

DISORIENTATION IN FLIGHT

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Summary—Two of the three main sources of information about orientation normally available to man, namely the special sensations responding to linear and angular movements respectively, usually prove misleading to a pilot except in steady straight flight. This fact alone explains many cases of pilot disorientation. But it also emphasizes the supreme importance of the eyes in this context; yet even these can at times prove misleading to a pilot who is then deprived of his last resort. Experiments are described which show how this can arise during manoeuvres involving a component of roll, owing to the generation of involuntary and inappropriate rotational eye movements. It is concluded that for stability of the man-machine combination, aerodynamics may not always be self-sufficient; for disorientation of the man can upset even the aerodynamically stable aircraft. A detailed knowledge of latent human failings such as these can materially assist both designer and pilot, and determination of the relevant limits by experiment provides an example of the kind of contribution Aviation Medicine has to offer to Aeronautical Science.

INTRODUCTION

SINCE the early days of aviation, when aeronautics was largely a matter confined to the mechanical engineer and aerodynamicist, contributions to the subject have come from an ever-widening field of science. Indeed the separate branches have become so numerous as to call for a new generic term, aptly supplied in the title of this First Congress of Aeronautical Science. Not unnaturally, initial contributions mainly came from the more physical sciences. Roughly twenty years ago, however, the capabilities of the machine were clearly out-stripping those of the unaided man and the more biological sciences began to be called upon, as a result of which the relatively new science referred to variously as Aviation Medicine, Human Engineering in Aeronautics, Aerobiology, etc., came into being. As in any new field it has taken time to establish a grounding of basic facts. But today a fair body of special knowledge has been accumulated and this new faculty has come to take its place along with the many other branches of science contributing information which both designer and user can ill afford to deny themselves. This paper is concerned with one aspect of the problem of human failure in the man-controlled aircraft, namely pilot disorientation, which may be defined for the purpose of this paper as misapprehension of attitude and change of attitude relative to the earth's surface during flight.

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The information upon which we base our assessment of orientation is normally derived from a wide variety of sensing elements throughout the body which can conveniently be classified into three main categories of sensation: first, the eyes eliciting visual sensation; second, nerve mechanisms sensitive to the effects of linear acceleration and gravity, eliciting what will be referred to below as Gravity sensation; third, nerve mechanisms specifically sensitive to the effects of rotation, the so-called semi-circular canals eliciting Rotation sensation. In everyday life on the ground these three sources simultaneously provide complementary information which integrates readily into an unique concept in the brain. But in the air this is not the case, for in most circumstances other than steady flight in a straight line, both gravity and rotation sensation tend to become actively misleading, providing information which conflicts with what the eyes can see. In some circumstances, to be mentioned later, it seems that even vision can prove misleading to a pilot during flight.

MISLEADING SENSATIONS

Gravity sensation tends to be misleading on account of the continuously changing direction and magnitude of the apparent gravitational field. When turning, for example, the pilot is subjected to the combined effects of forces due to gravity and centripetal acceleration and since to him these are indistinguishable from one another he senses their resultant as the apparent vertical. But with no side-slip the resultant always remains normal to the aircraft, that is in the same direction relative to the aircraft as in straight and level flight, and hence this provides no clue as to the real vertical (Fig. 1)*. During accelerated flight in a straight line the

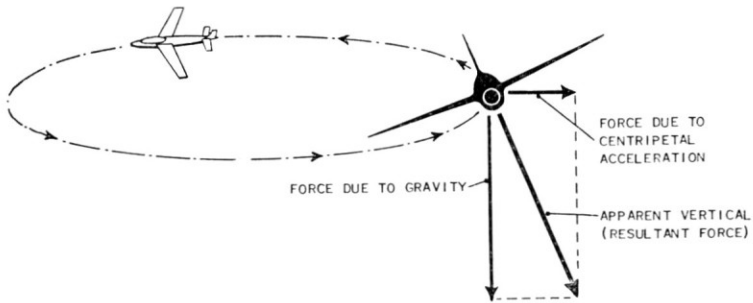


FIG. 1. Misleading impression of verticality. The resultant force is interpreted as vertical.

pilot is again subjected to the effects of forces due to both gravity and linear acceleration, again sensing their resultant as the apparent vertical which is in this case tilted backwards relative to the true vertical (Fig. 2b). It has been shown⁽¹⁾ that this tends to cause a misleading sensation of nose-

*For convenience, the vectors drawn in Figs. 1, 2, and 3 indicate the forces exerted by the body mass upon the aircraft seat.

