ratio.

Problem

Introduction

MANY advances have been made in flight simulation techniques in the past decade. These include devices for both visual and kinaesthetic cue simulation: they apply equally well to research and training simulators. Nevertheless, a gap exists between simulator and flight which pilots often find difficult to span. In consequence, the control technique which a pilot uses in a flight simulator will, under certain circumstances, differ from that which he uses in flight. Extrapolation from simulator to flight is then of severely limited value.

This difficulty can be circumvented in the training simulator by 'adjustments' to the simulator until the general concensus of pilot opinion is that the simulator behaves like the aircraft. Unfortunately, this technique is not valid for research simulation. However, the research engineer is allowed to be selective in the pilots he uses. Most investigations are therefore assessed by experienced pilots, familiar with the limitations of the simulation, and able to contribute to the interpretation of the results.

Much remains to be done in understanding the inability of the simulator to reproduce certain characteristics of the flight situation. It is easy to hypothesize—the lack of certain motion cues, limited field of view, the lack of stress in the real situation—are all cited as causes. The development of systems to reproduce such stimuli is a complex and expensive undertaking, and it is essential to know, prior to designing such a system, that the underlying hypothesis is correct.

The work to be described was intended to improve our understanding of a small part of this over-all simulator problem. It is concerned primarily with the visual display loop, since emphasis has been given at Warton for many years to the development and use of visual displays for research simulation. However, the principles involved have more general application, and appear as fundamental aspects of the aircraft control problem, as well as having strong implications on flight simulation techniques.

Approach

It is often convenient to consider the combination of aircraft, pilot, and task as a closed loop stability and control problem. If a suitable describing function can be found for the pilot, closed loop analysis akin to that used in autopilot design may be performed. Reference 1 discusses the merits of such models. The simplest of these, the cross-over model, suggests that at low frequencies (say <3 rad/sec), the pilot behaves as a pure gain, if the controlled element dynamics take the form Kc/s.

To carry the analogy between pilot and autopilot control loops further, it is also necessary to define the feedback signals which are available to the pilot, and which will enable him to perform a given task. In a fixed-base simulator these are derived from visual displays, which contain information about the position and orientation of the aircraft.

The pilot's view of the outside world from an aircraft in flight is substantially better than that obtained from most visual displays used in simulators. Shortcomings of the latter may lie in the inherently poor resolution of a television picture, or in the mechanical imperfections of a servo-drive system. It is likely, therefore that the feedback signals which enable the pilot to control a particular loop are degraded in the simulator compared with those available in flight. It is also possible that, even with a good visual display, the pilot may not be able to appreciate changes in orientation or position as well in the simulator as in flight. Consequently a threshold has to be exceeded before any corrective action is taken by the pilot. The delay in corrective action by the pilot approximates to the introduction of a dead-space into

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the feedback loop. Dead-space as used in this paper is a characteristic input/output relationship, whereby no output appears until a set input level is exceeded. The output is thereafter related to the input in a linear fashion.

We made a systematic study of the effects of a dead-space in the feedback loop of a control situation. First, we did analytical and computer investigations of the effect on closed loop stability of a dead-space in the feedback loop of an auto-pilot. Then we conducted an experiment with a pilot in the loop, in which similar parametric changes were made. The effects of these changes, both in terms of pilot performance and pilot opinion were observed.

Assumptions

A considerable choice exists in deciding which control loop to study. However, a lateral task, involving the control of heading and track, was selected, on the basis of the observed difficulties which inexperienced simulator pilots have when first confronted with a television landing-approach display. Furthermore, a track holding task is of a higher order than a height holding task.

To ease the analysis, the control loop was kept as simple as possible. The description of the aircraft was minimal: the aileron input simply produced proportional rate of roll via a lag of 0.25 sec. Sideways acceleration was assumed proportional to bank angle. The autopilot applied aileron as a function of bank angle, sideways velocity (or heading) and track error. The control loop both for the autopilot and pilot, is seen on Fig. 1.

The autopilot equation is $\delta_a = k_1 \phi + k_2\dot{y} + k_3y$. The following stability quartic may then be derived: $s^4 + 4s^3 + 4k_1s^2 + 4gk_2s + 4gk_3 = 0$, which, for suitably chosen values of k_1, k_2 and k_3 will factorise as $(s + a)$ $(s + b)$ $(s^2 + 2cs + d) = 0$.

The values of k_1, k_2, and k_3 were selected with the pilot-in-the-loop study in mind. Long period pilot-induced oscillations are not uncommon on records of tracking, from either flight or simulator. Assuming that the pilot's behavior equates to that of the autopilot in the use of several feedbacks, we can select the frequency of the oscillatory mode of the autopilot to correspond to a typical pilot-induced oscillation. A 12-sec period was taken as typical; it was further assumed that ideally the autopilot should give critical damping to this mode. On this basis, values of $k_1 = 1.0$, $k_2 = 0.0116$ and $k_3 = 0.00158$ were used, and the stability quartic is then $(s + 0.23)$ $(s + 2.75)$ $(s^2 + s + 0.25) = 0$.

