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On an Aspect of the Accident History of Aircraft Taking Off at Night

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in the University of Bristol, sometime Assistant Secretary,
Aeronautical Research Committee

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Summary.—An investigation is described into the cause of a series of accidents to aircraft taking off at night; it depends on the fact that the direction of the net reaction on a pilot's body during acceleration is the same as that corresponding to a steady climb. The analysis and a numerical illustration are given in Part I. The results of flight tests designed to check the analysis are summarised in Part II: the results confirm the theoretical findings. It is concluded that the only faculty which can be safely used is that of vision, and this implies the use of instruments throughout the whole of the take-off at night.

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1. *Introduction.*—The investigation described in the present paper began as an attempt to provide a possible explanation for a series of accidents to aircraft immediately after taking off at night. The majority of cases occurred during the period in 1940–41 when an intensive training of pilots for night flying was in progress. The accidents were all similar in character: following a normal take-off the aircraft was flown into the ground under power in a manner which suggested strongly that the pilot was in each case unaware that his aircraft was losing height.

In Part I are given the arguments and simple analysis which show that if, in the absence of visual aids, a pilot refers to the direction of the reaction of his body to assess the attitude of his aircraft, he may be completely misled. The analysis is substantially that of a note originally communicated to the Chief Inspector of Accidents of the Air Ministry (now of the Ministry of Civil Aviation), and submitted to the Aeronautical Research Committee[1]. This note contained also a simplified exposition of the argument, devised for the information of the Service, which formed the basis of an article in the Training Manual.

At the suggestion of the Chief Inspector of Accidents, the Director of Flying Training authorised some flights at the Central Flying School, Upavon, to check the implications of the theory. The flight tests are described and extracts from the flight reports are given in Part II. A summary of the tests was also communicated to the Aeronautical Research Committee.[2] On the whole, the tests give substantial support to the theory, and it may be concluded that an adequate explanation of the accidents has been provided. The obvious remedy, in view of this explanation, was that a pilot should give rigorous attention to instruments during take-off; in this way he makes use of his visual faculty—the only sense which is capable of giving him a true assessment of the attitude of his aircraft. It is to be remarked that the phenomena which affect the pilot can also affect those instruments depending on gyroscopes. However, these are not the only instruments which the pilot can consult; moreover, the response of gyroscopic instruments takes time to develop, whereas the effect on the pilot is instantaneous.

PART I

Theoretical Investigation

2. *Nature of the Accidents.*—The accidents were all of a similar character. The pilots had usually had considerable experience of day flying, but were new to night flying ; the aircraft were generally of the single-seater type. A normal take-off was made, and as the aircraft was gaining height the usual turn down wind was begun ; thereafter the aircraft was flown into the ground in a shallow dive under power. The fact that the accidents occurred at night made evidence from ground observation virtually impossible to obtain, except for a record of the noise of the aircraft. Examination of the wreckage showed, however, nothing to account for the accidents, and all the circumstances pointed to the fact that the aircraft was in each case inadvertently flown into the ground. The following extracts from a letter addressed to the Secretary of the Aeronautical Research Committee give a description of a typical accident.

> " . . . the attitude of the aircraft shows that it was flown into the wood, as opposed to having been stalled into the ground. There is no evidence of engine failure, and witnesses state that the engine was running normally until impact. The Chief Inspector of the Accidents Investigation Branch has stated . . . that this type of accident has been very common . . . and is caused by pilots, inexperienced in night flying, turning after leaving the ground to orientate themselves on the landing lights and flying into the ground after turning down wind, instead of settling down to fly the circuit by instruments."

3. *A Possible Cause of the Accidents.*—The accident history made it clear that the pilot was in each case flying confidently and unaware that he was losing height. This would not occur in daytime ; what then was the criterion which was giving the pilot a false sense of security ?