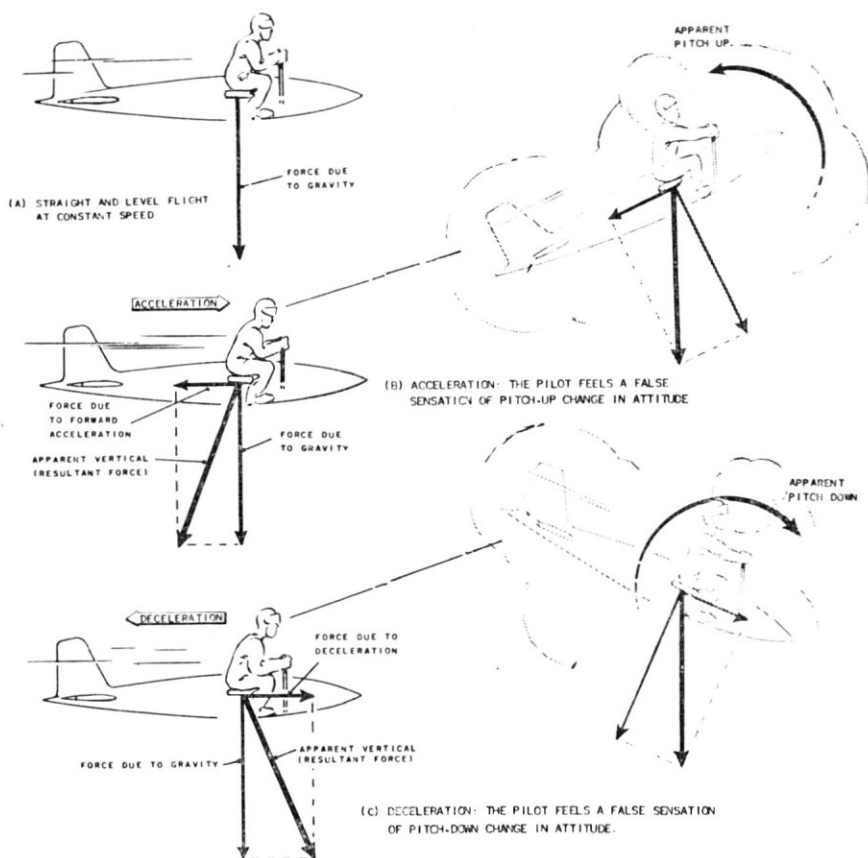


FIG. 2. Diagrams illustrating the misleading impressions of change in attitude due to the combined effects of forces due to gravity and linear accelerations in flight. The pilot tends to think that the resultant force is vertical.

up change in attitude, presumably because, when denied the use of his eyes, a pilot can only base his perception of the vertical upon the apparent direction of gravity. The illusion proves particularly dangerous during low-level overshoot on instruments, for when the true flight path is horizontal the pilot feels as though it were inclined upwards and when he feels that it is horizontal it is actually inclined downwards. A similar but reversed illusion of nose-down change of attitude arises during deceleration, as when extending the air brakes (Fig. 2c). In some aircraft the deceleration can approach 1 "g", with a consequent apparent pitch down change in attitude approaching 45° if flying straight and level, which can prove highly disconcerting to a pilot flying in cloud or at night in a high-performance aircraft. When the effects of radial acceleration, fore-aft

acceleration and gravity are all combined, a wide range of misleading impressions can arise, of which the following provides an example:

A pilot nearly lost control when he applied forward pressure on the stick to initiate recovery from a steady steep climb in cloud. Expecting to sense a nose-down change of attitude, he in fact felt he was pitching up into a steeper, nearly vertical, attitude.