Computer Study

Cases Considered

Figure 1 shows the two positions in the control loop where a dead-space was inserted, and its effect on loop stability observed. First, the effects of varying the amplitude of the dead-space in either the ϕ feedback, or the $\dot{y}$ feedback were investigated. Next the dead-spaces were inserted in both feedback loops simultaneously. In all cases, a limit cycle results.

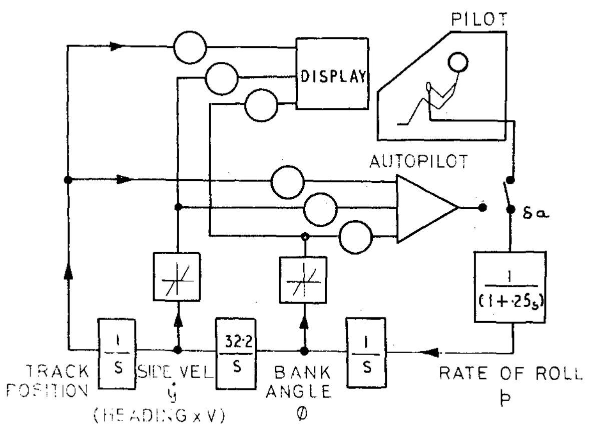

Fig. 1 Block diagram of loop closures.

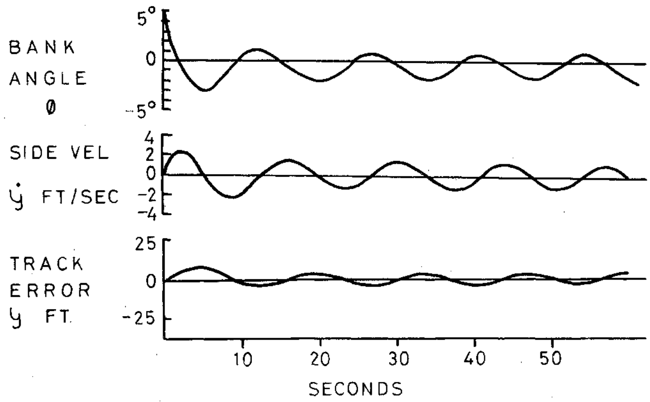

Fig. 2 Effect of 1.6° dead-space in bank feedback of autopilot.

Figures 2 and 3 show the limit cycles from dead-spaces in the ϕ feedback and the $\dot{y}$ feedback loops, respectively. A point to notice is that the frequencies of the two limit cycles differ. Furthermore, a linear relationship exists between the limit cycle amplitude and the size of the dead-space. That this is so can be derived analytically, by manipulating the loop closure of Fig. 1 into linear and nonlinear portions. Using the Describing Function technique, the nonlinear portion is replaced by an equivalent gain. The intersection of polar plots of the two components allows the amplitude and frequency of the limit cycle to be found. The results of this analysis are seen on Table 1.

Discussion of Results

The inclusion of a dead-space in either feedback loop results in a limit cycle. This is to be expected. Of more significance is the relationship of the amplitude of the resulting limit cycle for a given size of dead-space. A dead-space of 0.5° in bank causes an undamped oscillation in track of 1.2 ft. This magnitude of oscillation at a frequency of 0.60 rad/sec. is unlikely to cause concern in most aircraft applications. The associated bank angle limit cycle has an amplitude of 0.75°. On the other hand, a dead-space of 0.5° in heading at 120 knots (equivalent to a dead-space in $\dot{y}$ of 1.75 fps) causes an undamped oscillation in track of 7 ft. Even if it were unnoticed by the crew, this level of oscillation represents a significant degradation in track holding ability—for example, during I. L. S. approach.

It appears, then, that relatively small imperfections in the quality of the feedback signals can significantly affect the stability of a typical autopilot mode. Moreover, the loop

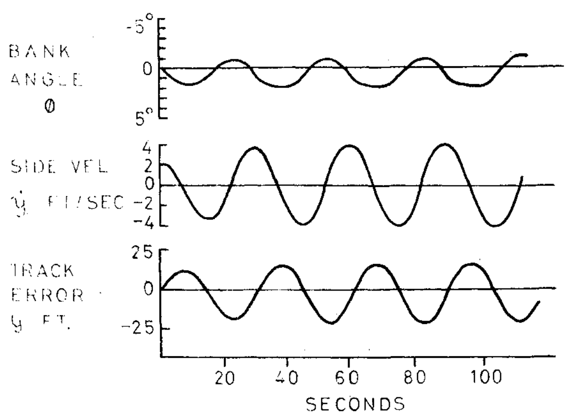

Fig. 3 Effect of 6 fps dead-space in $\dot{y}$ feedback of autopilot.