Having been deprived of visual aids in the form of a visible horizon, and on the assumption that he was not watching his instruments, the pilot must have referred (probably subconsciously) to one of his remaining four senses for guidance ; of these, only hearing and touch can possibly assist him. Hearing might help in the case of an aircraft with fixed pitch propeller, since the engine speed would tend to change with the forward speed ; but in the case of a constant speed propeller this help is denied. There remains the sense of touch, in the form of pressure on the pilot's body due to the reaction from his seat ; this seems to offer the only criterion—but a quite likely one—by which the attitude of the aircraft may be judged. This reaction is in fact a part of " feel "—that somewhat indefinite quantity by which pilots, unless they are schooled to the contrary, frequently assess the qualities of an aircraft.

An investigation was therefore made into the direction of the reaction on the pilot's body under the flight conditions leading to an accident. As shown below in paras. 4 and 5, to use this reaction as a criterion can be most misleading and will certainly delude a pilot ; it will not necessarily cause him to commence a dive, but will very effectively mask the fact that a dive has begun.

4. *The Forces on a Pilot.*—Since the pilot is in a gravitational field, he is subject to a " body force " which must be opposed by the reaction supporting him ; any external force additional to this reaction will produce acceleration. Moreover, it must be realised that the pilot will not be aware of the gravitational body force, since it acts unvaryingly on all particles of his body ; he will be aware only of the reaction, which is applied locally and which varies with his attitude.

Consider first the reaction on a pilot in *steady* horizontal flight during daylight—a condition in which most of a pilot's flying time is spent. Since he is unaccelerated, the only force of which the pilot is conscious is the reaction R opposing his weight, which is vertical and normal to the flight path (Fig. 1).

The pilot will regard this as a normal reaction and will subconsciously relate it to the aeroplane as a frame of reference ; thus his " normal reaction " N is in a direction fixed in the aircraft and approximately perpendicular to the centreline of the fuselage.*

* This argument neglects the changes of aircraft incidence due to changes of speed ; however, we are here concerned with changes of angle of flight path considerably larger than any incidence change, and for the purposes of qualitative argument we neglect the changes in incidence.

In steady horizontal flight (Fig. 1) the pilot's mind registers

(*a*) " The reaction on my body is along the normal direction, and I see that I am flying level."

Next consider the cases of *steady* climb and *steady* dive, also during daylight. Here again the only reaction on the pilot is that opposing his weight ; it is therefore vertical and inclined to the aircraft as shown in Figs. 2 and 3. Thus the pilot's mind registers, in relation to what he feels and sees,

(*b*) " The reaction on my body is inclined forward from the normal direction, and I am climbing ", or

(*c*) " The reaction on my body is inclined backward from the normal direction, and I am diving."

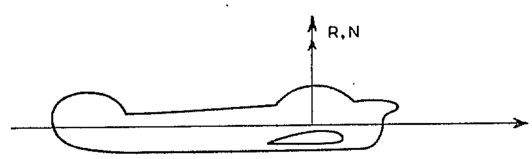

FIG. 1.

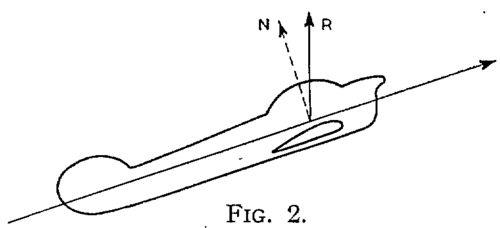

FIG. 2.

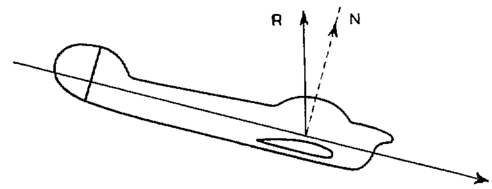

FIG. 3.

So much for steady conditions ; and it may be noted that, for steady conditions, the pilot may safely use (*a*), (*b*) or (*c*) to deduce from the direction of the reaction what is the attitude of his aircraft even when he can no longer see what is happening.