A probable explanation is to be found in Fig. 3, where it can be seen that, at the moment of initiating the push-over, the apparent vertical

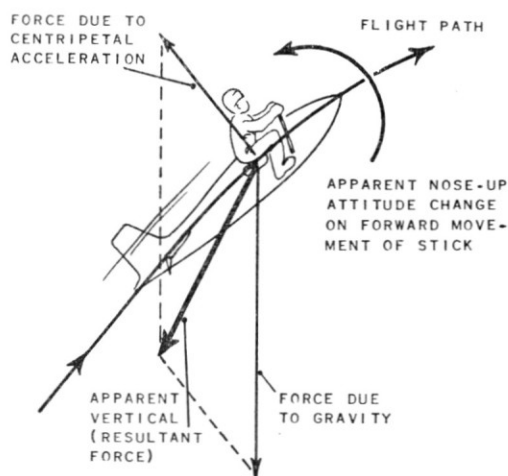
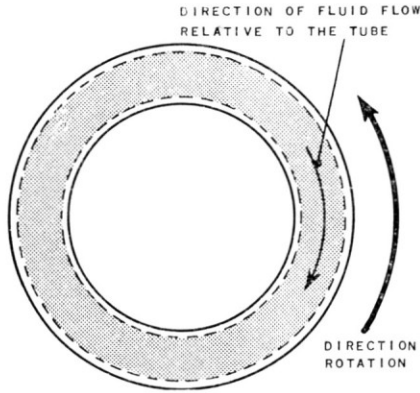


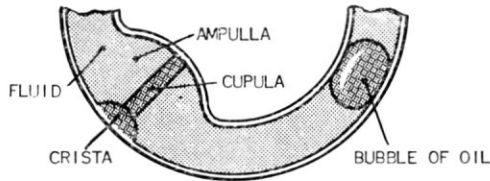
FIG. 3. Misleading sensation on commencing push-over from steady climb.

moves backwards on account of the centripetal acceleration. Hence, if the pilot senses this as the true vertical he feels as though he is pitching upwards when he is in fact initiating the reverse change of attitude. With decreasing angle of climb and constant thrust a sustained illusion of exaggerated pitch-up attitude is to be expected on account of the consequent forward acceleration.

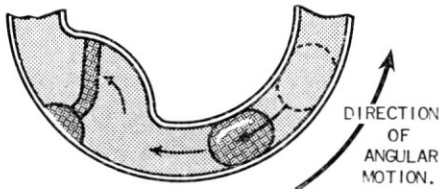
Rotation sensation tends to be misleading on account of the mechanical nature of the rotation sensitive devices contained in the skull. On each side there are three so-called semi-circular canals arranged in three planes approximately at right-angles to one another. For simplicity each of these may be considered as a circular tube of very small dimensions (roughly 0.7 cm diameter of the circle and 0.025 cm internal diameter of the tube) containing fluid together with a water-tight, spring-loaded, hinged flap (the cupula) which behaves as a sensitive indicator of the relative volume flow. Thus, as illustrated in Fig. 4, when the tube is given an angular impulse in its own plane, the contained fluid tends to be left behind on



(a) Circular tube containing fluid.



(b) Main functional components of a semi-circular canal, together with an artifact, a bubble of oil, inserted for the purpose of demonstrating fluid displacement.



(c) Displacement of fluid and cupula due to rotational movement.

FIG. 4. Mechanical nature of the semi-circular canals.

account of its inertia. The water-tight flap is then deflected by an amount proportional to the relative fluid displacement, as can be seen in Fig. 4c, with the aid of a bubble of oil, imagined as inserted into the tube for the purpose of demonstrating the fluid movement. In a system having so small a scale as this the viscous forces are relatively very high and the relative fluid flow is in practice very small indeed. Consequently the fluid is virtually carried round with the system so that the inertial force tending to cause fluid flow, and therefore rate of fluid flow, is at every instant very nearly proportional to the angular acceleration of the system. It follows that the actual displacement of fluid within the canal, and hence angular deflection of the flap, is to a close approximation proportional to the change in

angular velocity of the system as a whole. The flap in turn generates a nervous signal closely related to its angle of deflexion, over a fair range of angular velocities⁽²⁾ and the system as a whole therefore behaves as an angular speedometer feeding a rate of turn signal into the brain.