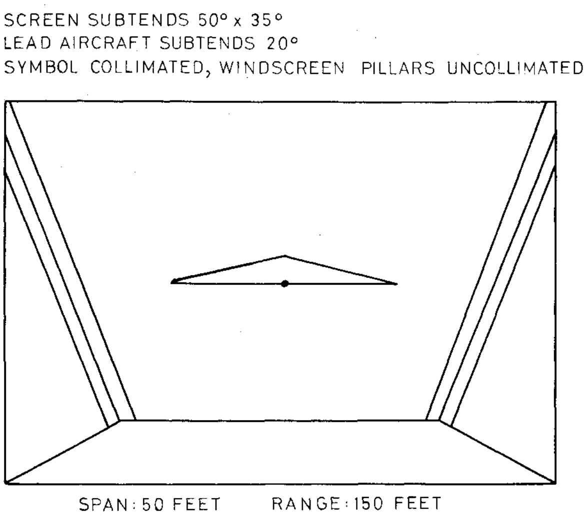

Fig. 4 Lead aircraft display.

considered possessed inherently good stability characteristics' because of the simple representation given to the dynamics of the aircraft. Autopilot loops in practice are likely to have lower stability margins. Also, several sources of threshold phenomena exist, in any practical application sensors, the autopilot actuators, and the aircraft control system are the obvious ones. That instances of this type occur regularly in flight is beyond dispute (Refs. 2 and 3 contain examples). Moreover, in the case of autopilot control the problem is well appreciated and understood. The purpose of this autopilot study is simply to provide a basis for comparison, so that the possibility of a similar effect occurring in piloted flight, particularly in simulators, may be investigated. Even at this stage, it may be concluded that quite small imperfections in, for example, bank or heading servos in a flight simulator are possible sources of trouble, in terms of reduced closed loop stability at small amplitudes.

Flight Simulator Study

Details of Simulation

For the flight simulator experiment, the analogue computer was connected to a fixed-base simulator cockpit. The pilot's display consisted of an electronically generated symbolic presentation of a "lead aircraft." The appearance of this display to the pilot is shown on Fig. 4, and the display principles involved are discussed in Ref. 4. The "lead aircraft" symbol obeys the laws of perspective relating the leader and the formating aircraft, and so provides a continuous tracking task involving the simultaneous control of bank, heading, and track. Because the display is generated electronically, good frequency response and good resolution of the symbols are ensured. The display is viewed by the pilot through collimating lenses, and presented in true angles.

The pilot's task was to formate behind the lead aircraft, line astern. After holding this position for perhaps fifteen seconds he was asked to formate on one of the wing-tips, and hold this new position for a similar period. He then returned to the center position. The longitudinal control of the aircraft was by the autopilot. Neither turbulence nor target manoeuvres were injected into the control loop. Forward speed was fixed at 120 knots.

Force for full aileron control was approximately 10 lb, and maximum control gave a rolling acceleration of 1.4 rad/(sec)^2. Pilots were not told which case they were assessing, although reversion to the basic case (no dead-space) was allowed when requested.

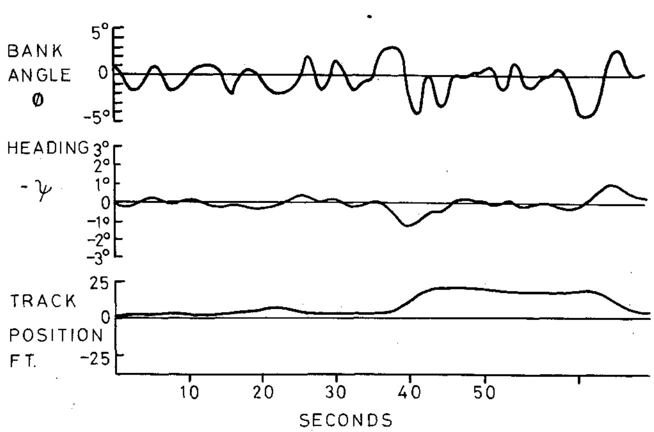

Fig. 5 Tracking record—no dead-space on display.

Cases Assessed, and Results

The underlying hypothesis of the investigation is that one of the inherent limitations of a fixed base simulator equates approximately to a dead-space in the signals received by the pilot. Thus the assumption is that a dead-space effect is present, even if none is inserted into the computer model. The configurations assessed by the pilots were as follows: 1) No intentional dead-space, 2) 1° dead-space in bank, 3) 1° dead-space in heading, 4) 2° dead-space in bank, 5) 2° dead-space in heading. Typical traces of tracking performance are shown for configurations 1), 2) and 3) on Figs. 5–7.

