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A FLIGHT SIMULATION STUDY OF DIFFICULTIES IN PILOTING LARGE JET TRANSPORT AIRCRAFT THROUGH SEVERE ATMOSPHERIC DISTURBANCES

by

D. H. Perry

J. Burnham

SUMMARY

A ground based flight simulator, having motion freedoms in pitch and roll, has been used to study the difficulties of flying a representative jet transport aircraft through severe storm turbulence. Random atmospheric disturbances of RMS velocity 15 ft/sec, combined with longer term draughts in the vertical plane of up to 200 ft/sec were studied during flight on instruments.

Most pilots had surprisingly little difficulty in controlling the aircraft despite the severe conditions represented. Some, who made power and trim changes freely however, tended to set up long period oscillations in speed and flight path, similar to those which have been reported in flight. The results provide a useful experimental demonstration of the validity of current rough air flying techniques.

One case of temporary loss of control occurred during the tests and this was attributable to the distraction of the pilot from the main flying task during R/T conversation.

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*Replaces R.A.E. Technical Report No.65195 - A.R.C. 27554

CONTENTS

1 INTRODUCTION

During the past few years a number of incidents have occurred in large jet transport operation which appear to fall into a similar pattern[1]. Broadly speaking they have all involved some loss of control* over the aircrafts' longitudinal motion, resulting in the aircraft entering a steep dive from which recovery has either not been achieved, or has been achieved only after subjecting the aircraft to excessive manoeuvering loads. The cause of these incidents has not yet been precisely determined.

In one or two cases the aircraft carried flight recorders from which continuous trace readings of a few variables, such as height, airspeed, normal acceleration and heading, have been obtained. As an example of this type of incident, Fig.1 shows extracts from a trace recording made in a Boeing 720 aircraft during a scheduled flight over Nebraska in July 1963. In this instance control was lost at between 35000 feet and 40000 feet, during an encounter with heavy turbulence, and recovery was only effected at a height of about 12000 feet.

Although many of these incidents have taken place under conditions of severe atmospheric turbulence, the first of the possible causes to come to mind - structural failure - has been eliminated, at least for those cases where control was regained before the aircraft struck the ground. The search for the cause has therefore been centered on other possible effects of severe turbulence, such as structural vibration of the pilot's cockpit, which might upset the flight instruments or the pilot's ability to read them; or the possibility of the pilot becoming dis-orientated as a result of apparently conflicting indications from his instruments, combined with unusual motion sensations. Possible causes arising from the aircrafts' aerodynamic or control system characteristics are also being studied.

The present simulator investigation was made as a preliminary attempt to establish what control actions a pilot might make when flying through severe turbulence, and in order to gain a practical 'feel' for the problem. It was also hoped to discover whether there were any obvious signs of dis-orientation, due to unusual or conflicting instrument indications. The study was confined to searching for possible explanations as to how the type of incident described above might start. Once a disturbed condition had become established there might be further problems arising in the recovery, but these were beyond the scope of the present study.

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* The term 'loss of control' is used in this context to describe any situation in which the pilot loses command over the motion of the aircraft. No specific cause, e.g. loss of control effectiveness is implied.

2 DESCRIPTION OF THE SIMULATION

The tests were made on the Aerodynamics Department research simulator at R.A.E. Bedford[2]. This simulator was designed for studying handling problems on small fighter or the research type of aircraft, and the cockpit layout and general environment were therefore not very typical of a large transport aircraft. For these tests however the fighter type control stick was replaced by a control column and wheel, so that the control forces and movements could be made representative of those used in larger aircraft.

The flight instrument layout was similar to that used on many British transport aircraft, currently flying, but the artificial horizon, although of a type still much in use, was not representative of the latest practice.

The instrument panel is shown in Fig.2, and the instruments themselves are described in more detail in Section 2.1 below.

This simulator is provided with several alternative visual devices for representing the pilot's view outside the aircraft, but none of these were used in the present study which was treated entirely as an exercise in instrument flying.

A limited amount of cockpit motion was provided in pitch and roll by a hydraulically driven moving mechanism. This aspect of the simulation is described in more detail in Section 2.2 below.

The flight conditions represented on the simulator were those appropriate to a large jet transport aircraft, (A.U.W. 280 000 lb), cruising at 250 knots E.A.S. at an altitude of 30000 feet. This speed was chosen as being a typical recommended 'rough air' speed for this class of aircraft. The corresponding Mach number was M = 0.67. The equations of motion used were in the usual small perturbation form and probably involved considerable simplification of the real aerodynamic characteristics of such an aircraft. In particular, Mach number effects such as drag rise, trim change and loss of elevator effectiveness were not represented, nor was there any trim change due to engine thrust changes. While the use of the small perturbation concept is therefore not wholly valid for the conditions represented in this study, it was felt to be adequate in the present context: further more such tests will show how far loss of "command" is possible even with no loss of (aerodynamic) stability and control.

The atmospheric conditions were represented by random noise signals, filtered to produce a power spectrum corresponding to that of atmospheric turbulence, and superimposed on longer term variations in air velocity corresponding to large scale vertical or horizontal draughts. Vertical draughts of up to 200 feet/second and horizontal draughts of up to 100 feet/second were studied in the tests. In the lateral plane only random atmospheric disturbances were represented.

Appendices A and B deal more fully with the representation of the aircraft and the atmospheric disturbances on the simulator.

2.1 Flight instruments

The flight instrument layout used in these studies is shown in Fig.2.

The artificial horizon was approximately 3 inches in diameter and consisted of a fixed aircraft symbol at the centre and a moving horizon bar. The sensitivity, for small altitude changes from the horizontal, was such that the horizon bar moved roughly 0.3 inches for each 10 degree change in aircraft attitude. The scaling was non-linear however and the sensitivity fell off increasingly rapidly at attitudes larger than about ±30 degrees, so that a total range of ±65 degrees could be accommodated. There was no pitch attitude scale marked on the instrument, nor were there any facilities for setting a datum attitude.

The A.S.I. was a single pointer instrument covering the speed range 60-600 knots in roughly one and a half sweeps of the pointer. The scale was linear and marked in divisions of 10 knots (about $\frac{1}{4}$" movement of the pointer tip).

The V.S.I. covered the range ±4000 feet per minute rate of climb and had a sensitivity such that the pointer tip moved through about $\frac{3}{4}$" for each 1000 feet per minute of vertical speed.

The altimeter was a three pointer instrument reading in hundreds, thousands and tens of thousands of feet.

The behaviour of the aircraft pressure instruments under the severely convective atmospheric conditions represented in these tests is a matter of some conjecture. In this simulation it was assumed that the A.S.I. faithfully indicates equivalent airspeed, and that the altimeter and V.S.I. would correctly indicate true height and its rate of change. Lags and position error in the pressure instruments were not represented.

The instrument panel also contained a turn and slip indicator, compass and engine R.P.M. indicator.

2.2 Cockpit motion

A general view of the cockpit and its motion system is shown in Fig.3. In the longitudinal plane the motion consisted only of a pitching rotation about an axis some six feet behind the pilot's seat. While the principal sensation imparted to the pilot was the one of changing attitude, there was, in addition, some normal motion due to the distance from the cockpit to the pivot.

In most of the present tests this single freedom of motion in the longitudinal plane was used simply to represent attitude changes of the aircraft. The translational motion experienced in the simulator was therefore deficient, partly because the component arising from the heaving motion of the aircraft c.g. was not represented at all, and partly because the translational motion of the pilot's cockpit, arising from rotation of the aircraft about its c.g. in flight, was only represented in a much diminished form on the simulator. (The effective distance from the pivot on the simulator being only six feet, instead of perhaps sixty feet on the aircraft.)

Despite these considerable limitations in the cockpit motion, pilots received this aspect of the simulation reasonably well and seemed to feel that the motion produced did enhance the general sensation of flying in rough air. However the motion was generally felt to be less severe than would be expected from the conditions shown by the flight instruments.

In some of the tests an attempt was made to represent the heaving motion of the aircraft by driving the motion system so that the translational, rather than the rotational component of the simulators movement matched that of the aircraft. This could only be done however by introducing attitude changes on the simulator cockpit which did not correspond to attitude changes in the real aircraft. In addition the translational motion resulting from the 30° range of attitude available on the simulator, i.e. 3 feet, was so small that the translational motion had to be artificially damped out almost as soon as it had been initiated in order to avoid hitting the limits of the motion travel.

Pilot's who tried both forms of motion simulation found that flight in turbulence was more difficult to control in the latter case than when the motion simply represented pitch attitude changes. Whilst this might be attributed to a genuine control difficulty, arising from the effects of normal acceleration, it seems much more likely that it was simply due to the presence of spurious motion sensations, because of the false attitude changes and because of the distortion of the acceleration inputs needed to keep the motion travel within bounds.

In the rolling plane the simulator cockpit was banked in proportion to computed aircraft bank angle, the available range of movement being ±15 degrees.

3 CONDUCT OF THE TESTS

Ten qualified pilots took part in the tests with the aircraft characteristics represented as described in Appendix A. Of these, five had considerable current experience of large jet transports in airline operations. (These are denoted by the code letters, D, E, J, K and L when discussing the results in Section 4.) The remaining five were pilots engaged on experimental or test flying, usually with a military background of medium or heavy aircraft experience, (A, B, H, I), although one had most of his experience on the lighter type of twin engined aircraft (N). All were well qualified in instrument flying.

Shortly after the experiment started it was discovered that the aircraft characteristics described in Appendix A had not, in fact, been correctly represented. The effect of this was to make the aircraft speed unstable, and also to simulate a more aft centre-of-gravity position than was used for the remainder of the tests. At the time of this discovery two other qualified pilots had made trials. The results of these are noted separately in Section 4, since they may be of some interest in indicating the effect of more adverse, but still practicable aircraft characteristics.

The pilot's briefing before the test was as follows:-

"You are flying a large jet transport aircraft at 30000 feet with the autopilot disengaged and at the recommended rough air speed (250 knots). It is known that there is thunderstorm activity in the neighbourhood. During the flight you may be asked to make changes in height or course and these instructions should be treated as though they had been made by an air traffic control centre. Try to fly the simulator as you would an aircraft under these conditions and make any calls to A.T.C.C. that you would consider appropriate."

There was no discussion, prior to the trial, as to how the aircraft might behave, nor of what action the pilot should try to take. However, by the time these tests were made, (in September/October 1964), airline pilots generally were well aware of the problems of rough air flying and had been given advice on the technique to use in such conditions. Broadly this was described as "attitude flying", but the interpretation of this technique in practice was one of the objects for study in the present investigation.

Before the experimental portion of each trial the pilot was given a learning period in which to become accustomed to the environment of the simulator and to the handling characteristics of the aircraft represented. The simulated turbulence, but not the large draughts, were demonstrated during this time. The actual trials were not started until the pilot said that he was happy that he knew how the simulated aircraft responded to the controls, this learning period lasting between twenty minutes and an hour for different pilots.

Each trial lasted between fifteen and twenty five minutes. During this time the simulated aircraft was subjected to continuous random disturbances, representing atmospheric turbulence having an RMS gust velocity of approximately 15 feet/second. In addition, five or six large draughts, with peak velocities of up to 200 feet/second and lasting for durations of from ten to twenty seconds were superimposed on the random disturbances. Towards the end of each trial the pilot was asked to reduce altitude from 30000 to 20000 feet, and then, about five minutes later, to turn onto a new heading. One of the larger draughts was usually made to coincide with the beginning of each of these manoeuvres.

Continuous trace recordings of the following nine variables were taken throughout the trials. These, together with the pilots comments, formed the data resulting from the tests.

Horizontal component of draught velocity
Vertical component of draught velocity
Elevator
Throttle
Aircraft pitch attitude
Normal acceleration at c.g.
True rate of climb
Equivalent airspeed

4 RESULTS AND DISCUSSION

4.1 Data from recordings

As an illustration of the type of records obtained during these tests Figs. 4(a) to 4(e) show the complete time histories for the trials with four of the airline pilots (i.e. D, J, K, L), and for the pilot, (N), who had the least experience of large aircraft. These records are included to provide an overall picture of the sequence of events during the trials, and to illustrate some of the longer term fluctuations in the variables. It is appreciated that these records may be difficult to interpret, because of the small scale on which they have had to be reproduced, and because of the intermingling of some of the individual traces*. Portions of some of the records are therefore reproduced in a clearer form in later figures.

Significant differences in the precision with which various pilots could control the simulated aircraft when flying through turbulence are apparent from the five records reproduced. Pilots K and L (Figs. 4(a) and (b)) were notable for the ease with which they limited the excursions in airspeed, pitch attitude and rate of climb to relatively small values, considering the severe nature of the applied disturbances. Negligible changes in throttle position and small, gentle elevator usage are a feature of these records.

Pilot J was performing almost as well, although using larger throttle movements and rather more activity on the elevator, until the start of the descent. At this point however a very large excursion in speed, attitude and rate of descent occurred, amounting almost to an upset, apparently similar in character to those which gave rise to this series of tests. This incident is described and discussed in greater detail in Section 4.

Pilot D (Fig.4(d)) maintained adequate control throughout the exercise but his excursions in speed, attitude and rate of climb tended to be larger than in the other cases just discussed. More use was made of the throttle, and there was a more distinct tendency towards long term oscillations of the flight path, which are most apparent on the rate of climb trace. The period of these oscillations was usually about 45 seconds, i.e. just under one half of the period of the aircrafts phugoid mode (about 110 seconds).

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* The following guide towards recognising the different traces in figures (a) to (e) may be useful.

The randomly fluctuating trace at the top of the record shows the output of the noise generator used for representing the vertical component of atmospheric turbulence, (see Appendix B.1). It is of little immediate importance in the present discussion. The two traces below this, which are steady for much of the time, but which may be identified by the occasional ramp-function disturbances, show the horizontal and vertical components of draught velocity, the vertical component being the lower of these two traces. Below this again is the trace showing throttle position, which may be identified by its generally steady behaviour, with occasional step like changes. Two traces in the centre of the record show elevator angle and pitch attitude. These often follow each other fairly closely, but the attitude trace may generally be identified by its smoother appearance and, frequently, by the presence of the aircraft short period oscillation, having a period of about four seconds. The normal acceleration trace may be identified by its typically spiky appearance. Towards the bottom of the record the rate of climb trace is distinctive for its smooth, long period, fluctuations, and beneath this, usually the lowest trace, is that recording indicated airspeed.

Pilot N (Fig. 4(e) found control of the simulator during this exercise more difficult than did any of the other pilots who took part. A tendency towards oscillation of the flight path was apparent, even in the absence of any draughts, with the period of this oscillation again being about 45 seconds.