But the flap is elastic, a necessary adjunct to provide a datum, and it is this "return spring" which gives rise to errors in the system when rotation is sufficiently prolonged for them to develop (Fig. 5). If, for example, an angular velocity is quickly generated and then maintained

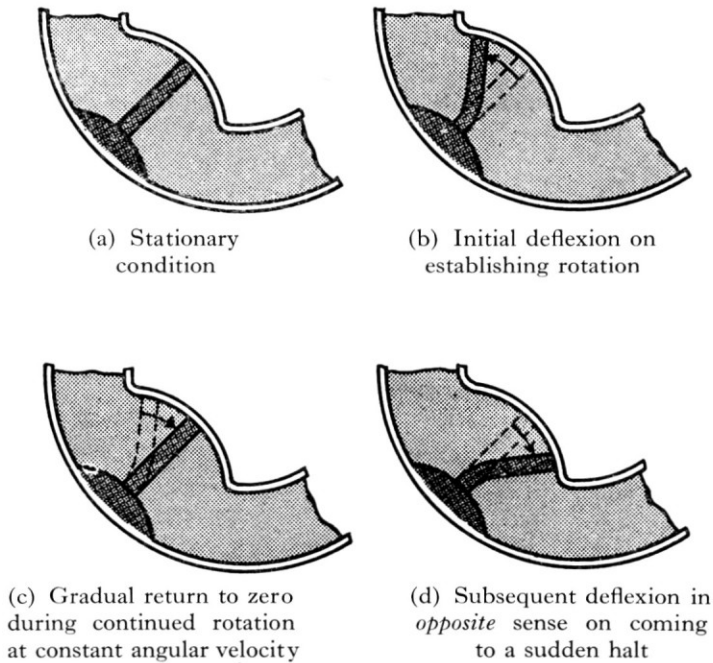


FIG. 5. The "return spring" effect of the cupula during prolonged rotation.

constant, the flap will at first be deflected as described but will then, because of its elasticity, return gradually to its datum position. An illusion is then created whereby all sensation of turning is lost despite the presence of actual, perhaps considerable, rotation (Fig. 5c). Moreover, if rotation is then suddenly brought to a halt, inertial forces will deflect the flap an equal extent but in the opposite direction, and a second illusion is created (Fig. 5d); this time there is a strong sensation of turning, equal but opposite to the original rotation, when in fact all rotation has ceased.

In practice, on the ground, where rotational movements are normally short and sharp, time does not permit significant errors of this kind to

develop, for the elastic restoring force in the flap is relatively very small. But in the air, where rotations are usually prolonged as in turning, looping, rolling or spinning, time frequently does permit the development of serious errors and the brain is then fed with misleading information. Of course there are all grades of misrepresentation between the two extremes illustrated in Fig. 5, and it can be appreciated that all manner of erroneous sensations of this nature are liable to be experienced during and immediately after a wide range of flight manoeuvres.

An instructor with many hours experience was being converted to a new type of jet aircraft. With some 30 hours experience on this type he was detailed for a night flight at high altitude when the weather conditions were bad, continuous cloud extending from 500 to 35,000 ft (150 to 10,700 m). After completing a number of manoeuvres above cloud he commenced to descend through it when he at once began to feel he was turning, with right wing down, although his instruments showed him that his wings were level. In his own words, he was "fighting every second of the time" to obey his instruments against what appeared to be his better judgment. The apparent right-wing-down attitude increased until he felt he was upside-down and he even went so far as to apply first forward, then backward pressure on the stick to determine whether air speed was responding as it would in erect or inverted flight. It was with the utmost difficulty that this pilot ultimately achieved a successful but hazardous landing. As an experienced pilot and a qualified instructor he was, of course, fully aware of the fact that when flying in cloud the instruments must be obeyed to the exclusion of all other sensations; yet on this occasion he was seriously misled into believing those sensations despite the clear presentation of the facts in the instruments before him.