Large numbers of such traces were obtained, and an attempt was made to analyze them. The significant information they contain is as follows. They show either the presence or absence of pilot induced limit cycles, of which the amplitude and frequency is of interest. They also give some subjective impressions of performance (by inspection of the track error trace) and of the pilot's activity with the stick. A study of the records enabled Table 2 to be compiled. It indicates for a particular configuration whether or not a well defined limit cycle existed, and gives a rough estimate of the frequency and amplitude of the oscillation in bank and heading. For some cases, a pilot rating, based on the Cooper scale, was obtained, and this is included on Table 2. However, the main emphasis of this investigation was on performance. It is also possible that the nonlinear nature of the loop makes pilot evaluation more difficult than usual. Each trace was, therefore assigned a 'performance rating' analogous to the Cooper scale (1 = very good, 10 = terrible) based on inspection of the tracking performance. This performance rating completes Table 2.

Discussion of Results

Before discussing the results in detail, it is necessary to emphasize the importance of the pilot's task in producing records of a certain character. By selecting speed (in this case, 120 knots), size of lead aircraft, and range of lead aircraft, the relative importance of the feedback quantities $\dot{y}$ and y can be changed. The selected values (Fig. 4) correspond to a plausible real-life situation, but minor variations

Table 1 Limit cycle due to dead-space

Position of dead-space	Amplitude ϕ (deg)	Amplitude $\dot{y}$ (fps)	Amplitude y (ft)	Frequency rad/sec
Bank feedback (dead-space, deg)	1.5 × dead-space	1.7 × dead-space	2.3 × dead-space	0.6
$\dot{y}$ feedback (dead-space, fps)	0.4 × dead-space	1.5 × dead-space	4.1 × dead-space	0.23

(still plausible) can radically change the character of the tracking records. To this extent, the experimenter controls the stability of the basic control loop.

Thus it may not come as a complete surprise to find evidence of a small pilot-induced limit cycle for the basic case (Table 2). It is pleasing to find that all the pilots exhibit the same tendency, although not all the pilots had the same familiarity with this particular simulator.

Of greater interest is the effect of change in configuration. It is abundantly clear that introducing a dead-space into either the bank or heading feedback loop causes a deterioration in both pilot opinion and performance. It is also clear that a 1° dead-space in heading has a greater destabilizing effect than a 1° dead-space in bank. This result is in good agreement with that observed for the autopilot. Also in agreement with the autopilot results is the increase in limit cycle amplitude when the dead-space in the ϕ or ψ feedback loop is increased to 2°.

The simulator trials, then, seem to confirm that under piloted control, a situation analogous to that under autopilot control with a dead-space present can arise.

Discussion

General Implications

The foregoing evidence points to the fact that the visual thresholds of the pilot in the simulator can cause a small amplitude limit cycle. It is tempting to try to deduce the magnitude of these thresholds by analyzing the experimental evidence of the effect of dead-space amplitude on tracking performance. Before doing so, a simple experiment was made to measure the pilot's visual threshold on the simulator. Four pilots took part. Their detection threshold in roll and yaw was measured with two CRT displays. The results are seen on Figs. 8 and 9. The significant result is that the pilot's visual threshold for both the lead aircraft display and a television display (without any aiming mark) is dependent on frequency. At low frequencies, the pilot cannot detect bank or heading errors even as large as 1°. At higher frequencies, very small errors are detected. In other words, he responds to rate of change of error. It follows, therefore, that even for flight instruments (such as a pitch attitude indicator) where visual acuity is not limiting (i.e. the displacements are not so small as to be nearing the eye's re-

Table 2 Results of the simulation tests

Dead-space position	Pilot	Pilot rating	Per-form rating	Limit cycle period, sec	Bank angle ampli-tude, ± deg	Heading ampli-tude, ± deg
—	A	3	5	5–8	1.5	0.3
—	A	3 1/2	4	5–6	1.5	0.4
—	B	5	3	5	1	0.2
—	B		4	4–5	1	0.2
—	C		4	6	1.5	0.3
—	D		4	5	1	0.2
—	D		4	5	2	0.4
—	D		3	5	1	0.1
ϕ Feedback	A	5	7	7	3	0.6
(1°)	A	5	7	6	2.5	0.3
	A	4	6	6–8	3	0.4
	B	5 1/2	4	6	2.5	0.4
	C		5	7	2	0.4
	D		4	4	2	0.4
	D		4	5	1.5	0.2
	A		4	5	2.5	0.3
y Feedback	A	6	8	9–10	5	1
(1°, or	A	6	9	12	7	2
3.5 fps)	B	6.5	6	8	2.5	0.6
	C		7	12–15	3	0.8
	C		7	11–12	4	1.0
	D		5	8	2	0.4
	D		6	8	2	0.4
2° Dead-Space						
ϕ Feedback	A	—	5	6	4°	1°
$\dot{y}$ Feedback	A	—	8	10–13	7°	2°
ϕ Feedback	B	6	6	6–7	4°	0.8°