We turn now, however, to accelerated conditions. During the take-off and immediately afterward the aircraft is gaining speed, and the pilot is being accelerated with the aircraft. So long as the thrust exceeds the drag there is a forward force on the aircraft and an exactly similar additional reaction on the pilot. The reaction on the pilot is therefore the resultant of a force in his " normal direction " and a forward component proportional to the excess of the thrust over drag ; it is inclined forward from his normal direction whatever the attitude of the aircraft. Accordingly, the angle between the direction of the reaction on his body and his " normal direction " is no criterion of the attitude of the aircraft except in steady conditions : even more important is the deduction that as a criterion it will give the pilot a false sense of security during take-off. For when the thrust exceeds the drag, the reaction on the pilot is inclined forward from his normal direction, and if he refers subconsciously to (*a*), (*b*) or (*c*) above, he will deduce that (*b*) applies and that he is climbing, when in fact he may be losing height.

The following alternative approach to the explanation may be helpful. Consider first the pilot in ordinary steady flight. Let his seat be slowly tipped back ; then he is thrown more and more heavily against the back of the seat. On the other hand, if his seat is tipped forward, he will tend to slide forward off the seat. Now imagine the aircraft to be given a forward acceleration. Since it is impossible to distinguish between this acceleration and that of a gravitational field* the pilot will interpret the combined reaction due to the acceleration and due to gravity as

* See, for example, Ref. 3, Chap. VI. This principle is of course well known in aeronautics, being given common expression in the statement that an aircraft is flying at 1*g* when it is in level flight.

meaning that the direction of gravity has changed relative to the aircraft, in a sense which throws him back in his seat. But in his experience the direction of gravity is almost always vertical and he deduces that the attitude of his aircraft has changed in a nose-up sense.

5. *The Formal Analysis and an Illustration.*—The mathematical expression of the foregoing argument is simple. Suppose the aircraft flight path is inclined at an angle θ to the horizontal: let the forces acting be as shown in Fig. 4. By resolution along and normal to the flight path we obtain

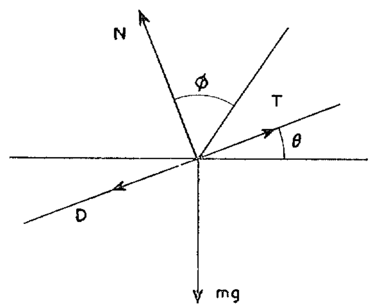

FIG. 4

$$T - D - mg \sin \theta = mf \qquad (1)$$

$$N - mg \cos \theta = 0, \qquad (2)$$

where f is the acceleration along the flight path. The forces acting on the pilot are in exact proportion to those on the aircraft, and we may now regard the diagram as representing forces on the pilot. The reaction he feels is therefore the resultant of the external forces T, D, and N; if this reaction makes an angle ϕ with the direction of N (the "normal direction") then we have

$$\tan \phi = \frac{T - D}{N}$$

which by (1) and (2) can be written in the alternative forms

$$\tan \phi = \frac{T - D}{mg \cos \theta} \qquad (3)$$

$$\tan \phi = \frac{mg \sin \theta + mf}{mg \cos \theta} = \tan \theta + \frac{f}{g \cos \theta} \qquad (4)$$

Consider first steady conditions; then $f = 0$, and by (4) $\phi = \theta$. Thus for θ positive, ϕ is positive, i.e. ϕ positive corresponds to a steady climb. But consider now the accelerated condition following take-off: here $T - D$ is positive. Equation (3) shows that in this case ϕ is positive, whether θ is positive or negative; and moreover the value of ϕ is insensitive to the value of θ for the range of values of θ concerned. Thus we have the somewhat paradoxical result that while in steady flight $\phi = \theta$, in accelerated flight ϕ is almost unrelated to θ; it is of course due to the fact that in steady flight $T - D$ is related to θ (see (1)) and changes sign with θ, while for the accelerated condition we are considering, $T - D$ is unrelated to θ.