In this incident, as in many other similar ones, the duration of illusory sensations persisted longer than would be expected from the normal mechanics of the semi-circular canals. But it is well known to the physiologist that persistent after-effects can be demonstrated when angular stimuli are much in excess of 60° per second, a figure which can easily be exceeded in the rolling plane by many modern aircraft.

Evidently both gravity and rotation sensation are liable to be misleading in most circumstances other than steady flight in a straight line. Fortunately, however, alarming experiences of the kind just described prove the exception rather than the rule, and a pilot normally acquires, during his training and subsequent flying experience, a special ability which in most circumstances allows him to discard such sensations in favour of what his eyes can see; an ability which incidentally can only be maintained by constant flying practice. But this at once throws great emphasis upon the eyes as the only source of information upon which he can rely and leads one to ask the important question, can the eyes be implicitly relied upon in all circumstances of flight?

MISLEADING EYE MOVEMENTS

To answer this question it is necessary to recall that each of the rotation sensitive semi-circular canals feeds an angular velocity signal to the brain which is therefore informed of both magnitude and direction of a rotation. For the remarkable thing is that this information is relayed, amongst other things, to the muscles which cause eye movement, in such a way as to assist the eyes in fixing the image of the surrounding world upon the retina during head movements. If one turns to the right whilst looking at the surroundings, the eyes turn in the opposite sense in their sockets until they reach the limit of their traverse, when they fly back and commence the traverse again. This repeated movement (nystagmus) is easy to understand when the eyes are open, for then the visual fixation reflex comes into play. But the nystagmus continues at roughly the same angular velocity when they are shut or in the dark. Moreover, when errors of the kind discussed above arise in the rotation sensing system, the eyes tend to follow the erroneous signal rather than the actual movement and it is evident they are driven by what amounts to an open-loop servo-link with the semi-circular canals. When the signal is sufficiently strong these inappropriate movements continue even when the eyes are open and the visual image then becomes a misleading one, an effect which has been long recognized and has recently been termed the oculogyral illusion⁽³⁾. Should such an eventuality arise when flying an aeroplane the pilot would be placed in a compromising situation indeed, since he would then be left without any reliable information at all about his orientation.

A programme of research has recently been initiated at the Institute of Aviation Medicine, England, to investigate the influence which this kind of effect may have upon the ability of a pilot to fly an aeroplane, emphasis being placed upon the stimulus about the rolling axis for two main reasons. First, the potential rotational stimulus in conventional aircraft is by far the greatest about the rolling axis, and second, the strong visual fixation reflex which substantially assists voluntary control of eye movements in the horizontal and vertical planes is probably less marked in rolling movements of the eye about a fore-aft axis. That such movements do occur is well established⁽⁴⁾, and that they are a frequent occurrence in flight is apparent from close-up films of eye movements obtained from the apparatus shown in Fig. 6, which essentially comprises a cine-camera mounted on a conventional flying helmet and carrying a periscope, so arranged as to take cine-photographic records of the movement of one eye relative to the head. The motor has been separated from the camera and mounted on the opposite side of the helmet for inertial balance, the two being connected by a flexible drive.

Fig. 7 gives extracts from the analysis of a film taken during and immediately after a 12 sec, four turn roll in a HAWKER HUNTER aircraft and demonstrates rotational nystagmic eye movements about the fore aft axis of the eye; ordinate being angular displacement of the eye, abscissa



FIG. 6. Apparatus for measurement of rotational eye movements.

being time. During the roll the slow phase of these movements is in a direction appropriate to maintenance of a steady image upon the retina of the eye. But immediately after recovery, when the visible horizon is actually stationary relative to the aeroplane, rotary eye movements are initiated having slow phase in the reverse direction, the angular velocity of which, as depicted by the slope of the line, gradually decreases over the course of several seconds. That is, sufficient time has elapsed during the continued rotation for errors to develop in the semi-circular canals which are in turn relayed to the eyes causing them to rotate involuntarily in a manner appropriate to following the *illusion* of rotation, but quite inappropriate to the actual circumstance. For the image of the horizon must then be rotating upon the retina when the actual horizon is in fact stationary relative to the aeroplane.