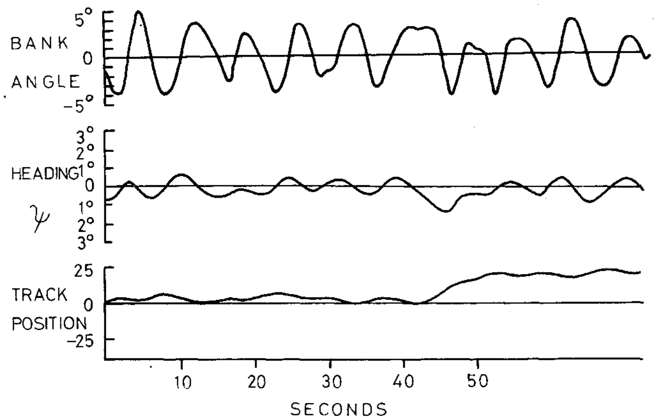

Fig. 6 Tracking record—1° dead-space on displayed bank angle.

solving power), scaling down the sensitivity of the indicator will increase the likelihood of pilot induced oscillations.

Much comment has been made on the inadequacies of present day flight data presentations for the operation of supersonic aircraft. Reference 5 briefly summarizes the comments made at the Society of Experimental Test Pilots Conference, held in Los Angeles in September 1967, where longitudinal control difficulties at high supersonic speeds were discussed. These take the form of long period undamped oscillations, and have occurred on both B-70 and SR-71 aircraft. A possible explanation is a threshold phenomenon of the type investigated here.

Many other instances of long period, pilot induced limit cycles are available. They are rarely of a serious nature, but they occur with surprising frequency in everyday operation of commercial transport aircraft. References 3 and 6 contain typical examples. They have been noted both in the lateral and longitudinal control loops.

The results of our experiment show that poor resolution in bank gives a higher frequency limit cycle than poor resolution in heading. Intuitively, this is correct, since heading and track influence the outer control loop, whereas bank angle control is primarily inner loop. They do illustrate that, in looking for the cause of a particular pilot induced oscillation, the frequency may provide a clue as to the feedback quantity which causes the trouble.

Of course, the supposition that threshold effects will cause pilot induced oscillations is not new. Reference 7 mentions this possibility, and even implies that 'the "pump-handling" of the pupil learning to fly, and the wobbling of the learner cyclist' are evidence of it. Reference 8, in making a formal classification of p.i.o's, attributes one class of p.i.o. to nonlinear elements in the feedback loop. However, this class embraces a large number of possibilities, and so the effect

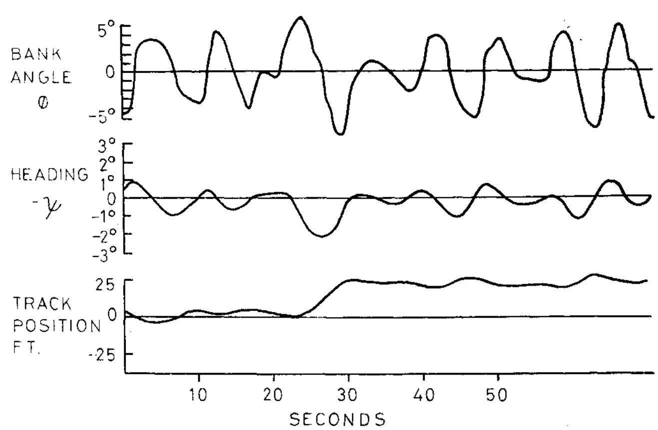

Fig. 7 Tracking record—1° dead-space on displayed heading.