The records shown in Fig. 4(a) to (e), together with those of the other pilots, were analysed to find the maximum excursions in airspeed and pitch attitude which occurred throughout each trial.

The results are shown in Table 1 below.

Table 1

ANALYSIS OF SIMULATOR RECORDS

MAXIMUM EXCURSIONS OF SPEED AND ATTITUDE DURING TURBULENCE

Pilot	Equivalent airspeed datum 250 knots		Pitch attitude Datum 0°	
	Slow	Fast	Nose up	Nose down
A	222 (-28)	270 (+20)	+4°	-15°
B	217 (-33)	278 (+28)	+12°	-16°
D	214 (-36)	268 (+18)	+13°	-14°
E	226 (-24)	268 (+18)	+4°	-16°
H	205 (-45)	288 (+38)	+13°	-14°
I	210 (-40)	268 (+18)	+14°	-13°
J[1]	211 (-39)	330 (+80)	+13°	-33°
J[2]	215 (-35)	270 (+20)	+10°	-13°
K	238 (-12)	270 (+20)	+10°	-10°
L	224 (-26)	278 (+28)	+10°	-14°
N	220 (-30)	280 (+30)	+15°	-23°

Notes 1. During 'upset' by pilot J.
2. Excluding values occurring during 'upset'.

Apart from the incident in pilot J's trial, which resulted in a peak airspeed of 330 knots and a maximum nose down attitude of 33°, the largest speed fluctuations recorded were from 205 knots to 288 knots, during pilot H's trial, and the largest attitude changes were from 15° nose up to 23° nose down during pilot N's trial. The smallest disturbances occurred during pilot K's trial when the speed was kept between 238 knots and 270 knots and the attitude changes to within ±10°.

As a more detailed study of pilots' control actions when encountering a large updraught, time histories have been taken from seven of the records in the immediate vicinity of such a draught and these are reproduced in Figs. 6(a) to (g). The draughts studied are all of similar shape and the particular one chosen was the first large draught that the pilot encountered during the trial. Before discussing these time histories in detail the response of the aircraft to a large updraught in the absence of any action by the pilot, (i.e. controls fixed), may be studied with the aid of Fig.5.

As the aircraft enters the updraught the direction of the airstream relative to it is inclined upwards and the aircraft is therefore subjected to an increase in incidence. This causes an increase in lift, so that the flight path also starts to incline upwards, but at the same time the static stability of the aircraft causes a nose down attitude change, in an attempt to restore the incidence to its trimmed value. At first sight it might have been expected that the combination of an upward inclination of the flight path, and an increase in incidence, would lead to an initial fall off in speed. However another immediate effect of the updraught is to incline a component of the lift vector forwards, along the flight path, with the net result that the speed rises initially. If the updraught persists for long enough, and no thrust changes are made, the aircraft will eventually stabilise in the original attitude, (i.e. that before entering the draught), but with a rate of climb equal to the draught velocity. Alternatively, if thrust is reduced so as to maintain constant height, the aircraft will stabilise in a nose down attitude equivalent to the upward gradient of the resultant velocity vector. In practice large updraughts of the type considered in this study probably do not persist for long enough for the stabilised condition to be established, and the aircraft is subjected to a continuously varying disturbance as it passes through the draught.

The magnitude of the updraught represented in the controls fixed response measurement shown in Fig.5 was similar to that which was represented in the piloted trials. At a true forward speed of about 600 feet/second the 200 feet/second updraught would cause the relative velocity vector to be inclined upwards at $\tan^{-1}\frac{1}{3}$ or 18°. The record shows that in practice the aircraft pitched down to about 13° before the upward inclination of the flight path began to reverse the nose down tendency. During this time the airspeed increased to about 275 knots. The maximum nose up attitude when the aircraft left the draught was 10°. Thereafter the motion died away through the lightly damped phugoid oscillation, which had a period of about 110 seconds.

For the piloted trials the draught was slightly more complex in shape, having two smaller peaks before the main draught, (see Figs. 6(a) to (g)). The pilots' attempts to prevent the nose dropping during the main draught, by the application of up elevator, can be clearly seen in most of the records. Pilots A, J, K and L were also very successful in anticipating the nose up attitude change as the aircraft flew out of the draught, managing to suppress this almost entirely by appropriately timed downward elevator movements. As a result the aircraft left the draught at roughly the datum flight condition and there was little subsequent phugoid like motion.

Pilots D and H, (Figs. 6(e) and 6(f)), were less successful in controlling this nose up attitude change on leaving the draught, so that the aircraft tended to depart further from the datum condition, leaving some residual disturbance to be damped out. In the process of doing this there was a tendency to set up the long period oscillations in the flight path, of period about 40 seconds, which were commented on above.

As mentioned earlier, Pilot N experienced much more difficulty in controlling the simulator than the rest of the pilots. His record for the large draught encounter, (Fig. 6(g)), differs from the others, partly because the aircraft was less well stabilised before flying into the disturbance. Fig. 4(e), the complete time history of this trial shows that the portion of the record shown in Fig. 6(g) actually starts in the middle of a long term oscillation of the flight path, which the pilot was attempting to control by thrust changes. Initially the pilot's control action was such as to reinforce the nose down tendency produced by the draught, and in consequence a maximum nose down attitude of 23° was reached. This, combined with a deficiency in thrust at the beginning of the disturbance, led to an overall loss in height during the updraught.

The general conclusion to be drawn from these records is that pilots who limited the attitude excursions by small, gentle elevator movements, and who made few thrust and trim changes, were more successful in controlling the aircraft than those who made power and trim changes freely. The latter showed a distinct tendency to set up fairly long period oscillations in speed and flight path, and although these were not dangerously divergent on the simulator they were somewhat reminiscent of the oscillations occurring during at least one of the real flight incidents (Fig.1). These findings may be seen as a useful experimental demonstration of the validity of the techniques now laid down for rough air flying.

4.2 Data from pilot comment

The general opinion of the pilots was that the simulator represented the handling qualities of a large jet transport aircraft quite well, despite the limited realism of the cockpit layout.

One pilot who had experience of flying through storms felt that the representation of storm turbulence was realistic, but perhaps not violent enough, while most felt that the actual cockpit motion was less severe than would have been expected from the behaviour of the flight instruments. Other comments concerned the lack of any lateral component in the draughts, and the absence of any real element of fright.

When the loss of control incidents first occurred in flight it was thought that a contributory cause might be the pilots' concern with maintaining the cruising flight level, which they had been given by the air traffic control centre, even if this conflicted with best turbulence flying technique of minimizing power changes. Most of the pilots who took part in these tests were questioned on this point and they affirmed that they would try to maintain their flight level "as long as it seemed safe to do so". One of the reasons for including in the briefing the instruction to "make any calls to A.T.C.C. that you would consider appropriate" was to see how many pilots informed the A.T.C.C. of their inability to maintain height during the draughts. None did, but this was possibly due to the lack of operational realism in the simulation.

4.3 Loss of control incident

Towards the end of pilot J's trial an incident occurred which warrants particular comment because of its resemblance to some of the loss of control incidents which have occurred in flight. It may be identified in the complete time history of the trial, Fig. 4(c), by the excursion of the rate of climb trace off the edge of the record, while a clearer time history of the incident is reproduced as Fig.7.

It occurred when the pilot had been asked to reduce height from 30000 feet to 20000 feet, and, as was usual during these tests, this instruction was made to coincide with a large downdraught. In this particular instance the pilot was also in conversation on the R/T with the scientist running the experiment, making some comments about the performance of the aircraft. The record shows that the aircraft fairly slowly assumed an excessive nose down attitude, with consequent build up in rate of descent and airspeed. A peak nose down attitude of 33°, and a maximum airspeed of 330 knots were attained before recovery.

In discussing the incident afterwards the pilot said that he was simply distracted from controlling the aircraft, when making comments on it's performance, and failed to notice the situation building up. A contributory feature in delaying the recovery was the cramped conditions in the cockpit which made it difficult for him to apply as much up elevator as he wished.

The time history of the sequence of events shown in Fig.7 may be tentatively analysed as follows:-

Power was reduced to initiate the descent (which had been called for) from 30000 feet to 20000 feet. This was followed a few seconds later by a nose down elevator movement, perhaps to counteract the fall off in airspeed which was beginning to occur as a result of the power reduction. At this stage the aircraft entered the downdraught which caused a sudden further loss in airspeed and a nose up pitching tendency (see Section 4.1). The nose down elevator movement was therefore maintained and power was increased. A few seconds later however the aircraft flew out of the downdraught and its effects were therefore suddenly removed. It would appear that at this stage the pilot was distracted by the conversation, for little effective action was taken for about 10 seconds, during which time the speed and rate of descent were rapidly increasing. The first recovery action seems to have been an increase in power, possibly to bring about a reduction in rate of descent, but the excessive speed condition then seems to have become apparent and this decision was reversed, with the power being reduced to idle and up elevator applied. The major part of the recovery was then completed at idle power, although full thrust was used at one later stage to prevent a large amplitude flight path oscillation from occurring.

Although recovery in this instance was fairly straightforward it should be remembered that additional effects, not represented on this simulation, could occur in practice which might combine to make the recovery more difficult. These include nose down trim changes with Mach number and thrust reduction, and loss of the elevator effectiveness.

4.4 Investigation of other flight conditions

Apart from the basic investigation described in the previous sections, the results of several subsidiary tests may be briefly recorded. These were; flight through turbulence with the artificial horizon inoperative; deliberate attempts by pilots to minimise speed or altitude deviations; and the results from the two tests in which the aircraft stability was wrongly represented. (Section 3.)

After they had completed the main part of the tests several pilots were asked to try again, but with the pitch attitude indication on the artificial horizon inoperative. In view of the emphasis which has been placed on maintaining close control over the aircraft attitude when flying in turbulence these tests showed surprisingly little difference compared with those with the horizon operating.

In some cases the pilots were also asked to concentrate on maintaining speed or height constant, to the exclusion of controlling the other variables. These tests were rather inconclusive however because of the difficulties which the pilots found in complying with such an 'unnatural' method of control.

Finally, the first two pilots were tested with the aircraft characteristics wrongly represented, (see Section 3), so that the aircraft was speed unstable. Even in this condition successful turbulence penetrations were made, but much greater variation in engine thrust was needed and speed excursions of ±40 knots were recorded.

5 DISCUSSION

In discussing the results of the present simulator tests it may be useful to consider the possible causes of 'loss of control by the pilot' in three broad classes. They are those arising from inattention or distraction, those due to excessive demands on piloting skill and those due to confusion or disorientation.

The main cause of the one complete loss of control incident which occurred during the present trials (Section 4.3) was clearly of the first type, although its severity was probably increased by the demanding nature of the task. Inattention or distraction might be expected to occur either through boredom, (an unlikely explanation in the present context) or through such absorption in one aspect of the task that others are neglected. It may be felt that a distraction from the main flying task of the type reported here would be less likely to occur under the rather more compelling conditions of real flight. On the other hand at least one incident has been recorded in actual civil operations where a flight path divergence, following an unnoticed autopilot disengagement, was first brought to the attention of the pilot by operation of the high Mach number warning.

It is also a feature of the present day jet transport that, because of its aerodynamic cleanness, increases in speed and Mach number as a result of flight path changes may occur much more rapidly than was the case with propeller driven aircraft. Thus even fairly short periods of inattention may be of unusual importance. This situation could be greatly worsened in the absence of such devices as Mach trimmers.

Generally speaking loss of control due to causes of this first type are more likely to occur as straightforward divergences in speed, attitude and height. In contrast, loss of control arising from excessive demands on piloting skill show a greater tendency to be oscillatory in character.

For many years aircraft handling qualities studies have aimed at establishing those characteristics of aircraft dynamic response which are necessary for satisfactory controllability. However such studies must be related to the operating conditions and task which the aircraft has to perform, and consequently there are no universal criteria against which the handling qualities may be judged.

In several of the present trials there was a noticeable tendency for the pilot to induce comparatively long period oscillations, ($p \simeq 45$ seconds), in speed and flight path when attempting to control the effects of the disturbances. Fig.1 shows that such oscillations also occurred during at least one of the real flight incidents, although with the important difference that the oscillations then tended to be divergent, whilst those on the simulator were always satisfacorily damped.

In Fig.8 the longitudinal dynamic characteristics of the aircraft represented in the present tests have been compared with the results of systematic handling qualities studies[3] made in flight on a variable stability aircraft. The size of aircraft used for these tests was considerably smaller than that of a jet transport, and the role was also somewhat different, but the comparison is nevertheless felt to be worthwhile. Fig.8 shows that the jet transport characteristics lay in a region considered to be acceptable but unsatisfactory in the systematic tests, while rearward movement of the c.g. to reduce the restoring margin from 20% to 10% would cause the characteristics to lie in the unacceptable region. (The effect of height variation is also shown in Fig.8.)

Of equal importance are the comments made by the pilots who flew the variable stability aircraft. Nearly all complained of the difficulty of trimming the aircraft and of the proneness to induce oscillations when these characteristics were represented. This was attributed to the rather sluggish initial response, combined with the tendency for the motion to continue, or build up unexpectedly. These same comments could be readily applied to the simulated aircraft.

As already mentioned there was a considerable difference between the ease with which different pilots controlled the disturbances. Those who followed the recommended techniques of limiting attitude changes most closely tended to maintain the best control.

There was no evidence in the present tests of confusion or disorientation arising from apparently conflicting instrument readings or from unusual motion sensations. It must be remembered however that the severity of the motions which could be applied on the simulator were much less than those which would occur in flight. Also, by the nature of the briefing, pilots were aware that the cause of any unusual instrument indications was likely to be atmospheric disturbances. In a brief preliminary trial before this experiment, pilots taking part in another simulator exercise were subjected to large updraughts without being told what was happening. Only one pilot promptly recognised the instrument readings as indicating a large 'thermal', while the others were all more or less confused. At least one formed the impression that some sort of instrument failure was being represented.

This pilot also felt that, in any unusual situation, the pilot might instinctively try to fly on the pressure instruments, but he shared the view that this could be a most dangerous practice when flying in turbulence.

6 CONCLUSIONS

These tests showed that worthwhile investigations of the difficulties of flying in severe atmospheric disturbances could be made on a ground based simulator. In particular the simulator provided valuable practical experience, and a 'feel' for the problem, which would otherwise be difficult to obtain. The limitations of the representation, particularly as regards motion simulation, and the absence of any real sense of danger must be recognised however.