We may make one further relevant deduction. Consider an aircraft which throughout a flight maintains a positive acceleration f. Then such a flight must end by impact with the ground; for since the speed continuously increases the thrust T decreases and the drag D increases, so that $(T - D)$ decreases and will eventually change sign. But in order to maintain a positive f, equation (1) shows that $\sin \theta$ must also decrease continuously, and must become negative before $(T - D)$ changes sign. Thus the aircraft will fly in an arc beginning and ending on the ground. Moreover, there will by (4) be a positive difference between ϕ and θ, such that ϕ will change sign later than θ — in fact, when $(T - D)$ changes sign. Thus the pilot will sense the dive much later than the actual entry, if indeed he senses it at all before impact.

As an illustration, consider the case of an aircraft for which $(T - D)$ has the form $(a - bV^2)$, where a and b are constants. Actually, owing to variations of thrust with speed and propeller efficiency and of drag with speed, attitude, undercarriage and flap position, etc. (see para. 6), the variation with speed will be much more complicated; but the simple form assumed will not be seriously in error. Thus (1) becomes

$$a - bV^2 - mg \sin \theta = mf. \qquad (5)$$

Now let a constant acceleration f be assumed. Then for a shallow flight path, V^2 will be a linear function of the distance x flown horizontally, and we may identify $\sin\theta$ with dy/dx, where y is the height. Thus (5) takes the form

$$p - qx - mg\frac{dy}{dx} = 0$$

which on integration shows the path to be a parabola. To obtain a quantitative idea of the circumstances under which a pilot might sense the dive in an actual case, let us write the parabola as

$$\frac{y}{h} = 4\frac{x}{l}\left(1 - \frac{x}{l}\right) \qquad \text{(6)}$$

where h is the maximum height reached and l the horizontal distance flown (not necessarily in a straight line) from take-off to impact. Then we may write (1) as

$$\frac{T - D}{mg} = \frac{f}{g} + \frac{dy}{dx} = \frac{f}{g} + 4\frac{h}{l}\left(1 - \frac{2\,x}{l}\right), \qquad \text{(7)}$$

and if the take-off speed is V_0 we have

$$2fx = V^2 - V_0^2,$$

which on substitution for x in (7) shows the variation of $(T - D)$ with V to be of the form assumed. Now the pilot senses the entry into the dive when $(T - D)$ changes sign, i.e. when, by (7)

$$\frac{2\,x}{l} = 1 + \frac{fl}{4hg} \qquad \text{(8)}$$

As a numerical case, let

$$h = 500 \text{ ft.}$$

$$l = 10{,}000 \text{ ft.}$$

$$f = \tfrac{1}{6}g \text{ ft./sec.}^2.$$

Then by (8), $x = 9{,}167$ ft., and the corresponding value of height is $y = 153$ ft. Now the dive is actually entered at a height of 500 ft. and for $x = 5{,}000$ ft. Thus, after entering the dive, the pilot flies about three-quarters of a mile and loses nearly three-quarters of his maximum height before he senses it.

In terms of time the figures are more striking. The time from the take-off is given by

$$ft = - V_0 + \sqrt{V_0^2 + 2\,fx} \qquad \text{(9)}$$

and with $V_0 = 120$ ft./sec., we find that the time from take-off to impact is 42·6 secs.; that the dive is actually entered at $t = 26{\cdot}2$ secs., i.e. 16·4 secs. before impact, but that it is not sensed until $t = 40{\cdot}2$ secs., i.e. 14 secs. after the actual entry and only 2·4 secs. before impact. The speed at impact is 349 ft./sec.

This example illustrates in striking fashion how badly misled the pilot may be. We need only remark further that had the acceleration chosen been slightly greater, namely $f = \frac{1}{5}g$, the pilot would not sense the entry until the actual instant of impact.