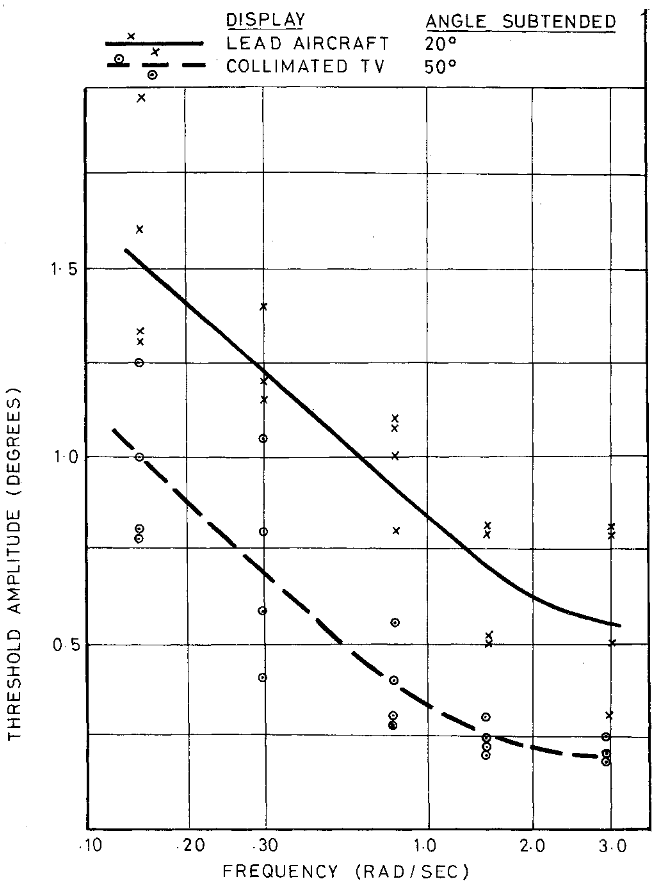

Fig. 8 Visual threshold of bank angle—four pilots.

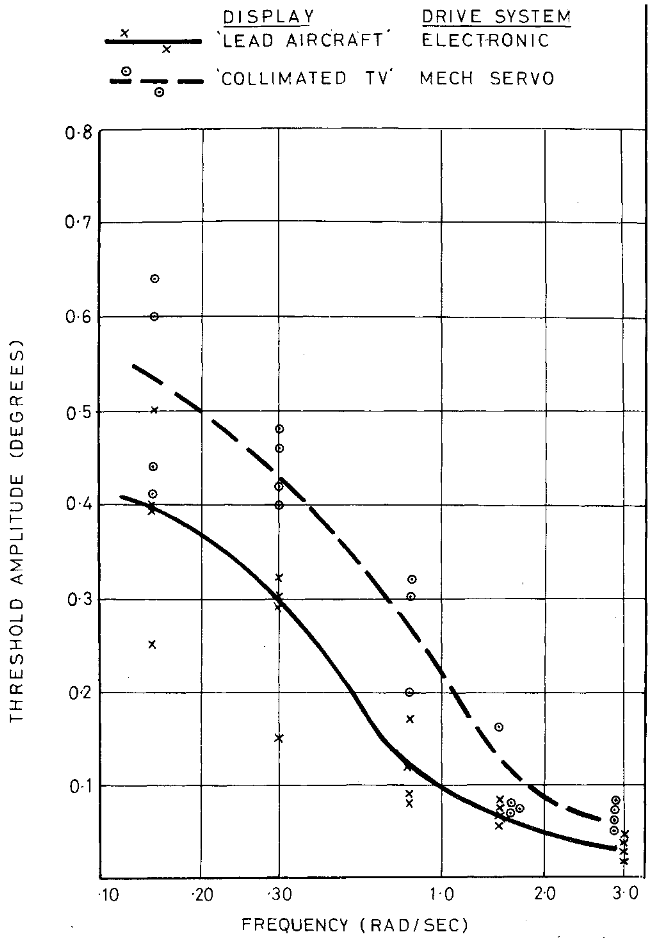

Fig. 9 Visual threshold of heading—four pilots.

of the pilot's visual threshold is not considered. Note also that poor resolution will have a much more serious effect in a display feedback loop than in the control system from stick to elevator.

Implications for Flight Simulation in General

A pilot in flight has more information on which to base his control strategy than he does in a flight simulator. The information is also of better quality. The question arises "is the limited information given by the simulator adequate to produce a good representation of the control loop in the aircraft?". Because there is in flight a considerable redundancy of information, circumstances undoubtedly exist where the answer to this question is "yes." In fact, a whole industry is based on this answer. Nevertheless, other simulated flight situations yield a firm "no." Often, these situations involve a complex closed loop task, in which stability margins are low, even in the real environment. The loop which has been studied is in this category; a multitude of other loops could be conceived in which poor airframe dynamics make a major contribution to the low stability.

In these situations, the pilot's ability to perceive the deviation of a response parameter from the ideal will affect the stability margins at small amplitudes. It is therefore essential that the accuracy with which the flight simulator can present to the pilot these critical parameters is as good as, or better than, the pilot's inherent ability to resolve the error. Most simulators employ positional servos for display purposes. Figures 8 and 9 suggest the accuracy that the bank and heading servos should achieve at moderate frequencies. (It would be unwise to assume that poor static accuracy is always acceptable, since this result is only valid if the assessment is made without a fixed reference.)

Implications for Approach and Landing Flare Simulation

Most users of T.V. visual systems have observed pilots having difficulties in elevation control, as well as in the azimuth plane—particularly if the pilot is unfamiliar either with the display or with flight simulators in general. These difficulties usually take the form of a poorly damped or even unstable pilot induced oscillation. Two such phenomena can undoubtedly be attributed to the threshold effects discussed previously.