The tests showed that some pilots had surprisingly little difficulty in controlling the aircraft despite the severe conditions represented. Those who limited attitude excursions by gentle use of the controls and made few thrust and trim changes had less difficulty in their flying than those who used throttle and trim changes freely, the latter tending to set up long period oscillations in flight path and speed which resembled, to some extent, those which are known to have occurred in at least one of the real flight incidents. These findings seem to provide a useful experimental demonstration of the validity of the techniques now laid down for rough air flying.

Only one incident which could be classed as a complete loss of control occurred during the simulation, and this could be attributed to the temporary distraction of the pilot from the main task of flying the aircraft. It serves to underline the rapidity with which an out of control situation may develop from short lapses in concentration.

No cases of disorientation or severe confusion which might be attributed to apparently conflicting instrument indications were noted. Some pilots commented however that they could easily imagine the situation becoming confusing, particularly if any attempt were made to chase the deviations shown up on the pressure instruments.

The present study was confined to searching for the way in which loss of control incidents might start. Further study may be needed of problems occurring subsequently, during attempts to recover control, and it is considered that the ground based flight simulator should provide a useful experimental tool for this work.

7 ACKNOWLEDGEMENTS

The authors wish to acknowledge the part played by the pilots who took part in these tests, and the help afforded by discussion with others concerned in this problem.

Appendix A

REPRESENTATION OF THE AIRCRAFT ON THE SIMULATOR

The flight conditions to be represented on the simulator, (see Section 2) were those appropriate to a large jet transport aircraft in cruising flight at a typical 'rough air speed'.

A.1 Equations of motion

The equations of motion were written in the well-known linearised form, obtained by considering relatively small perturbations in the variables about a datum flight condition. The equations were referred to an axis system fixed in the aircraft, and the orientation of the axes was chosen so that they lay along and normal to, the relative wind when the aircraft was in the datum condition.

Because of the presence of disturbances in the velocity of the air mass itself, due to turbulence and the longer term draughts, it was necessary to differentiate between the kinematic velocity components of the aircraft, (i.e. those with respect to some inertial datum, such as the ground), and the components of the aircraft's motion relative to the air immediately surrounding it. In the equations below the kinematic velocity components are denoted by unsuffixed symbols, e.g. U, W, $\dot{U}$, etc, while the components relative to the air are suffixed, e.g. U_R, W_R, etc.

Coupling between the longitudinal and lateral components of the motion was ignored.

Longitudinal

The following equations were used to represent the aircraft dynamics:-

$$m\dot{U} = U_R X_U + W_R X_W + t X_t - m_g \sin\theta \qquad \underline{\text{forwards}}$$

$$m\dot{W} = U_R Z_U + W_R Z_W + mqV + mg(\cos\theta - 1) \qquad \underline{\text{normal}}$$

$$B\dot{q} = U_R M_U + W_R M_W + \dot{W} M_{\dot{W}} + qM_q + M\eta \cdot \eta \qquad \underline{\text{pitching*}}$$

---

* In the equation for pitching moments the third term on the R.H.S. should strictly be $\dot{W}_R M_{\dot{W}}$. However this term could not be readily represented in the computer and it is felt that the form given was adequate in the present context.

where	U, W	perturbations in the components of velocity along the forward and normal axes respectively
	X_u, X_w, X_t	force derivatives along the forward axis
	Z_u, Z_w	force derivatives along the normal axis
	m	aircraft mass
	g	acceleration due to gravity
	t	throttle movement from datum setting
	B	pitching moment of inertia
	$M_U, M_{\dot{W}}, M_W, M_q, M_\eta$	pitching moment derivatives
	q	rate of pitch
	V	aircraft datum speed
	θ	pitch attitude
	η	elevator angle

Flight instrument indications

The assumptions made about the indications of the aircraft pressure instruments are mentioned in Section 2.1. Briefly it was assumed that the instruments correctly depicted the actual motion of the aircraft, without lags or other imperfections.

$$\text{Airspeed indication} = \sqrt{\sigma}\,(V + U_R)$$

$$\text{Vertical airspeed indication} = (V + U)\sin\theta - W\cos\theta$$

$$\text{Altimeter indication} = h_D + \int [(V + U)\sin\theta - W\cos\theta]\,dt$$

where h_D datum height

Lateral equations

The lateral equations were written in the conventional small perturbation form:-

$$\dot{\beta}\hat{t} - y_V\beta + r\hat{t} - \frac{C_L}{2}\phi = 0 \qquad \underline{\text{sideslipping}}$$

$$\dot{p}\hat{t}^2 - \mu_2\frac{\ell_v}{i_A}\beta - \frac{\ell_p}{i_A}p\hat{t} - \frac{\ell_r}{i_A}r\hat{t} = \mu_2\frac{\ell_\xi}{i_A}\xi \qquad \underline{\text{rolling}}$$

$$\dot{r}\hat{t}^2 - \mu_2\frac{n_v}{i_C}\beta - \frac{n_p}{i_C}p\hat{t} - \frac{n_r}{i_C}r\hat{t} = \mu_2\frac{N_\zeta}{i_C}\zeta \qquad \underline{\text{yawing}}$$

Because the primary interest in this study was in the longitudinal behaviour of the aircraft, several small terms have been omitted from the complete equations in the interests of simplicity. The notation for these lateral equations is that given in R and M 1801[4].

A.2 Numerical data

The aerodynamic and other data used in the simulation were drawn from a number of unpublished sources. They were taken to be broadly representative of the large jet transport class of aircraft at the rough air cruising speed.

Datum conditions and general aircraft data:-

Weight	280 000 lb
Wing area	2800 ft^2
Equivalent airspeed	250 kt
Altitude	30000 ft
Mach number	0.67
Relative density	0.374
True airspeed	409 kt (690 ft/sec)
Lift coefficient	0.47
Pitching inertia	5 500 000 $slug/ft^2$

Longitudinal derivatives (see Section A.1)

The derivatives are given in the dimensional form used in the simulation. Values of the corresponding non-dimensional derivatives are given in brackets.

$$\frac{X_u}{m} = -0.0059 \text{ ft/sec}^2 \text{ per ft/sec} \qquad (x_u = -0.03)$$

$$\frac{X_w}{m} = +0.0102 \text{ ft/sec}^2 \text{ per ft/sec} \qquad (x_w = +0.055)$$

$$\frac{Z_u}{m} = -0.0934 \text{ ft/sec}^2 \text{ per ft/sec} \qquad (z_u = -0.47)$$

$$\frac{Z_w}{m} = -0.445 \text{ ft/sec}^2 \text{ per ft/sec} \qquad (z_w = -2.31)$$

$$\frac{M_w}{B} = -0.192^\circ/\text{sec}^2 \text{ per ft/sec} \qquad (m_w = -0.162)$$

$$\frac{M_q}{B} = -0.595^\circ/\text{sec}^2 \text{ per }^\circ/\text{sec} \qquad (m_q = -0.448)$$

$\frac{M_{\dot{w}}}{B} = -0.0188$ °/sec^2 per ft/sec^2 $(m_{\dot{w}} = -0.171)$

$\frac{M}{B} = -1.71$ °/sec^2 per ° $(m = -0.122)$

(also $i_B = 0.15$, $\mu_1 = 53.6$ and $\hat{t} = 5.04$ sec)

Lateral derivatives (see Section A.1)

$\mu_2 = 49.5$ $i_A = 0.10$ $i_C = -0.20$.

$y_v = -0.37$

$\ell_v = -0.138$

$n_v = +0.086$

$\ell_p = -0.40$

$n_p = -0.075$

$\ell_r = +0.15$

$n_r = -0.14$

Appendix B

REPRESENTATION OF THE ATMOSPHERIC DISTURBANCES

(see Section 2)

The simulated atmospheric disturbances used in this study consisted of two distinct components; a comparatively high frequency, randomly varying part, representing moderate to severe turbulence, and a component which varied more slowly, but which attained maximum velocities of up to 200 feet/second. These latter variations were termed 'draughts'.

B.1 Simulation of randomly varying atmospheric turbulence

Voltage analogues of the fore-and-aft, normal and lateral components of atmospheric turbulence were produced by three independent noise generators, which were based on a design by Douce and Shackelton[5]. The main feature of this design is the use of a clipping circuit, acting on the audio frequency noise produced by a conventional thyratron, to generate noise with a substantially uniform power spectrum at low frequencies, (up to, say, 15 cps). This uniform power spectrum was then shaped by a filter to match, approximately, the power spectrum of atmospheric turbulence.

For the present tests no actual measurements of spectrum shape for the severely convective conditions of turbulence being represented were available. The analytical expression usually used in the past[6], however, for the spectrum shape under more moderate conditions is:-

$$\frac{\Phi(\Omega)}{\sigma^2} = \frac{L}{\pi} \frac{1 + 3\,\Omega^2 L^2}{(1 + \Omega^2 L^2)^2} \tag{B1}$$

where $\Phi(\Omega)$ is the power spectrum, (feet/second)^2 per radians/feet
σ RMS of turbulence feet/second
L turbulence 'scale', feet
Ω space frequency, radians per feet

In the spectrum given above the turbulence distribution is considered as a function of space. For an aircraft traversing this spatial turbulence distribution the spectrum may be converted into a time distribution by the simple relationship

$$\omega = V\Omega \tag{B2}$$

where ω = frequency, radians/second
V = true speed, feet/second

so that the spectrum in terms of time frequency is

$$\frac{\Phi(\omega)}{\sigma^2} = \frac{L}{\pi V}\left[\frac{1+\dfrac{3\,\omega^2 L^2}{V^2}}{\left(1+\dfrac{\omega^2 L^2}{V^2}\right)^2}\right] \qquad \text{(B1a)}$$

For the purposes of representing turbulence during piloted simulation it is usually sufficient if the general shape of the spectrum is reproduced. The expression (B1a) above shows that at very low frequencies the power spectrum tends to a constant value:-

$$\frac{\Phi(\omega)}{\sigma^2} \rightarrow \frac{L}{\pi V} \quad \text{as} \quad \omega \rightarrow 0$$

while for high frequencies:-

$$\frac{\Phi(\omega)}{\sigma^2} \rightarrow \frac{3V}{\pi L \omega^2}$$

Thus, the high frequency asymptote of the power spectrum given by (B1a) is the same as that which would be obtained by passing uniform white noise through a simple first order filter having a 'break frequency' given by:-

$$\frac{3V}{\pi L\,\omega_B^2} = \frac{L}{\pi V} \qquad \text{(B3)}$$

i.e.

$$\omega_B = \sqrt{3}\,\frac{V}{L} \text{ radians/second}$$

Although the value for the turbulence scale which has generally been used in the past[6] is L = 1000 feet, there is some unpublished evidence which points towards considerably larger values. For the present tests a scale of L = 2750 feet was represented since this allowed existing filters for the noise generator to be used.

The power spectrum given by the analytical expression, (B1a) is compared in Fig.9 with the spectrum which would, theoretically, be obtained by passing uniform white noise through a simple first order filter. Also shown in the same figure is the measured power spectrum of the filtered noise which was used to represent turbulence during this simulation. In practice it was found necessary to include additional components in the filter in order to maintain the d.c. level at zero and to achieve the desired fall off in power at the higher frequencies. This was presumably due to departures in the shape of the pre-filtered spectrum from its ideal form.

B.2 Simulation of 'draughts'

The time history of the draughts was assumed to be a series of linear ramp functions of velocity against time, whose gradients could be varied between ±50 feet/second^2, (i.e. a 'draught' shear of about 0.085 second^{-1}), and whose peak velocity components were ±200 feet/second. Any desired draught time history could be approximated to, within these limits, by a succession of such ramp functions.

Having generated the draught time history, its orientation, i.e. whether a vertical, horizontal, or inclined draught, could be selected by taking proportions of it to represent the horizontal and vertical components. Finally these horizontal and vertical components were resolved along the aircraft's body axes:-

$$U_R = U + U_G + \lambda \cos\theta - \nu \sin\theta$$

$$W_R = W + W_G + \lambda \sin\theta + \nu \cos\theta$$

where λ and μ are the horizontal and vertical components of the draught, and, as in Appendix A.1, U, W are the kinematic velocity components along the aircraft body axes, while the suffices R and G denote velocities of the aircraft relative to the air mass, and the velocity components due to the random turbulence.

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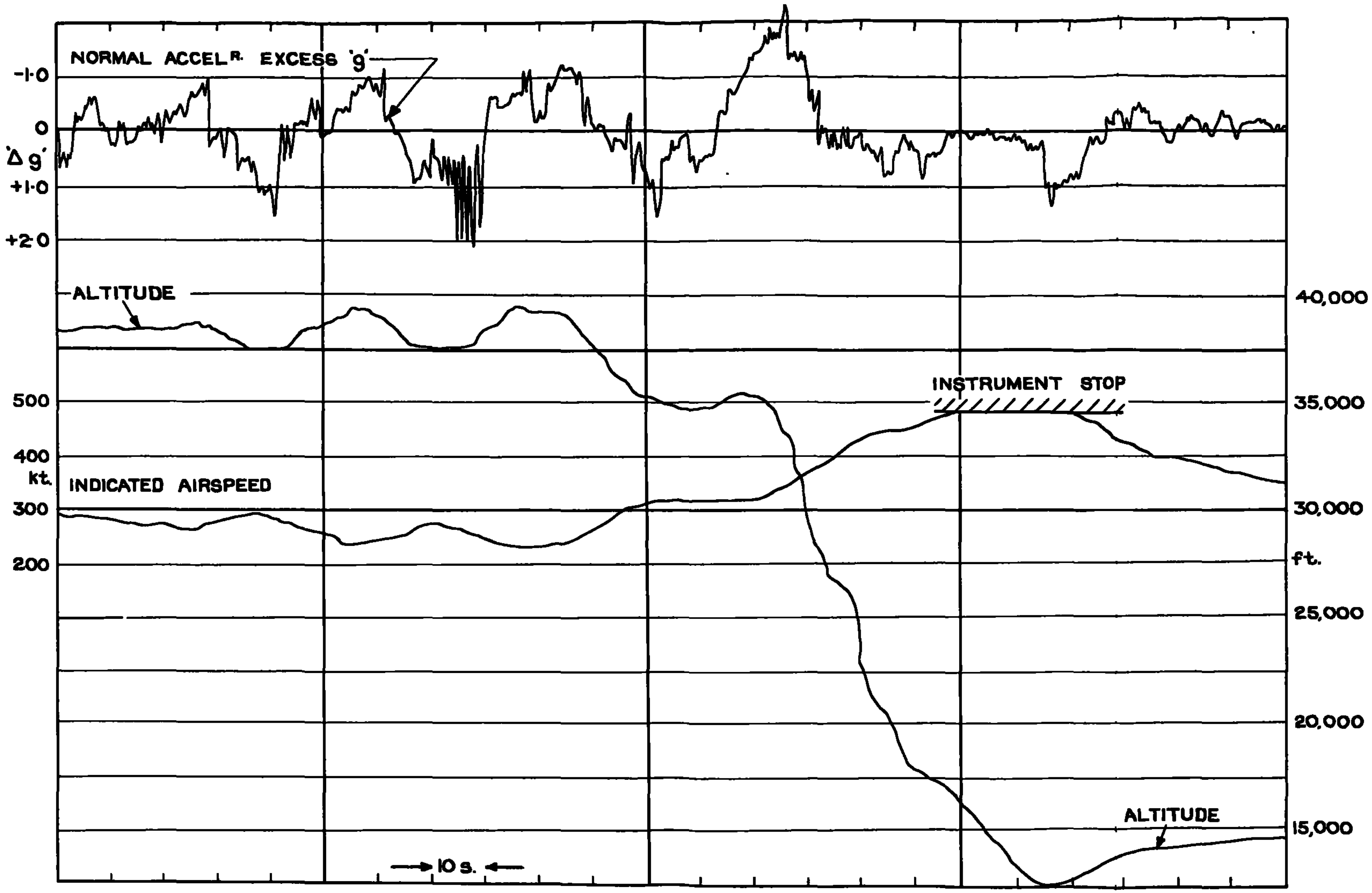