From initial experimental results obtained with the apparatus in Fig. 6 it also transpires that when making small angles of bank the eyes rotate through a nearly equal, but opposite, angle in their sockets, and may remain in this "tilted" position for several seconds. One is led to

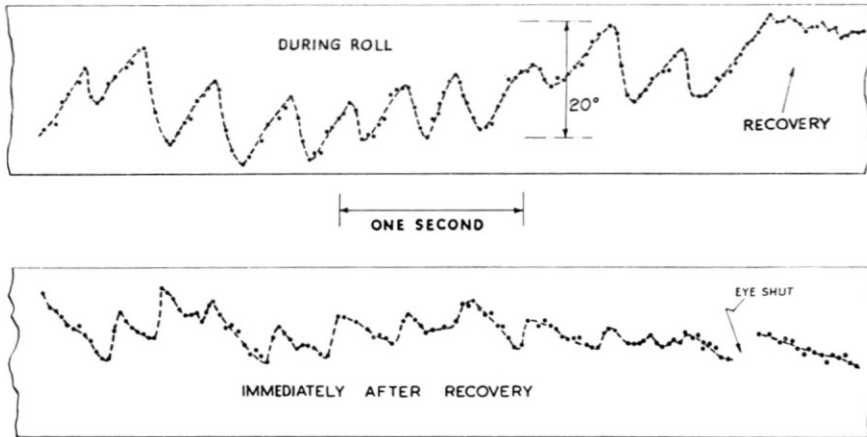


FIG. 7. In flight record of rotational eye movements during and immediately after a 12 sec, four turn roll.

infer that here, too, there are features which could interfere with a pilot's interpretation of what he sees. On suddenly rolling out of a prolonged turn, for example, the eye is liable to be left in a tilted position for some time, with the possible consequence that the visual image will appear to be correspondingly tilted. Certainly on performing this simple manoeuvre in a closed-in cockpit one can be left with the temporary visual impression that it is tilted with respect to oneself.

Evidently both theoretical considerations and the results of experiment lead to the conclusion that misleading eye movements constitute a potential cause of disorientation in flight. That this is so in practice is substantiated by the fact that it is common for a pilot to experience difficulty in recovery from a rapid rolling manoeuvre extending over three or more complete revolutions, or indeed from any manoeuvre involving prolonged rapid rotation, as in spinning. When the rotation is very fast, additional factors come into play and difficulty can be experienced after but a few seconds. For if the actual angular velocity exceeds the maximum compensatory angular velocity of eye movement, then the image, being a moving one upon the retina, becomes blurred and difficult to interpret. Moreover, if the angular stimulus exceeds the point at which the cupula reaches the limit of its traverse, then on subsequent deceleration its return will be out of phase with the actual event and the pilot may be expected to lose his datum very rapidly, both on account of strong misleading rotation sensation and the consequent generation of misleading eye movements. Fig. 8(a) shows the time course of rate of roll of an aircraft and displacements of the three primary controls in a very rapid rolling manoeuvre in which complete loss of control occurred during the recovery phase.