6. *Some Relevant Correspondence.*—Following the formulation of the above theory, the writer had some correspondence with the Chief Technical Officer of the Aeroplane and Armament Experimental Establishment, the object being to obtain information on factors affecting drag and thrust and on the use of instruments. Extracts from this correspondence are appended. It will be seen that, at the time of the accidents, it was not usual for pilots to take off on instruments alone; indeed, it appeared that in some cases the artificial horizon was not working properly in any case, insufficient time having been allowed for the gyroscope to attain its full speed.

The following are relevant passages from the correspondence:—

> "1. With reference to your letter . . . there may, as you suggest, be some connection between acceleration and attitude which combine to confuse the pilot after take-off at night. The following items all affect the acceleration after take-off . . . .
>
> (*a*) Position of undercarriage. Pilots are now instructed to raise the undercarriage immediately the aeroplane is airborne. The time taken for the undercarriage to retract fully varies considerably on different aeroplanes; seven seconds for some of the fighter types. . . .
>
> (*b*) Engine conditions. For the take-off the throttle is moved to fully open almost immediately and the airscrew controls (on constant-speed airscrews) are set to give the maximum allowable r.p.m. The airscrew and throttle controls are kept in these positions until the aeroplane has reached about 1,000 ft.
>
> (*c*) Flap angle. The flaps are usually lowered 15 to 25 degrees before the take-off. . . .
>
> 2. Pilots, in general, take off at night as they do during the day; that is, they do not keep their heads inside the cockpit looking at the instruments, but look out over the side of the aeroplane. When the aeroplane is airborne, however, they transfer their eyes from outside to the blind flying instrument panel, and . . . it takes them some time to adjust their senses properly and to keep a correct climbing attitude.
>
> I know there has been a tendency on the part of some instructors and pilots to concentrate on the instruments during the whole of the take-off run, although I am not sure whether this procedure has yet been adopted."

PART II

Flight Tests

7. *Initiation of the Experiments.*—The gist of the theory given in Part I was communicated at an early stage to the Chief Inspector of Accidents, who forwarded the papers to the Director of Flying Training. It was decided that flight tests to check the theory were desirable. The following extracts from a letter addressed to the Commandant, Central Flying School, Upavon, by the Director of Flying Training, describe the tests to be undertaken and give some relevant information.

> "3. The Chief Inspector of Accidents, in commenting on this report, has drawn attention to one of the commonest forms of night flying accidents in which after reaching a height of about 500 ft. the pilot turns and flies downhill with engines on until the aircraft strikes the ground. Such accidents cannot, of course, occur if the pilot is flying by instruments and the cure is better instrument flying. But in many instances it is clear that the pilot's main attention was outside and not inside the cockpit. . . .
>
> 5. It is . . . desired to undertake a simple experiment to determine whether the sensations are felt in the manner suggested . . . and if so, whether they are sufficiently powerful to be likely to influence a pilot's judgment if he is not looking at his instruments.
>
> 6. I am, therefore, to ask that you will arrange for a suitable instructor to be flown as second pilot blindfolded and that he should note during the take-off and subsequently in the air what he considers the attitude of the aircraft to be, i.e. his sensations as to climbing or descending. The important part of the circuit is that during the take-off and on the down-wind leg, and the pilot should reproduce the type of flying which ends in the aircraft striking the ground on the down-wind leg. . . ."

8. *The Flight Tests and Reports.*—Flight tests were carried out at Upavon in a Master (Wasp) aircraft. In the first instance, the tests were made by two very experienced pilots, with over 8,000 hours flying time between them ; the tests were later repeated by one of these officers with three other pilots of varying experience. In all cases, the observer was blindfolded and communicated his impressions to the pilot, who recorded both the impression and the actual manœuvre. Conditions during the tests were varied as far as possible, in that the observer flew with hands and feet on and off the controls and with hood open and shut, and so forth.