FIG. I EXAMPLE OF AN ACTUAL INCIDENT DURING COMMERCIAL JET TRANSPORT OPERATION. TIME HISTORY FROM FLIGHT RECORDER DATA. O'NEILL, NEBRASKA. JULY 1963

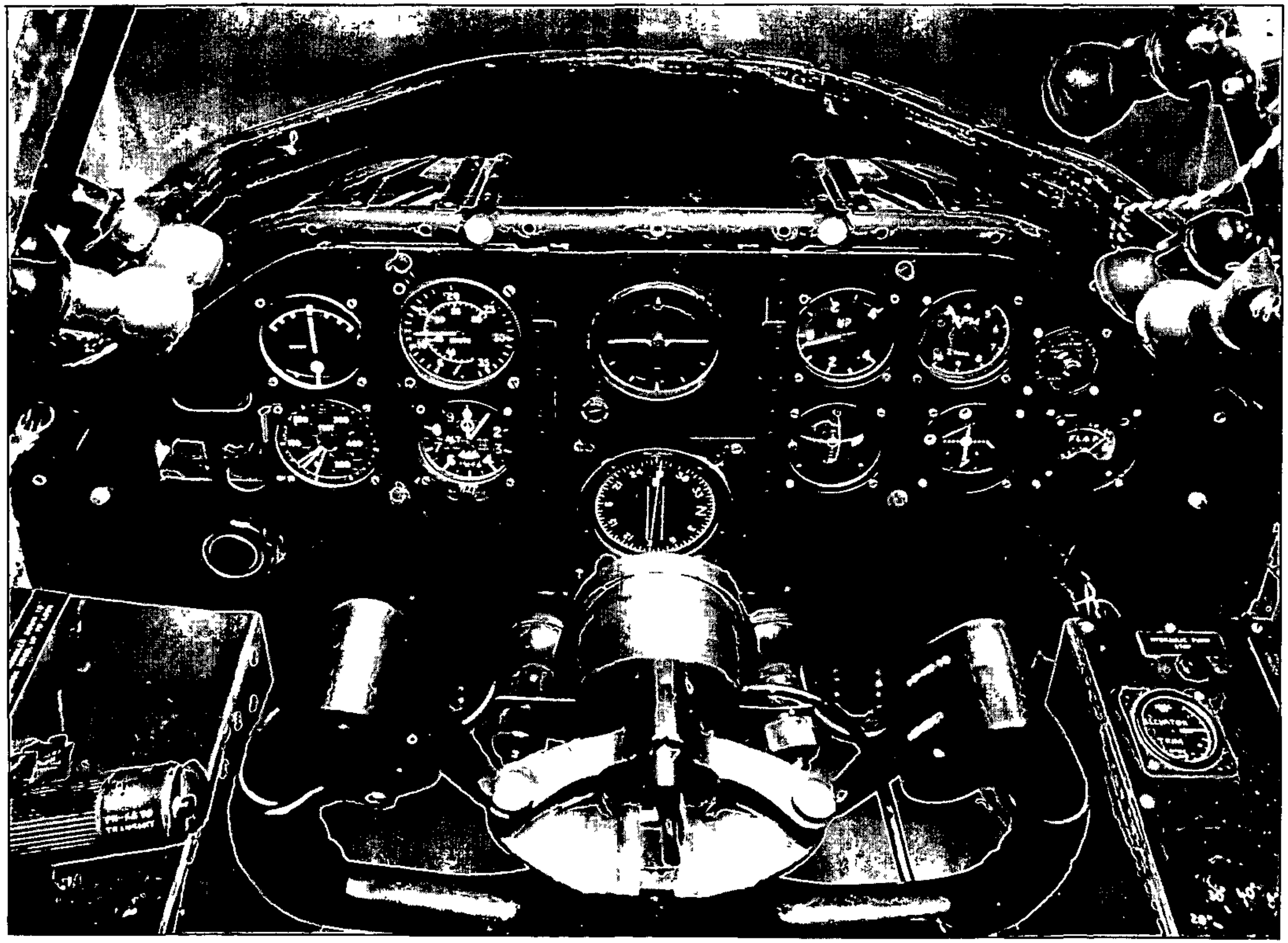

Fig.2. Simulator instrument panel

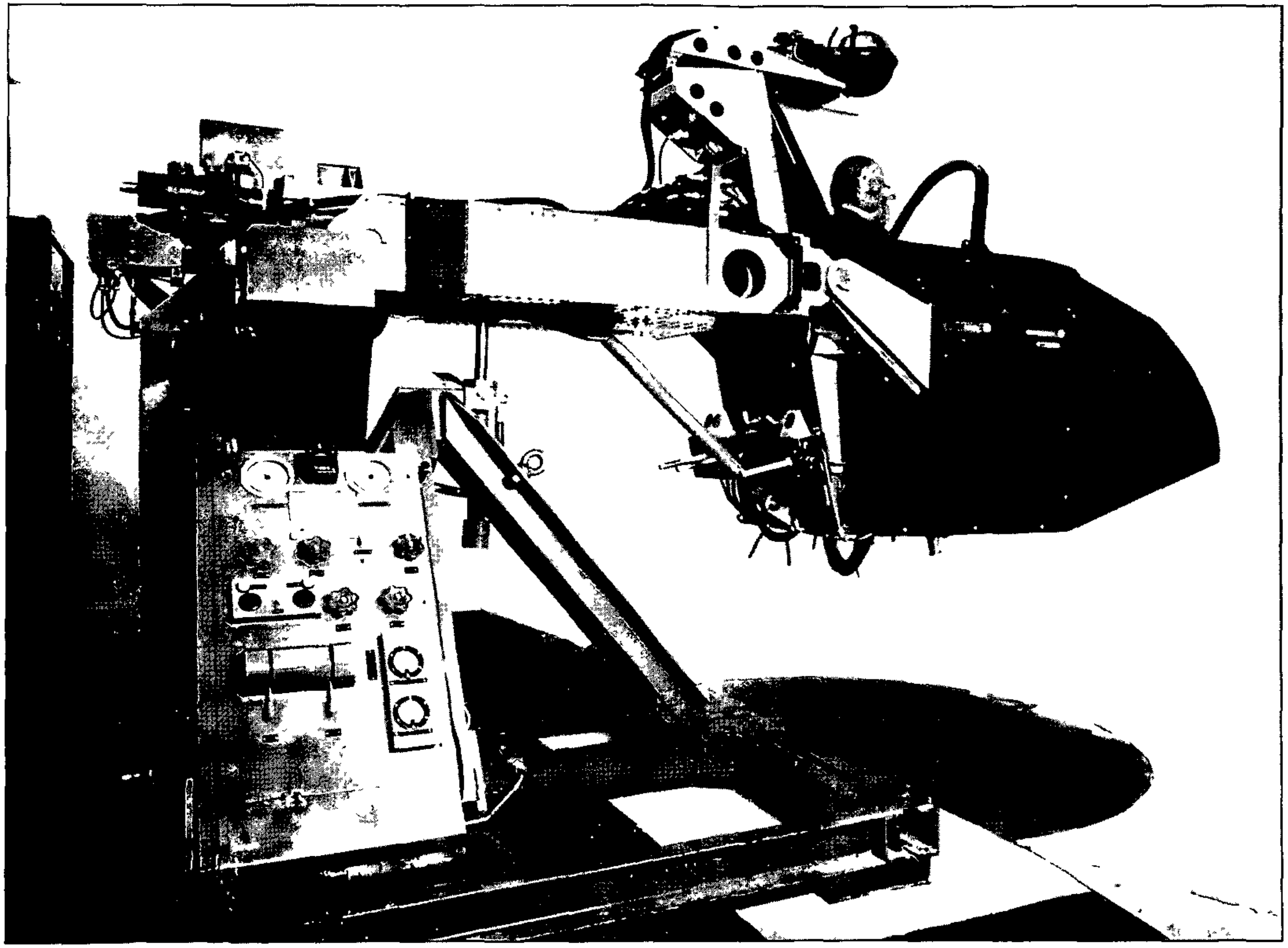

Fig.3. General view of the simulator

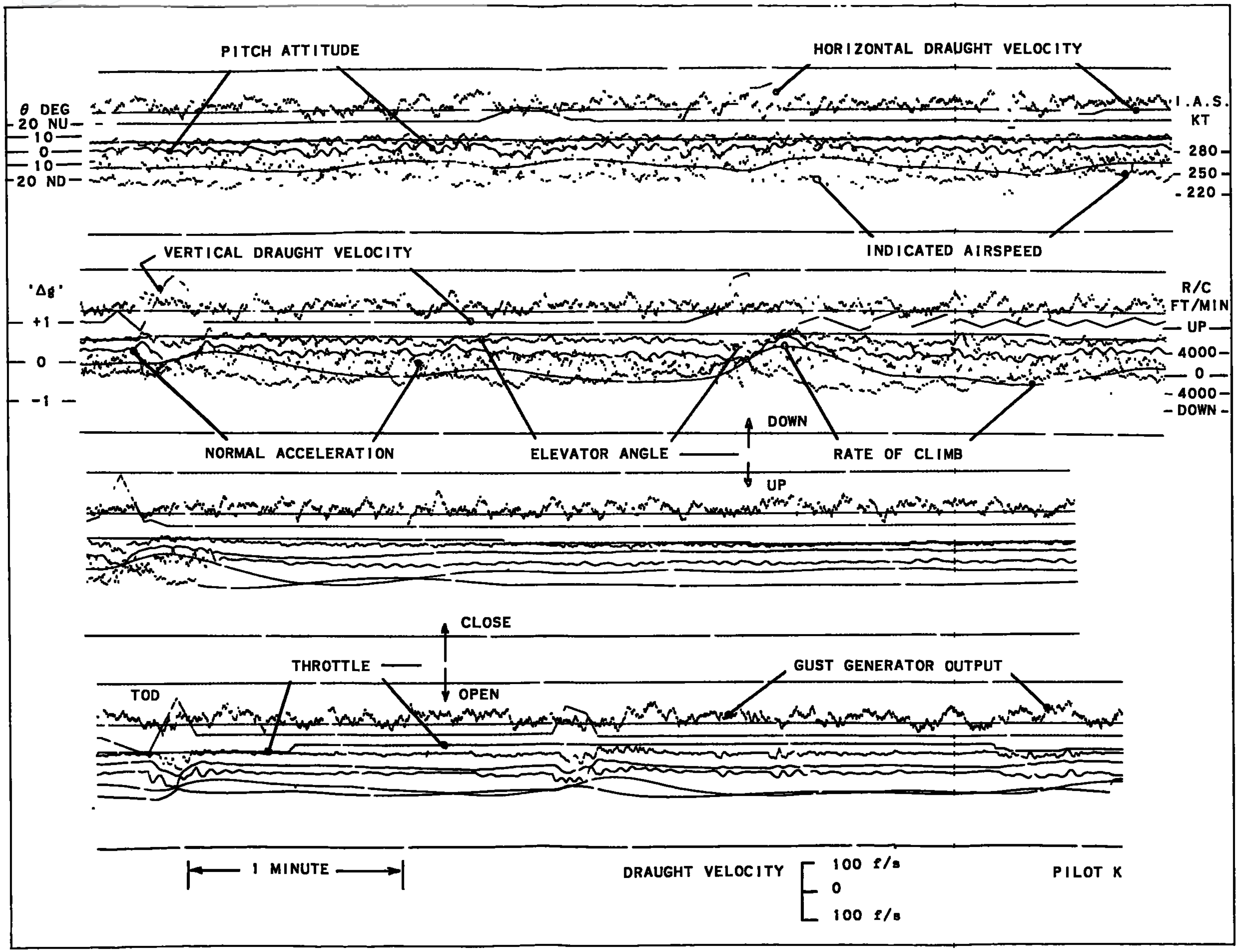

Fig.4a. Time history of a complete trial. Pilot K

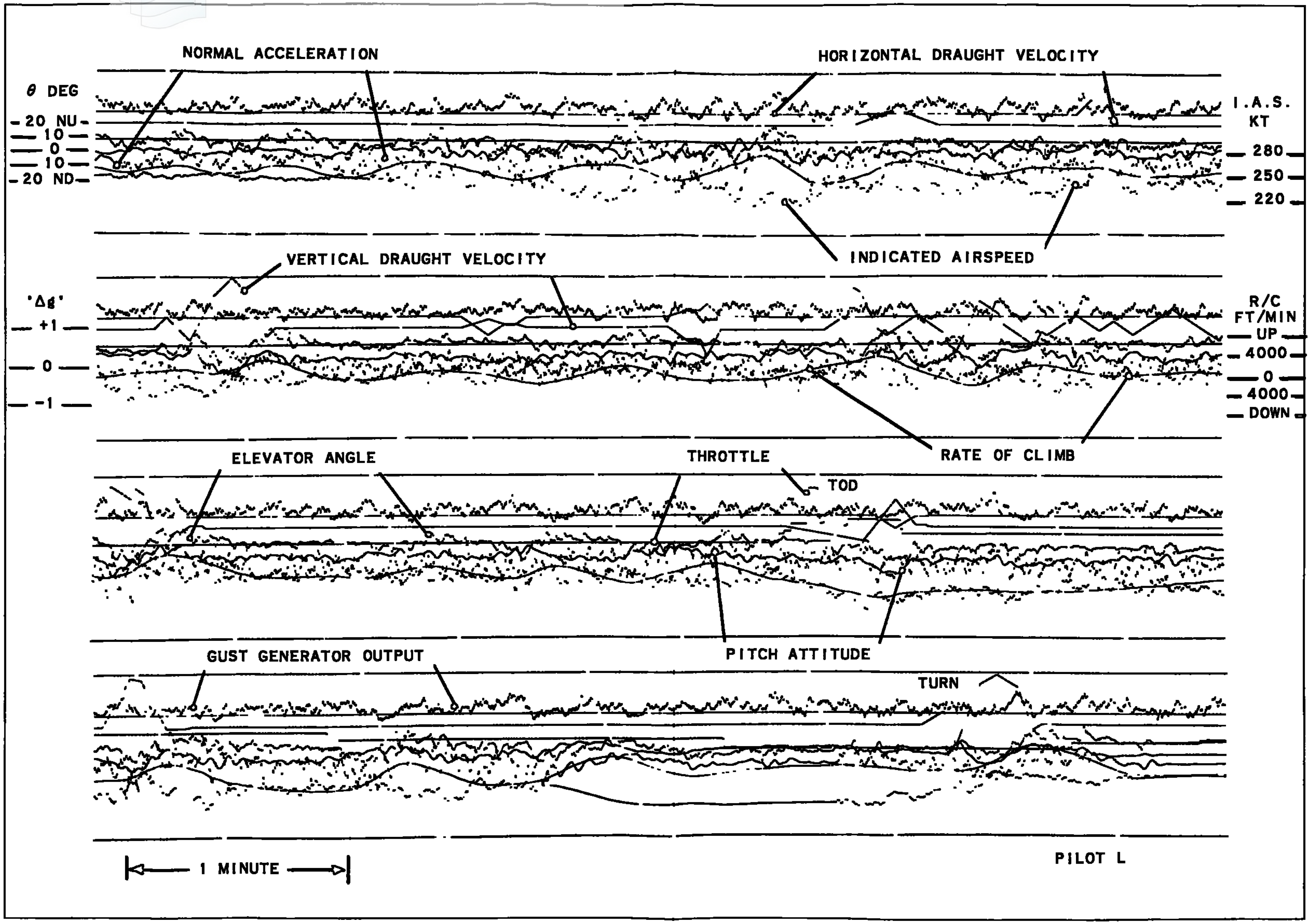

Fig.4b. Time history of a complete trial. Pilot L