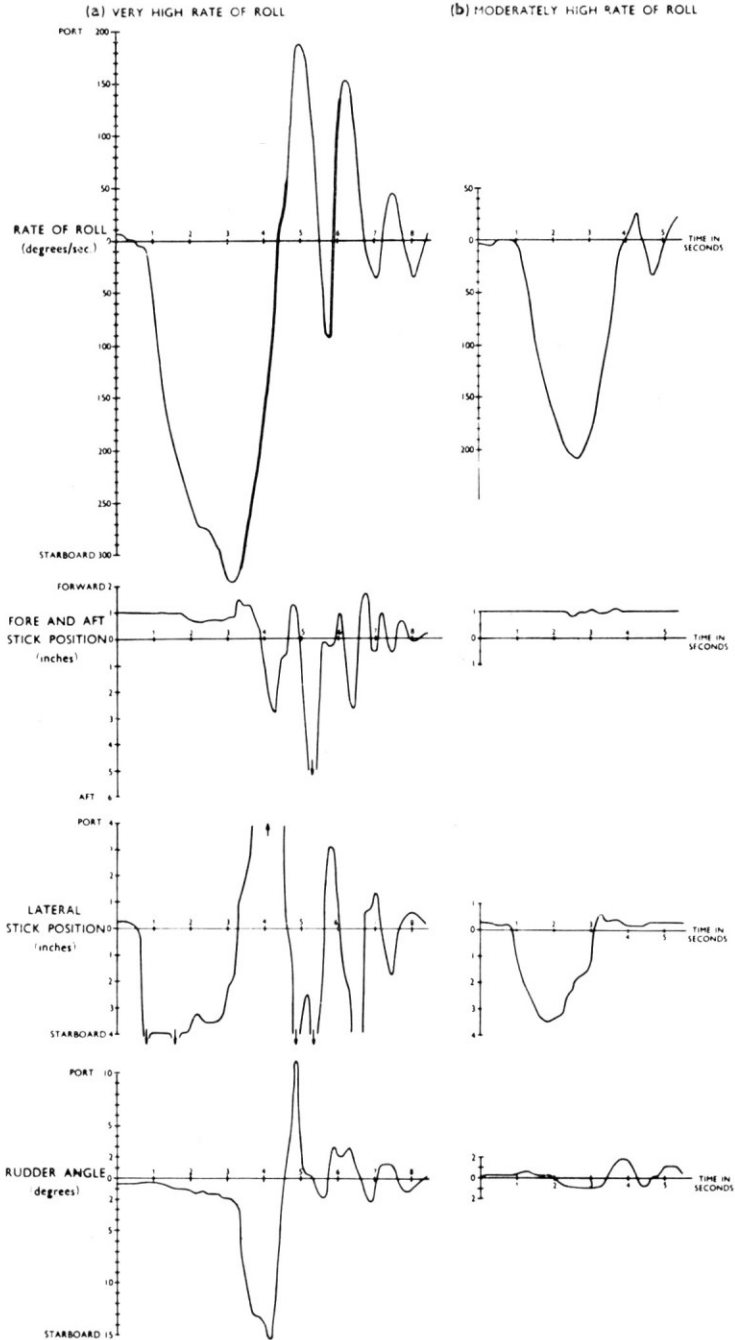


FIG. 8. Comparison of control movements during the very high rate of roll manoeuvre in which aircraft control was lost with those for a moderately high rate of roll manoeuvre in which control was not lost.

An initial lateral stick movement was made and the roll commenced with the high angular acceleration of roughly $400^\circ/\text{sec}$. When the angular velocity approached $330^\circ/\text{sec}$, the pilot took recovery action and the rate of roll rapidly decreased. But instead of coming to a halt as intended, a rapid roll in the opposite direction was initiated. Simultaneously a series of violent and somewhat unco-ordinated movements occurred in all three primary controls and a series of violent oscillations followed. The pilot then wisely abandoned conscious attempts at restoring control and fortunately the intrinsic stability of the aircraft rapidly damped out the subsequent oscillations.

The unusual character of these events can be judged by comparison with Fig. 8(b), which is a similar series of records taken during a similar but somewhat slower manoeuvre conducted by the same pilot in the same aeroplane, but in which control was retained throughout.

The difficulties experienced by the pilot in this incident must have been in part due to the high frequency of the oscillations, once they had been established; for even a normal undisturbed man can find difficulty in tracking a sinusoidal oscillation with frequency approaching 1 c/s. But the pilot affirms that, in place of a clear-cut horizon, he was only able to distinguish a blurred impression of dark and light and that he became violently disoriented. One may conjecture therefore that it was this which initially caused him to stimulate the oscillations which would not otherwise have occurred in an aerodynamically stable aircraft.