The first of these p.i.o's concerns pure pitch attitude control. Assuming aircraft dynamic characteristics of the type normally associated with low speed flight, an investigation similar to the previous one, but based on Fig. 10, reveals that a pilot induced limit cycle of troublesome amplitude is easily produced by a threshold of 0.5° pitch attitude. The frequency of this oscillation lies in the range 1–2 rad/sec, and it appears to the pilot to be due to poor damping of the short period mode. If this phenomenon occurs on a flight simulator, the cause is invariably that of a poor mechanical pitch drive system to the visual display, rather than the pilot's inability to resolve pitch attitude. Figure 9, which may equally well be used to determine pitch thresholds, supports this argument, since the pilot's pitch threshold in the range 1–2 rad/sec is less than 0.1°.

The second phenomenon is a much longer period p.i.o., associated with the control of height, as well as pitch attitude. The period of this oscillation depends on the tightness of the height control, and will vary from 15–20 sec at moderate heights, to perhaps 6 sec near the ground. This type of p.i.o. may be observed on most visual landing displays during the flare—in fact it seems that the trained simulator pilot is the one who has learned to suppress or stabilize this particular mode. The likely cause appears to be the pilot's inability to detect height changes on the visual display. In other words, the pilot's visual height threshold causes an outer loop limit cycle very analogous to the heading dead-space effect discussed previously. It is interesting to note that in this case, unlike the pure pitch control case, the trouble lies in the information transmitted to the pilot by the display, and not in the means of driving the display. The trained pilot, in fact, achieves stability either by reducing the effective loop gain (avoiding over-controlling), or by assimilating more of the available information (better interpretation of the visual cues).

Simulation of the landing flare is perhaps the least satisfactory aspect of the T.V. visual display system. Most airlines will not accept landing flare simulation for pilot training, and there is ample evidence from both research and training simulators to show that substantial differences in landing performance exist between flight and simulator.[9] Therefore, an understanding of the landing flare problem will have far reaching consequences. It now seems that we are not far from achieving this understanding.

Two extreme possibilities must be considered: Either 1) the judgment of height in the simulator is approximately as good as that which is achieved in flight. In that case, the difference in performance can only be attributed to other information available in flight (motion cues) which stabilizes this troublesome height control mode. Or 2) the judgment of height in the simulator is significantly worse than that which is achieved in flight, and this is the cause of the trouble. (In reality, a situation between these extremes may pertain, but an independent examination of each of the previous possibilities is first needed.)

It should be relatively easy to find experimentally if possibility 2 is true. But if the height judgment is the same, or can be made the same, in simulator and flight, and if the landing flare problem remains, then the next step is more difficult. It will depend on a parametric study of the closed loop stability during a simulated landing flare.

Our experience has shown that four factors bedevil and confuse the results of such experiments. These factors are 1) the nonstationary nature of the task—the loop closures change during the flare, 2) the statistical nature of the results. Even good pilots occasionally made bad landings. In consequence, several simulated flares are needed in each configuration, 3) pilot learning grossly influences the results, and yet 'simulator trained' pilots may give the wrong answer, 4) all pilots do not use the same control technique.

If the cause of piloting difficulties during landing flare can be established without doubt, the introduction of remedial measures in the simulator is possible. It is likely that such measures would be designed to compensate for the simulator deficiency, rather than remove it. For example, this height-judgment p.i.o. can be avoided by rate of change of height feedback. A convenient way to demonstrate this fact is illustrated on Fig. 12. The $\dot{h}$ feedback is introduced in this

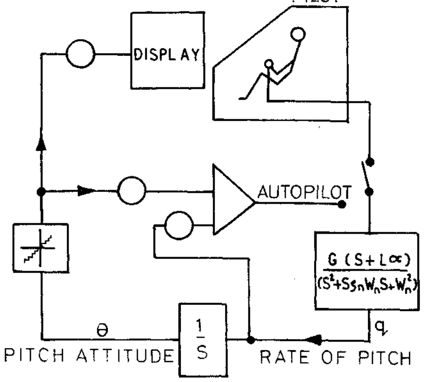

Fig. 10 Loop for pitch resolution p.i.o.

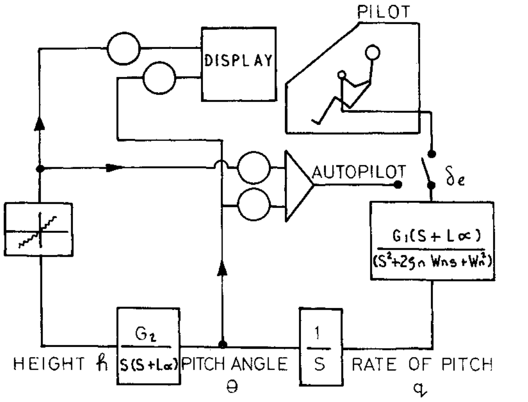

Fig. 11 Loop for height resolution p.i.o.

case via an adaptive loop (although this refinement is not necessary for the demonstration). We have made a few exploratory tests with the loop closure of Fig. 12, with promising results.