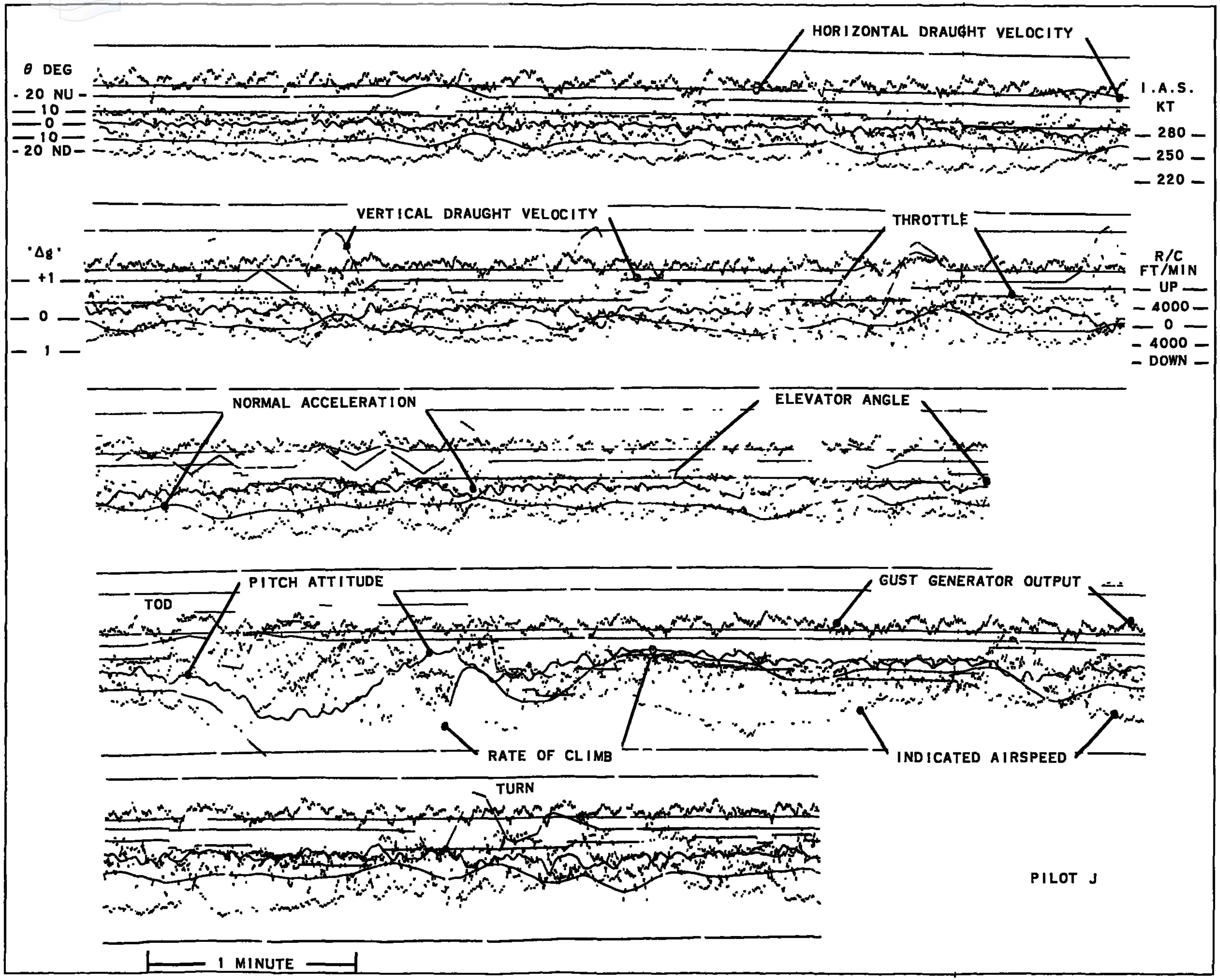

Fig.4c. Time history of a complete trial. Pilot J

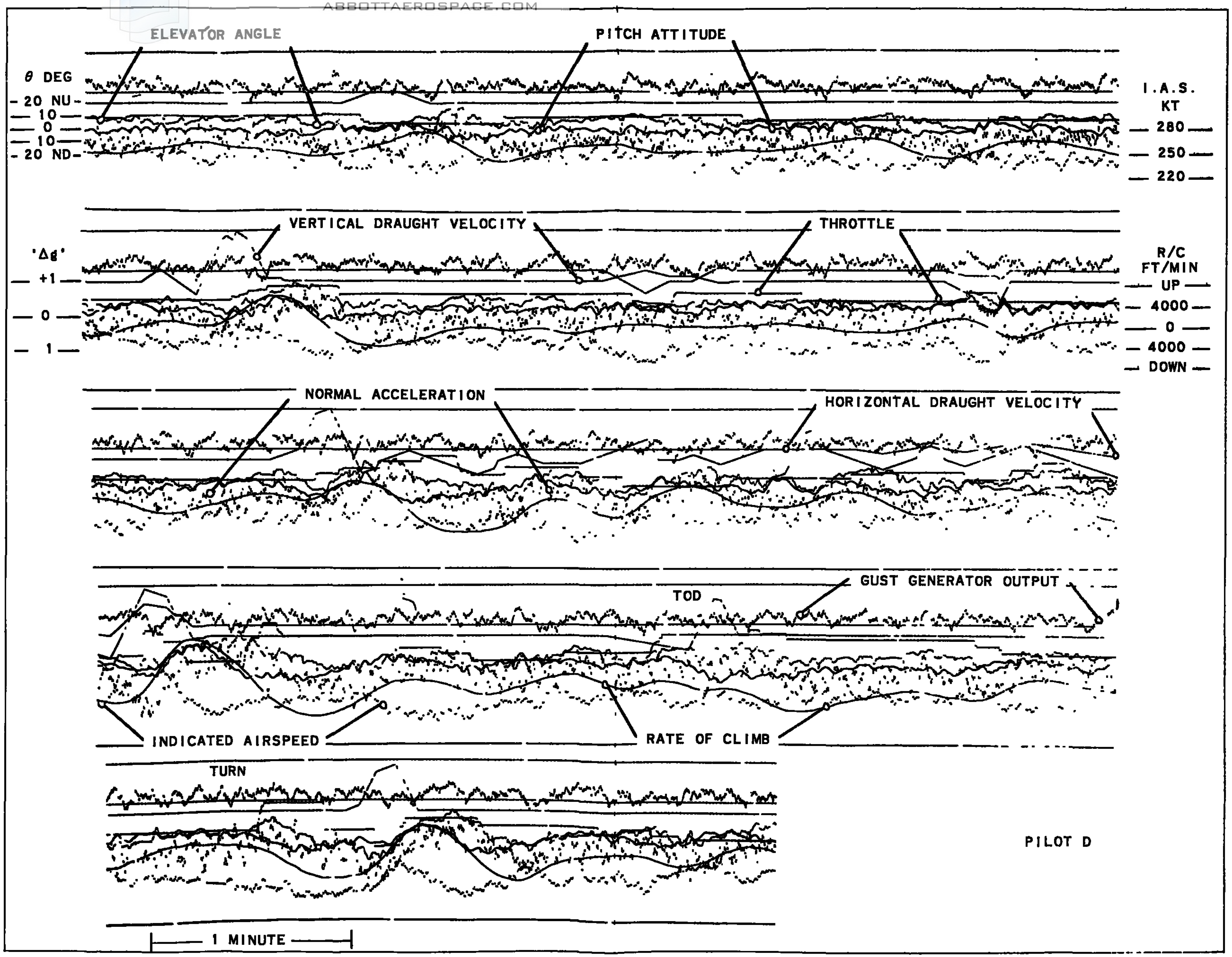

Fig.4d. Time history of a complete trial. Pilot D

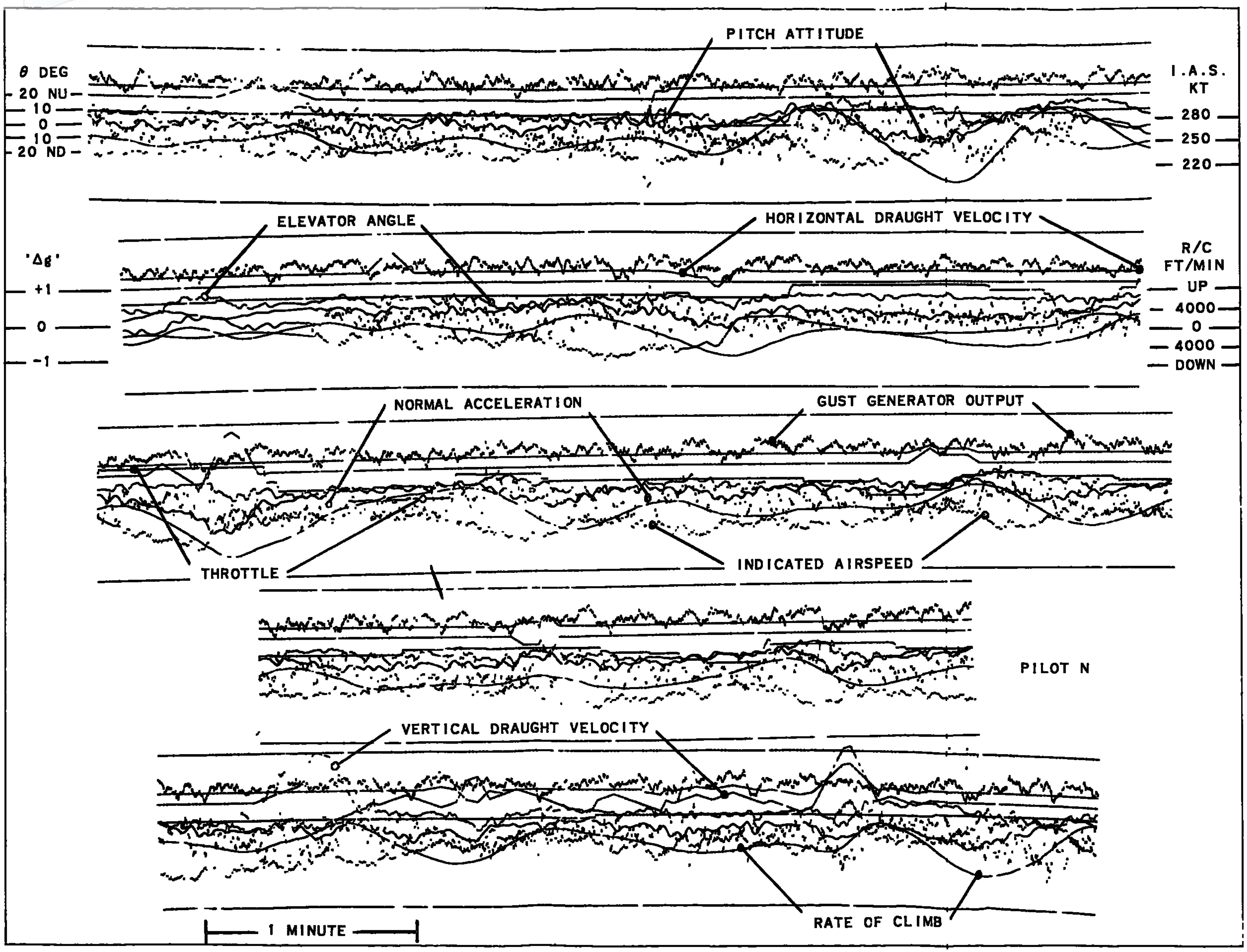

Fig.4e. Time history of a complete trial. Pilot N

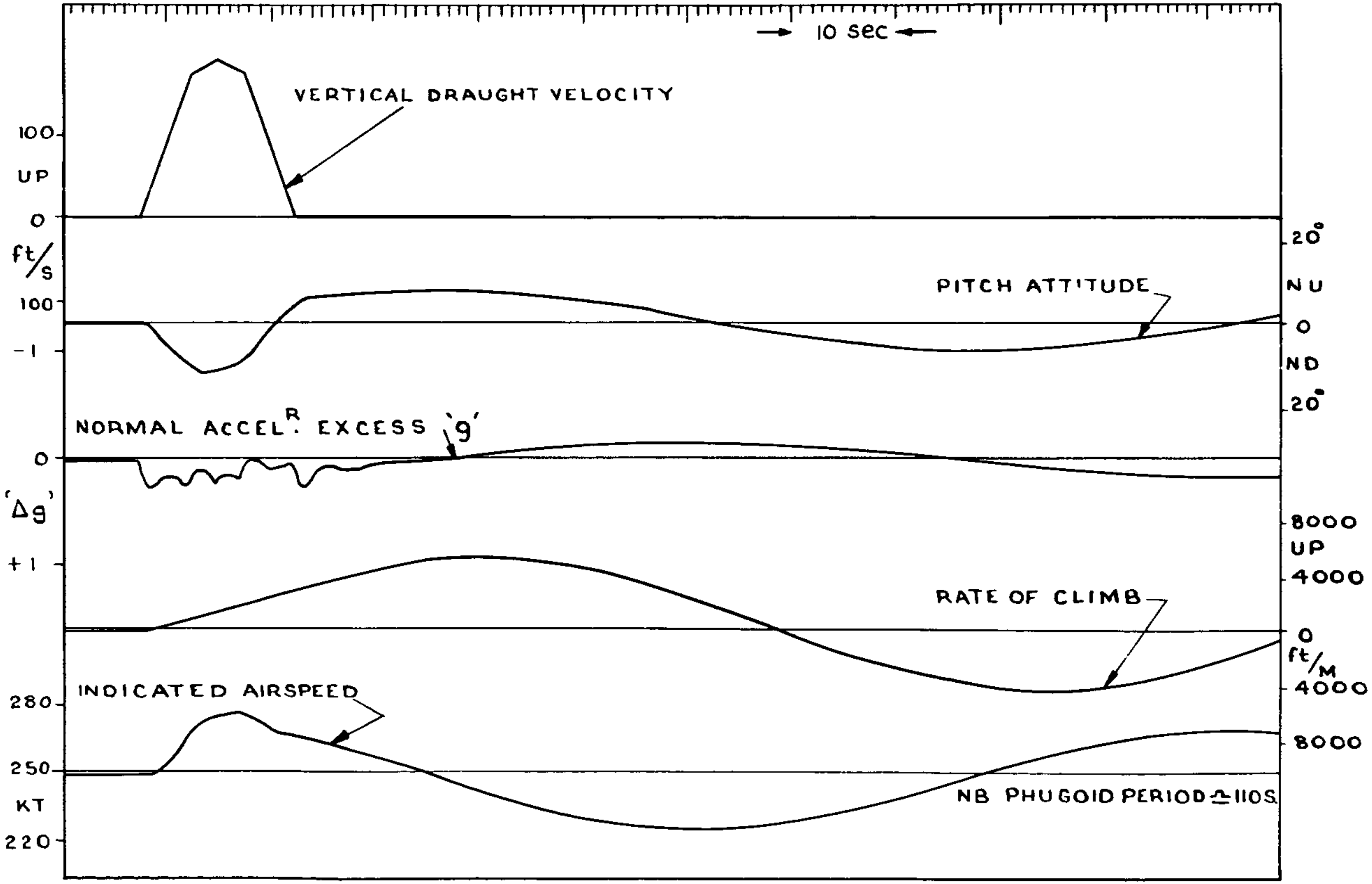

FIG 5 RESPONSE OF THE AIRCRAFT (CONTROLS FIXED) TO A LARGE UPDRAUGHT

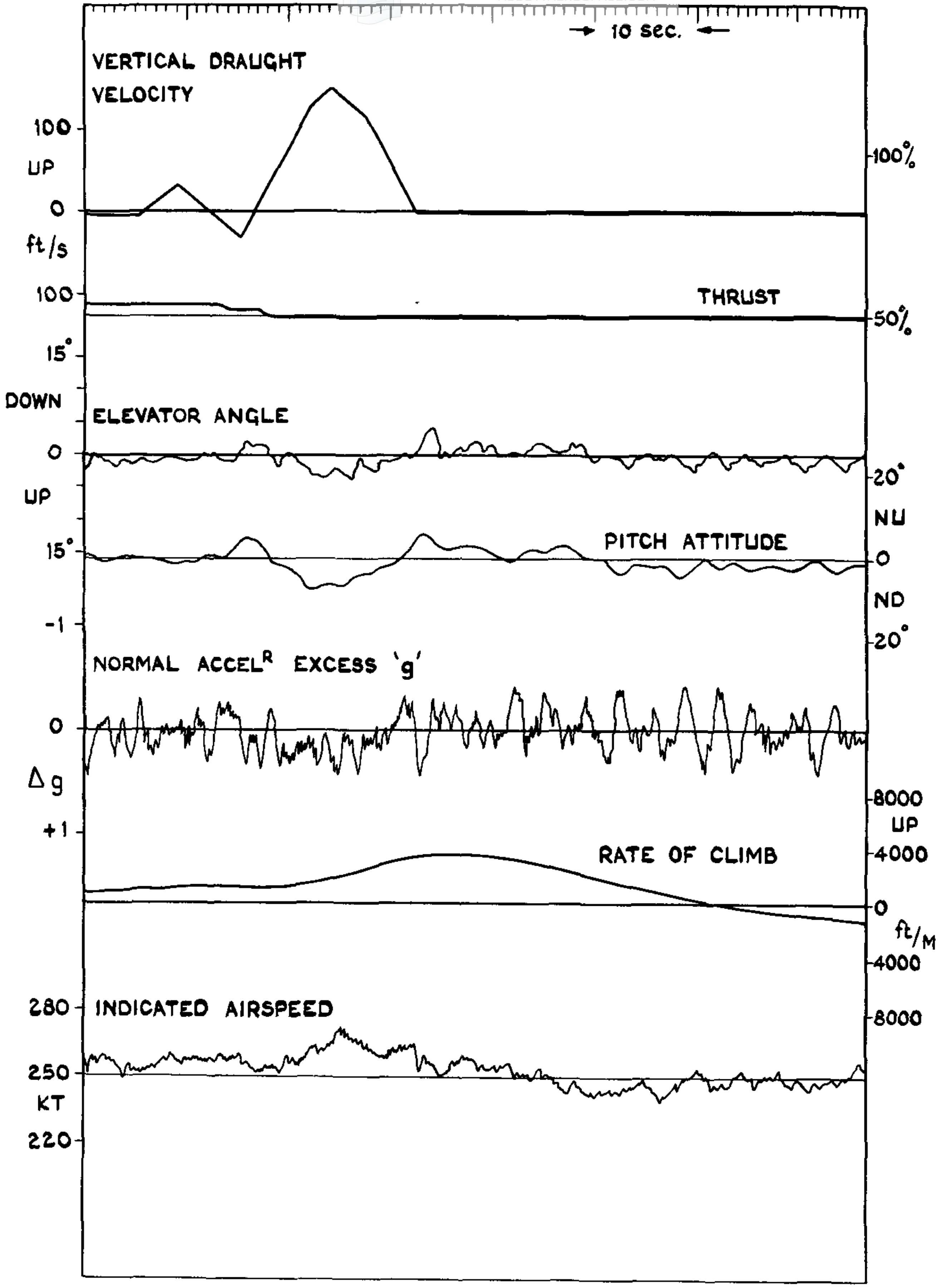

FIG 6(a) SIMULATED ENCOUNTER WITH A LARGE UPDRAUGHT. PILOT K

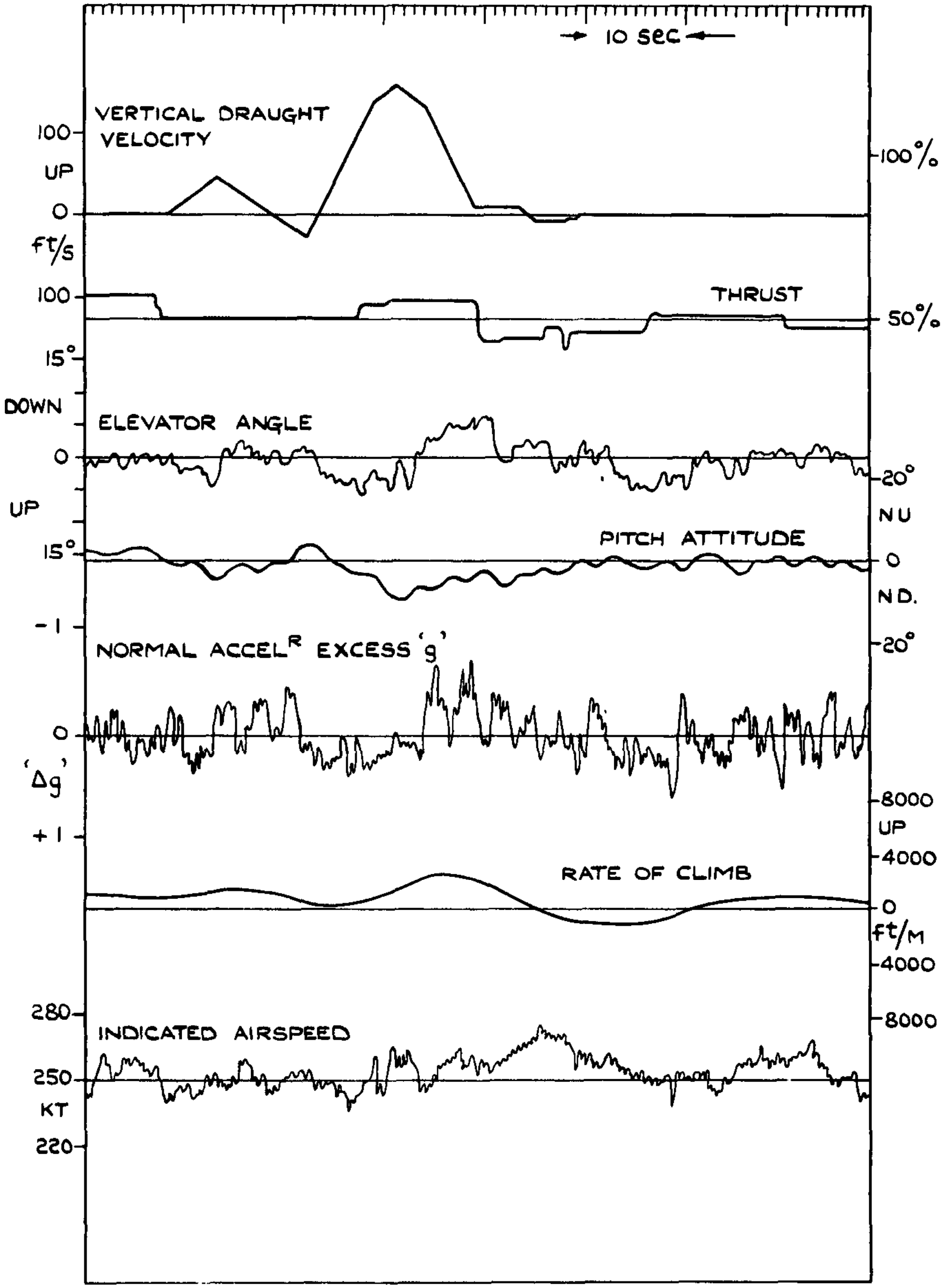