CONCLUSIONS

To sum up, attention has been drawn to the unreliability of sensing mechanisms other than the eyes during flight, and evidence has been given suggesting that even the eyes may at times feed misleading information to the brain. Research into the many facets of the problems raised is at an early stage and factual data as yet available in this particular field are somewhat limited. But perhaps the evidence to date is enough to lead one to the conclusion that aerodynamic stability is not always in itself sufficient for maintenance of control in the man-machine combination, since disorientation of the human operator can upset even the aerodynamically stable aircraft. In some branches of Aviation Medicine it is possible to adapt the man artificially to the flight environment as by breathing oxygen, if necessary under pressure, at high altitude; or by heating or cooling him to confine the limits of temperature change within his tolerance. But it is hard to see how to avert disorientation in a similar way. Perhaps the aim here should be rather to establish by experiment where the human limits lie, with a view to assisting both designer and user in avoiding their being exceeded during flight. For example, it is desirable that an aircraft should be incapable of entering the spin, or at least easily prevented

from doing so in the incipient stage, because once the spin is entered, even if the aircraft will recover on its own, the error signals to which a pilot rapidly becomes subjected may cause him to prevent its recovery. It has also been suggested provisionally that the likelihood of incurring pilot disorientation may rapidly increase with angular velocity, at rates of roll in excess of $200^\circ/\text{sec}^{(6)}$.

Finally, it is worth noting that an aircraft simulator, however well it may be designed, cannot impose the linear and angular accelerations which generate the misleading sensations to which a pilot must needs acclimatise himself for proficiency in flying an aircraft on instruments.

In this paper, time and space of course permit no more than a glance at one facet of one problem in the increasingly difficult matter of matching the man to the machine and *vice versa*. Nevertheless, the material considered provides a useful example of the way in which hidden characteristics of man can reveal themselves in the somewhat hostile environment of flight, and it is hoped that it has been possible to give some insight into the kind of contribution which the science of Aviation Medicine has to offer to the broader field encompassed by the term Aeronautical Science.

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DISCUSSION

K. O. LANGE*: Dr. Jones suggests that a great deal of experimental research is needed on the interrelation between aircraft motion and human senses. I am glad to be able to report briefly on one phase of such work which has been underway since 1957 through collaboration between the Aero-Medical Laboratory of the Wright Air Development Center and the Wenner-Gren Aeronautical Research Laboratory of the University of Kentucky.

This research is particularly concerned with the effects of buffeting-vertical motion caused by high speed flight through turbulent air—such as occurs in the landing of boost glide vehicles. Here the motion is fundamentally only in one degree of freedom which simplifies the problem compared to Dr. Jones' research, but the accelerations alternate up and down so rapidly that no orderly adjustment of the human sensory mechanism can be expected. The ordinary blind flying instrumentation is inadequate for such flight, so that the control of the aircraft

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depends on the pilot. In severe buffeting the pilot can lose his sense of equilibrium, and the exact limits are being established with the help of a special vertical acceleration simulator capable of simulating the vertical components of aircraft motion of up to 20 ft double amplitude and up to 5 *g* maximum acceleration.

After the loss of the sense of equilibrium, the pilot depends on vision alone to control the vehicle. Present experimentation on the effect of buffeting on visual acuity, following earlier work by R. R. Coermann, is to establish also where the limits of human vision lie under such flight conditions.

It should prove very valuable to be able to utilize Dr. Jones' investigations into the exact behaviour of the eye under acceleration, in interpreting and explaining this American research which is chiefly concerned with determining the limitations of the human pilot and with developing means of improving his performance.

D. M. JAMESON*: Suppose a pilot, fully competent at flying on instruments, had to recover on instruments from, for example, a spin in cloud: would eye movements such as we have been shown interfere with reading the instruments, even though the instrument panel formed a frame of reference?

G. MELVILL JONES: It is not possible to answer this question with a categorical yes or no. For although a pilot certainly can learn to recover from a spin on instruments, it is well known that this is a difficult procedure. In my opinion, based on cine records taken during and immediately after spinning manoeuvres in an aeroplane, misleading eye movements can contribute substantially to this difficulty. But here it is probably not so much a matter of misinterpreting position and movement of instrument pointers relative to their frame of reference, as of loss of definition due to movement of the image across the retina. One pilot exclaimed, "I couldn't see my instruments; they were going off to the left!"

At the present stage in this research one cannot say more than this, but it is hoped that in the near future it will be possible to make a more accurate statement on the matter.

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