Finally, it is not the intention of this paper to suggest that all pilot induced instabilities observed on simulators are due to threshold effects. Many cases can be shown, by both analysis and experiment, to be due to the gain, frequency and phase relationships assuming linear control, plant, and display dynamics. They are covered by a plethora of reports, over a long period of time. Nor is it easy to separate linear and nonlinear phenomena in a complex control situation like the pilot control of aircraft. Even so, the foregoing results do illustrate that in an otherwise stable situation, display resolution can and does cause control difficulties, both in simulators and in flight.

Conclusions

An analytical and flight simulator study has shown that if a dead-space is introduced into the feedback loop, a low frequency limit cycle results. The amplitude and frequency of the limit cycle depend on the position of the dead-space, the feedback gain, and the size of the dead-space.

The gains and display sensitivities used in this study are similar to those which occur in flight, and it therefore seems that many flight instances of low frequency pilot induced oscillations are attributable to threshold phenomena.

The pilot's physiological makeup includes thresholds which will ultimately cause a degradation in his control capabilities. Two of these thresholds—the visual thresholds in bank and heading—were found experimentally.

The flight simulator does not fully represent the flight environment, and stability margins are probably less than in flight. Hence the occurrence of threshold induced oscillations is more likely in the flight simulator than in actual flight.

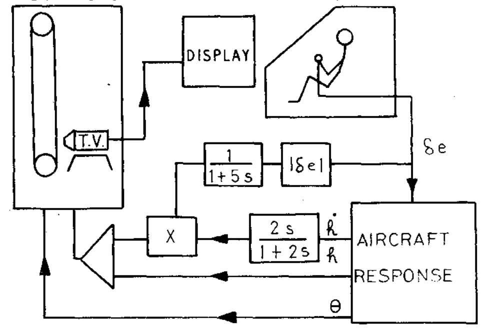

Fig. 12 Adaptive loop to stabilize height control.

Piloting difficulties during the simulated flare manoeuvre are associated with height judgment, rather than the resolution of pitch attitude. If this effect is quantified, methods of compensation can be developed, and landing flare simulation will be much improved.

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Optimum Complementation of VOR/DME with Air Data

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Although the VOR/DME system has served efficiently as the primary domestic air navigation aid for some number of years, its navigational data are subject to sizable errors—errors produced principally by multipath propagation, which distorts the desired VOR signal. This paper demonstrates how augmenting the basic VOR/DME information with air data can significantly improve positional accuracy. The air data, when integrated, are used as a second source of position, and the data from the two sets of sensors are combined in an optimum filter. Results show that this optimally complemented system has an rms position accuracy 2.5 times better than that of unaided VOR/DME and that it can estimate wind components (for use in flight control) to about 20 knots rms. An example of the system's response to an actual noisy VOR signal is given.

Introduction

THE VOR/DME system† has been the primary domestic air navigation aid for a number of years. Its operational effectiveness is a matter of record, and the fact that it requires a minimum of relatively economical, easy-to-use, airborne equipment assures it continued longevity.

Although the system has proved to be quite efficient, its navigational data not infrequently contain sizable errors—errors springing primarily from multipath propagation phenomena, which distort the desired VOR signal. Because increasing air traffic densities demand increasingly accurate navigational information, the VOR/DME system errors loom larger and larger. Indeed, these errors may soon become a factor in limiting the capacity of airways.

Clearly, the key to more accurate and smoother guidance data lies in reducing VOR errors. Although it is true that improved system designs such as the doppler VOR[1] have become available, it is unlikely that such systems will be deployed in the near future because of the tremendous costs involved. Consequently for the near term any improvement in guidance data will have to be obtained through onboard signal processing. The most straightforward and most frequently used form of signal processing is low-pass filtering of the VOR output. Unfortunately, although low-passing quite effectively removes high-frequency errors, one finds that a filter designed to substantially attenuate frequencies on the order of 1 cycle/min begins to pose stability problems for the aircraft flight control system. Thus, the very errors that produce the most undesirable aircraft responses are difficult to extract by low-pass filtering.

Another form of signal processing is to augment the basic VOR/DME data with information derived from other sensors. A scheme of this type, wherein air data‡ are used to complement VOR/DME, is discussed in this paper. Specifically, the components of air data are integrated to provide an aircraft position measurement that is combined with the VOR/DME position information in an optimum filter. The performance of the resulting system is compared with that of the VOR/DME in an rms sense, and the response of the augmented system to some actual VOR data records is examined.

The optimally complemented system is shown to have the following characteristics: 1) Its rms position accuracy is substantially better than that of uncomplemented VOR/DME.

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† VOR (very high-frequency omnirange); DME (distance measuring equipment); the VOR and the DME measure bearing and distance, respectively, to a ground station.

‡ In this paper air data are defined to be true airspeed resolved into north and east components.