FIG. 6 (b) SIMULATED ENCOUNTER WITH A LARGE UPDRAUGHT. PILOT A

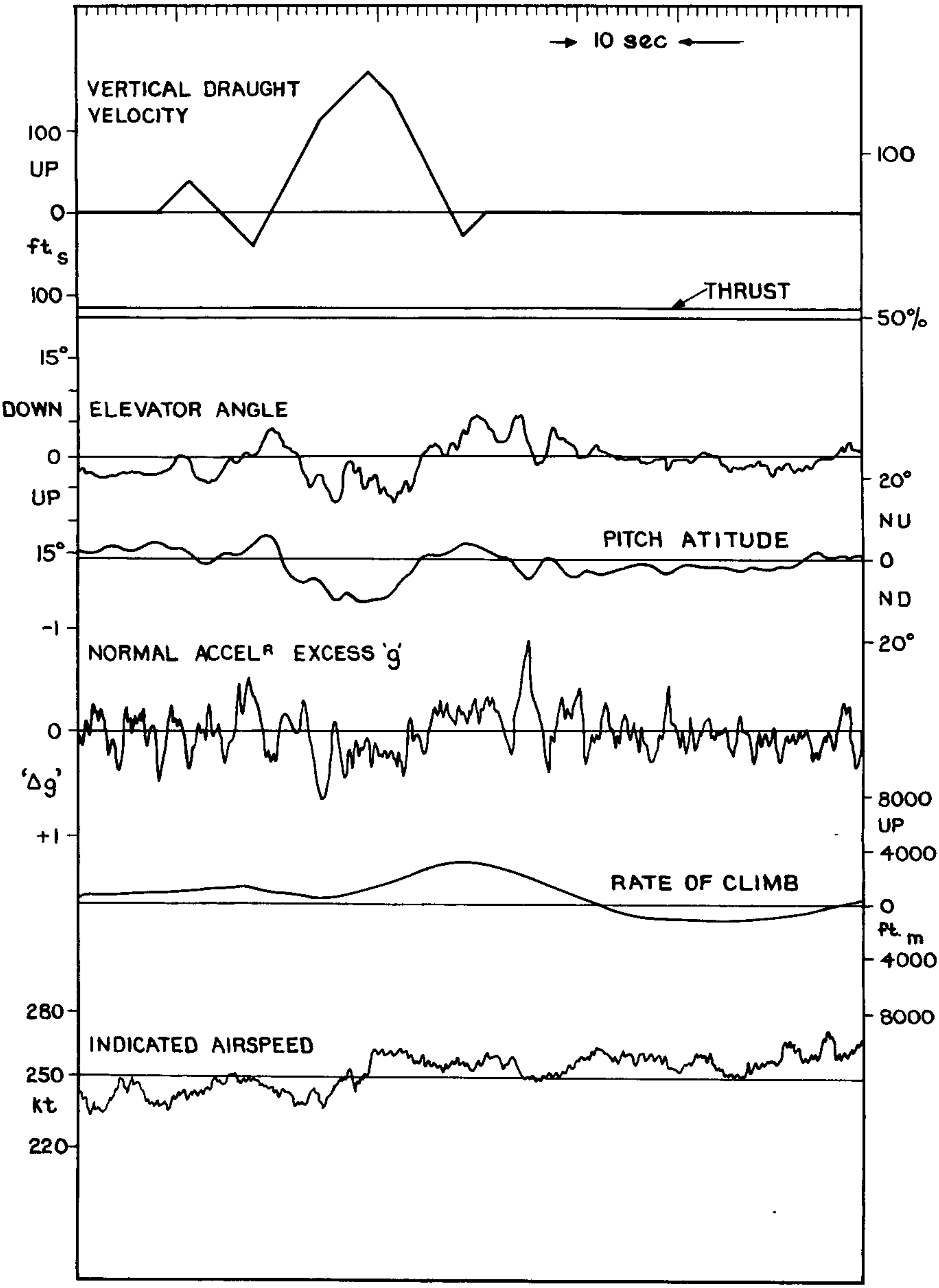

FIG.6(c) SIMULATED ENCOUNTER WITH A LARGE UPDRAUGHT. PILOT L

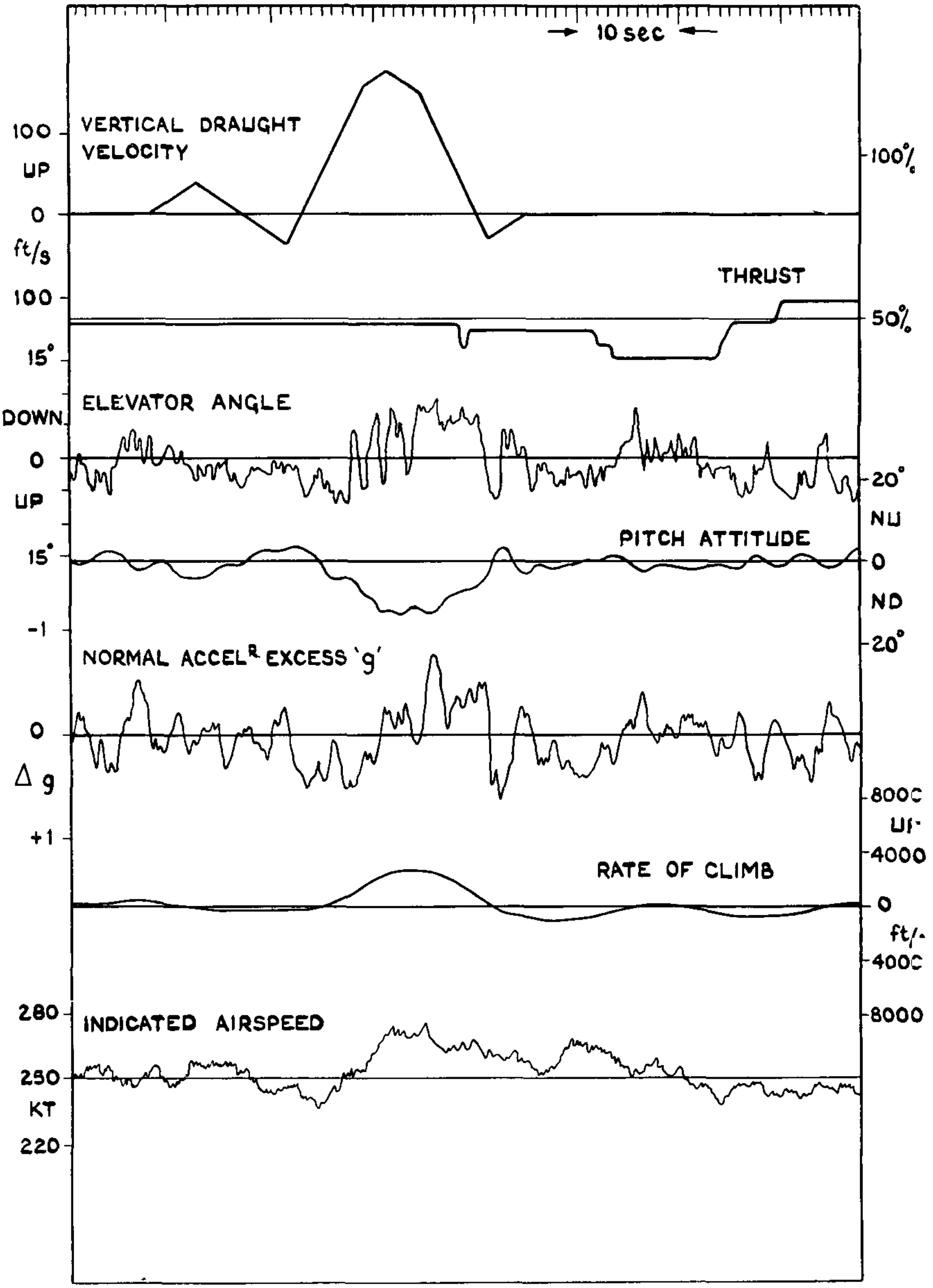

FIG. 6 (d) SIMULATED ENCOUNTER WITH A LARGE UPDRAUGHT. PILOT J

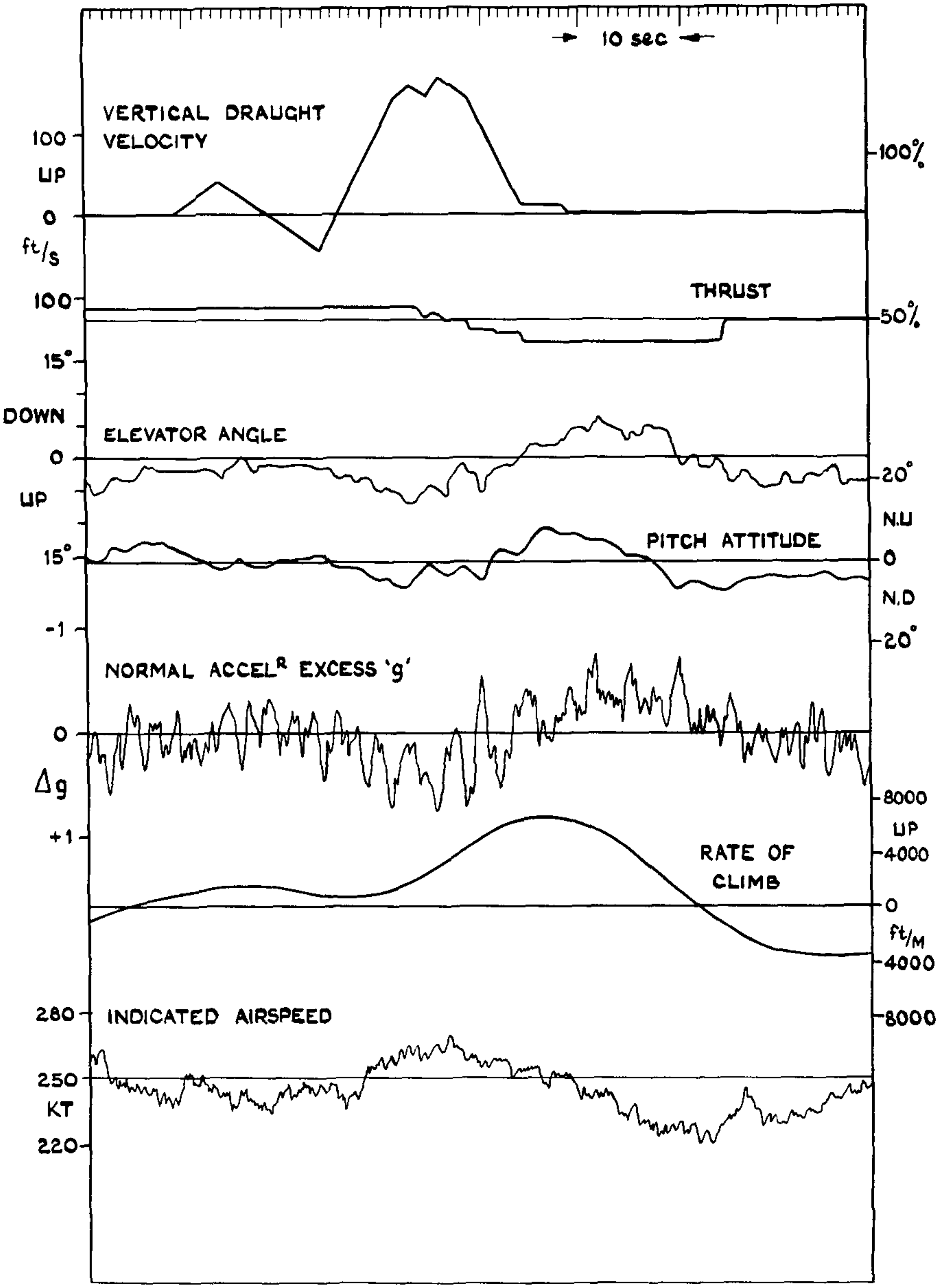

FIG 6(e) SIMULATED ENCOUNTER WITH A LARGE UPDRAUGHT. PILOT D

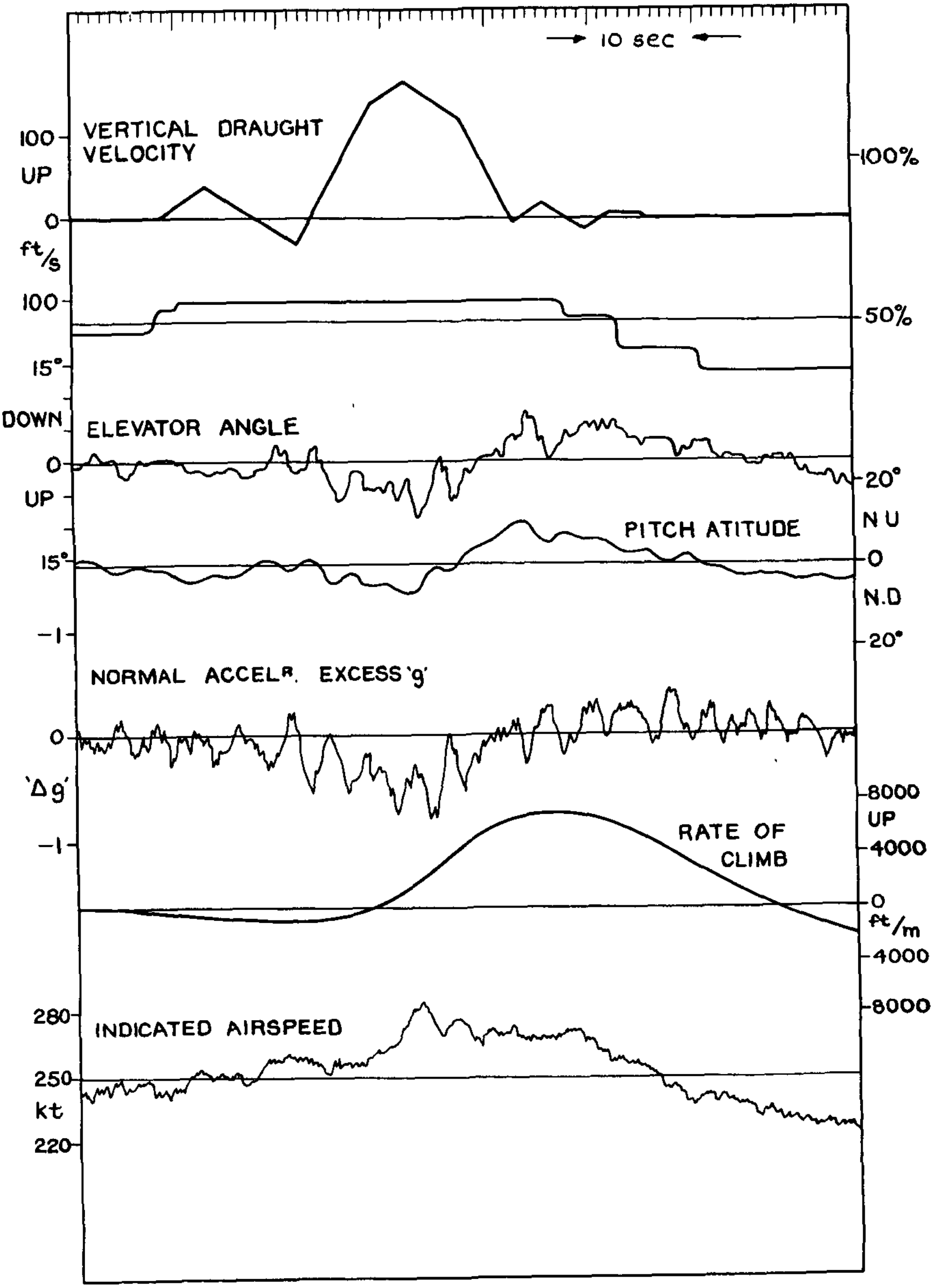

FIG 6 (f) SIMULATED ENCOUNTER WITH A LARGE UPDRAUGHT. PILOT H

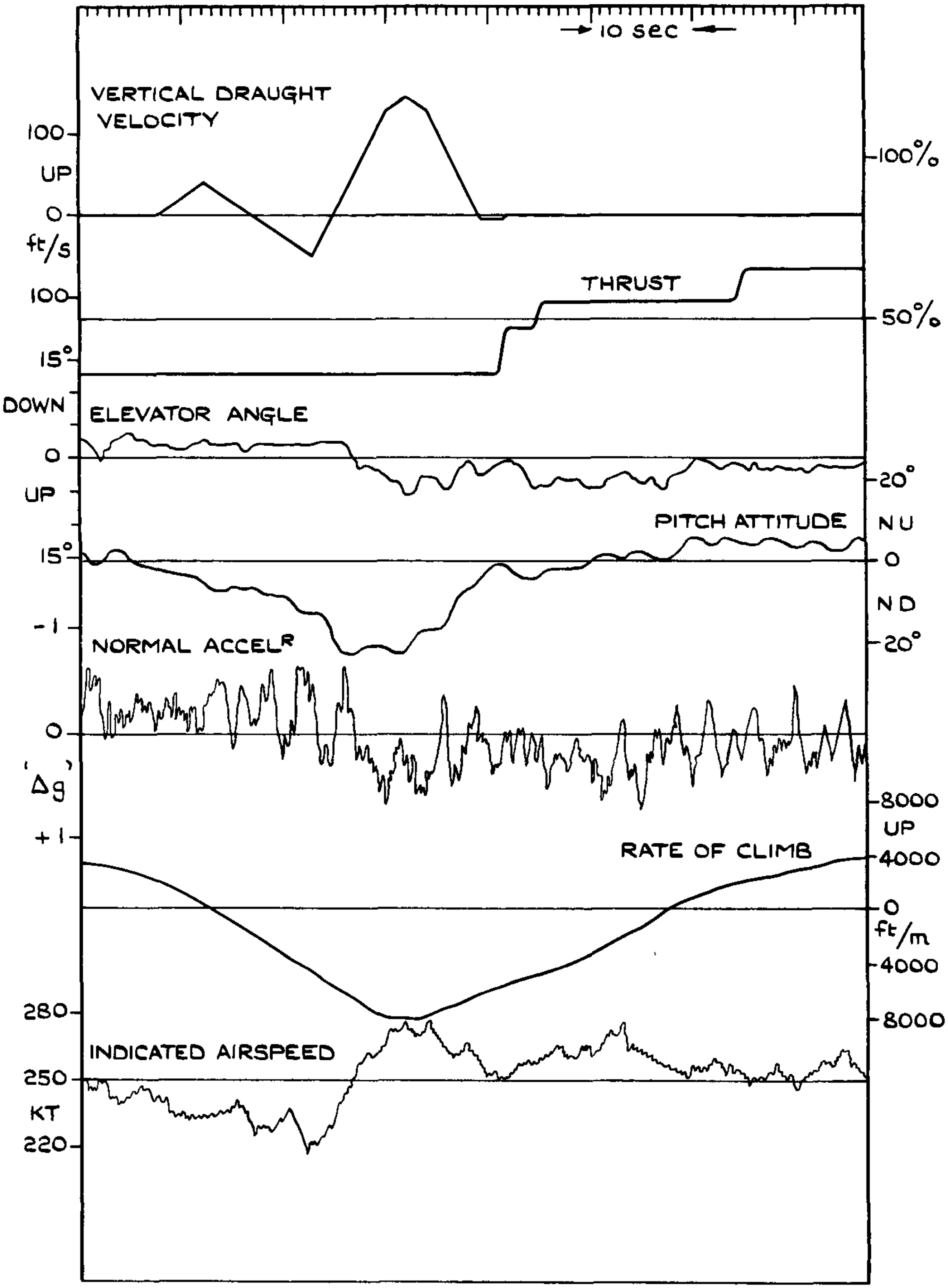