The following table gives a few extracts from the flight reports : the impressions of each of the five pilots concerned, while acting as observer, are included in the table. The extracts quoted are some of the reports giving most direct support for the theory of Part I ; in some other cases (not quoted) the observer was confused by bumps, turns, etc., and these reports do not give direct confirmation, except of the general conclusion that no reliance can be placed on the physical sensation as a criterion of attitude.

Aircraft movements	Sensations of blindfolded pilot
Normal take-off followed by a gradually increasing right-hand turn with the nose slowly dropping (maximum height attained 200 ft.). This was followed by a shallow dive while still turning down to ground level. This was done three times with the same result.	Steady straight climb throughout. (A climbing turn was sensed on one occasion.)
Normal take-off to 500 ft. followed by a gradually steepening right-hand turn with the nose dropping and keeping a steady backward pressure on the stick. This was carried on to below aerodrome level fully down wind. This was done twice, both times with the same result.	Steady climb followed by a right-hand climbing turn, nose dropping and aircraft diving. Sensation of dive did not develop until nearly down to ground level, with a speed of well over 200 m.p.h.
Take-off and climb to 400 ft. going into gentle dive down to 50–100 ft.	Climbing turn to left followed by a gentle straight dive. Dive sensed rather late.
Take-off, straight climb to 300 ft. followed by climbing turn right to 400 ft. gradually steepening turn and changing to diving turn through 180 degrees to ground level.	Straight climb followed by a climbing turn to the left, then changing to a right-hand turn and level flight (fore and aft). This change to a right-hand turn was felt during steepening of the original right-hand turn. Observer had no idea of loss of height nor sense of diving.
Take-off followed by an early climbing turn left from 50 ft. up to 300 ft. going into a diving turn left until down wind at ground level.	Straight climb followed by a climbing turn to the right, followed by a diving turn still to the right. At one period observer thought we were still climbing although we were actually diving, i.e. the dive was sensed long after it had started.
A climb of 200 ft. followed by a gradual diving turn to the right through 180 degrees.	A climbing turn to the left.
Climb to 200 ft. followed by a gradual left-hand climbing turn to 400 ft. developing into a diving turn (left) through 180 degrees down to a height of 50 ft.	Climb, followed by a climbing turn to the right. No sensation of dive or loss of height observed.

In submitting the flight reports to the Commandant, C.F.S., the officer principally concerned made the following observations :—

" . . . the following conclusions were reached :—

(i) If the aeroplane continued to accelerate after the take-off a turn and dive could develop without any reaction or change in attitude being felt, i.e., a normal climb was indicated.

This was most apparent if the turn and dive were started gradually from say 200 ft. (max.) while still accelerating after taking off.

(ii) As soon as the acceleration period was over following a take-off, and a steady climb assumed, then the pilot's reactions became more normal. . . . On two occasions a gradual turn and dive from 500 ft. following the take-off was not sensed until much too late to make a satisfactory recovery and no idea of the magnitude of the dive was realised. Provided a backward pressure was maintained on the control column throughout turn and dive it was almost impossible to recognise that a dive had developed—certainly there was considerable delay in recognising it."

9. *Conclusions.*—The flight test reports bear out the results of the analysis of Part I, and there can be no reasonable doubt that the explanation suggested for the accident history was correct : i.e. that the pilots concerned were misled by their physical sensations, in the way envisaged in Part I, into thinking that at the time of impact the aircraft were still climbing, or at least were still at a safe height.

The remedy was to hand : it was an insistence on the proper use of instruments. The use of instruments had been stressed at an early stage by the Chief Inspector of Accidents ; and the investigation described here provided a timely hammer to drive home the necessity of rigorous attention to instruments at night. The matter was accordingly brought to the attention of the Service in the Training Manual. Since that time, although some accidents of the same kind have occurred, the accident history has been much improved.

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