FIG. 6 (g) SIMULATED ENCOUNTER WITH A LARGE UPDRAUGHT. PILOT N

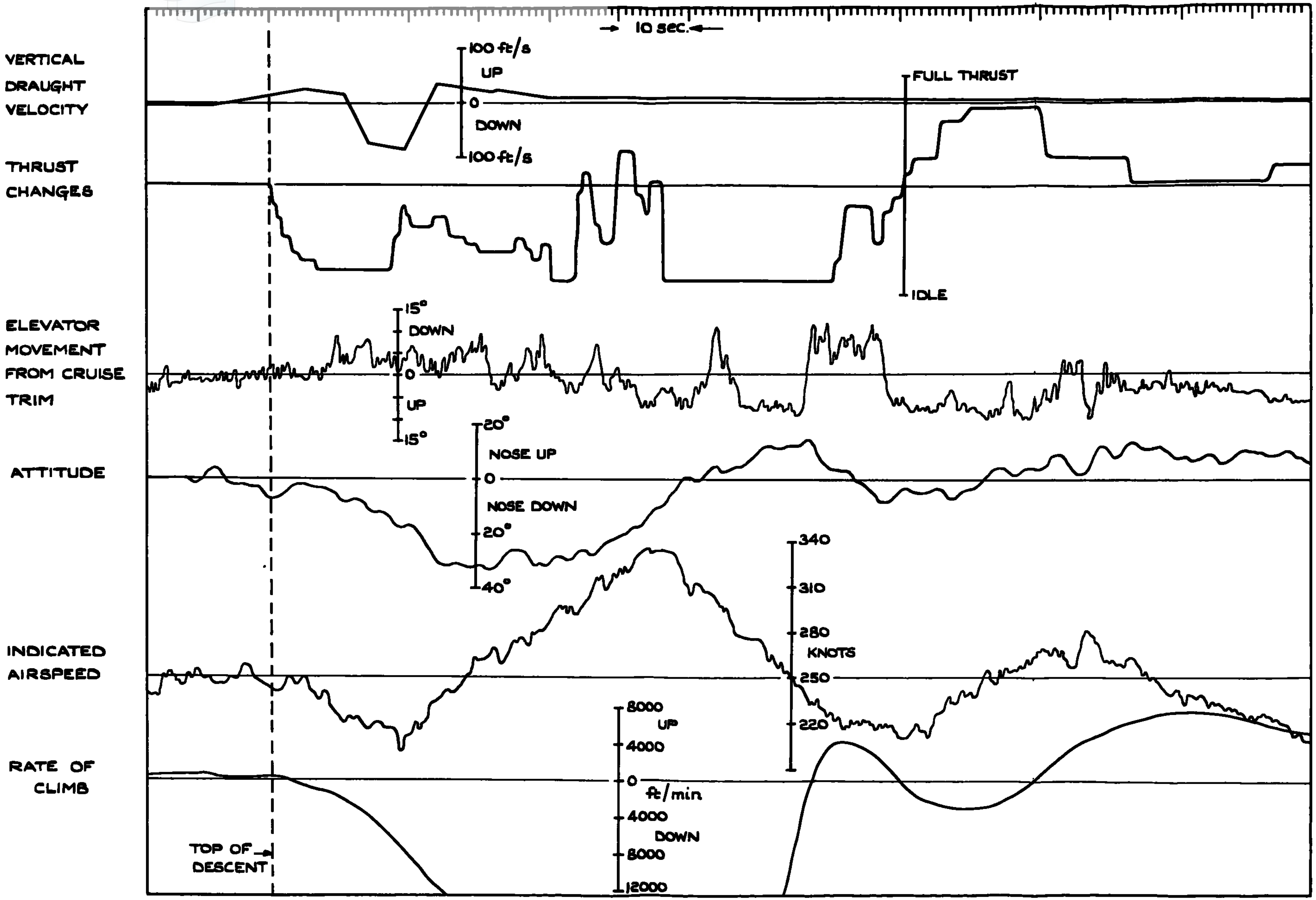

FIG.7 TIME HISTORY OF AN UPSET ON THE SIMULATOR AT THE START OF A DESCENT

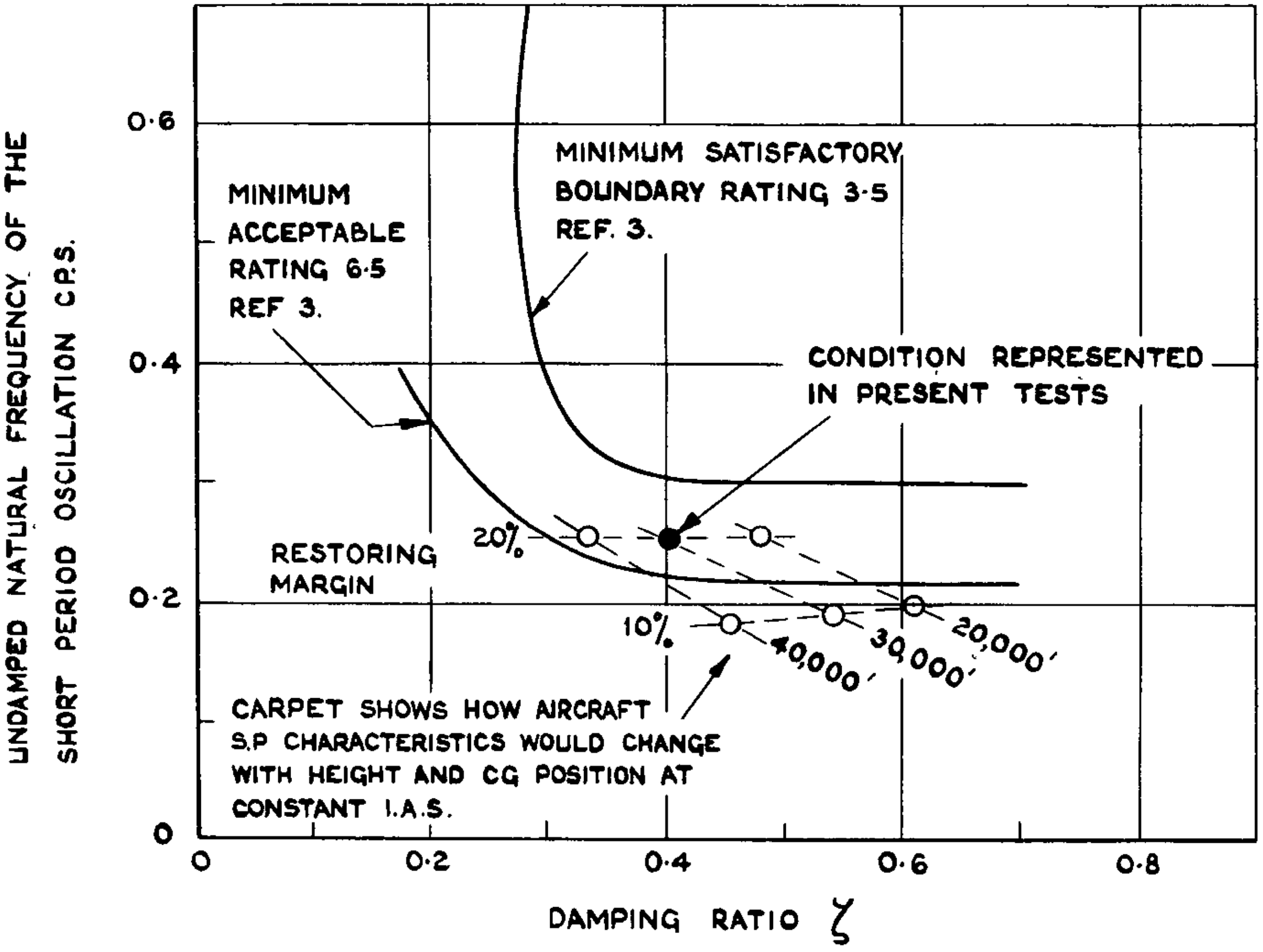

FIG. 8 COMPARISON OF SHORT PERIOD LONGITUDINAL CHARACTERISTICS OF AIRCRAFT REPRESENTED ON SIMULATOR WITH HANDLING QUALITIES DATA OF REF 3.

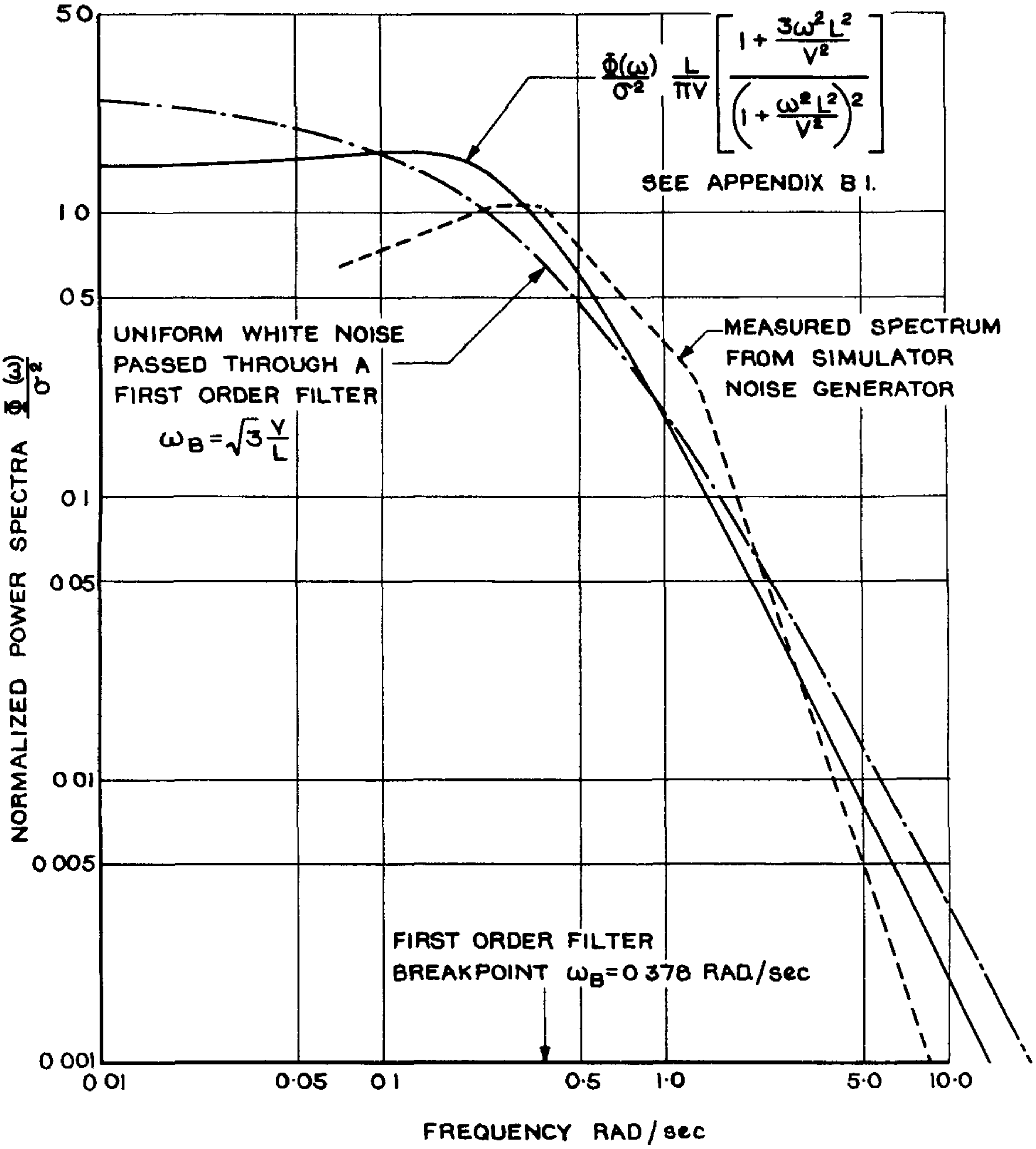

FIG. 9 TURBULENCE POWER SPECTRA. (APPENDIX B.I.)
L=2750 FEET V=600 ft./sec.

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533.6.013.425

A FLIGHT SIMULATION STUDY OF DIFFICULTIES IN PILOTING LARGE JET TRANSPORT AIRCRAFT THROUGH SEVERE ATMOSPHERIC DISTURBANCES

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Most pilots had surprisingly little difficulty in controlling the aircraft despite the severe conditions represented. Some who made power and trim

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DETACHABLE ABSTRACT CARDS

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