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PILOTED SIMULATOR INVESTIGATIONS OF FLIGHT NEAR ZERO RATE OF CLIMB SPEED

by

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SUMMARY

The problems associated with flight at or below the zero rate of climb speed (V_{ZRC}) have been investigated in piloted flight simulations of a supersonic transport aircraft and of the BAC 221 slender wing research aircraft. The accuracy of determining V_{ZRC} by piloted tests was examined, and the height losses in recoveries from below V_{ZRC} were compared with theoretical calculations. Agreement was very good for one simulation, though not quite as good for the other. Tests showed that height losses are generally minimized by a rapid recovery manoeuvre, but no detailed study was made of the optimum recovery technique.

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* Replaces RAE Technical Report 70016 - ARC 32171.

CONTENTS

1 INTRODUCTION

The slender delta aircraft, unlike conventional aircraft with a wing of high aspect ratio, stalls at an incidence substantially above the range of practical interest. Thus, for this class of aircraft, the stall is unsuitable for use as a datum in the definition of the speed and manoeuvre margins required to establish the low speed portion of the operational flight envelope. Pinsker has described[1] how a number of other characteristics might be used as a datum, and has discussed one of these, the zero rate of climb speed, in detail. This speed (V_{ZRC}) is defined as the lowest speed at which, for a particular condition, level flight can be maintained. Reduction of speed below V_{ZRC} will cause an imbalance of drag over thrust, resulting in further speed reduction or loss of height. Recovery to a speed above V_{ZRC} will necessarily involve a loss of height; this is, of course, equally true for recovery from the stall. Both V_{ZRC} and stalling speed can be defined accurately, but whereas the stalling speed is aerodynamic in origin and is largely defined by wing incidence and aircraft configuration, the zero rate of climb speed is a performance limitation and depends on the aircraft weight, power setting, configuration and aerodynamic loading, and factors affecting engine thrust such as air temperature and altitude.

In order to use V_{ZRC} as a datum for flight envelope limitations, it is necessary to consider the consequences of allowing speed to fall to or below V_{ZRC} and, in view of these consequences, to establish suitable speed margins above V_{ZRC} to define a safe lower limit to the flight envelope. The likelihood of airspeed falling below V_{ZRC} is probably greatest during take-off at high weight when performance is limited, especially of course after engine failure. Because of this, V_{ZRC} is now being used as one of a number of factors determining the initial climb-out speeds of supersonic transport aircraft.

The incident shown in Fig.1 illustrates vividly the practical significance of zero rate of climb speed in a condition of critical performance. This record has been obtained during simulator tests of the take-off behaviour of a supersonic transport aircraft, reported in Ref.8, when the pilot was presented with an engine failure just after reaching V_1. In the condition simulated, V_{ZRC} with an engine failed was 188 kt with undercarriage lowered, and 179 kt with undercarriage raised. The initial climb-out speed for the engine failure case was scheduled at 207 kt and the rotation speed, V_R, at

180 kt, with a target lift-off speed of 202 kt. In the particular event recorded in Fig.1, too rapid a rotation at V_R has resulted in a premature lift-off at 189 kt. Initially the aircraft managed to climb very slowly with speed constant at a value just above V_{ZRC}; after undercarriage retraction, performance gradually began to improve. The aircraft had travelled 3½ miles (5½ km) from lift-off before achieving a height of 250 ft (75 m). It is readily seen that the situation could easily have become catastrophic in slightly more extreme conditions, particularly as the favourable influence of ground proximity on lift and drag will permit lift-off in ground effect at a speed which cannot be sustained in level flight away from the ground.

Ref.1 discusses the relationship between speed margins based on stalling speed and those based on V_{ZRC}, and also performs simple calculations on the height lost during recovery from flight below V_{ZRC}. The aim of the work reported here was to investigate on a piloted flight simulator some of the practical problems associated with the determination of V_{ZRC} and to compare the actual loss of height during simulated recovery manoeuvres with that predicted by the calculations of Ref.1.

Two investigations are described, both using the flight research simulator of Aerodynamics Flight Division, R.A.E. Bedford; both investigations were undertaken as parts of more comprehensive simulator experiments described in Refs.2 and 3, and took place in 1967.

The first of these simulations represented the low speed behaviour of a supersonic transport aircraft (SST), using data available in December 1965 relating to the Concorde prototype design. Two R.A.E. test pilots few 4 trials, and tests to establish V_{ZRC} and to measure height losses in recoveries from below that speed were performed. The second simulation was of the BAC 221 slender wing research aircraft, and three pilots each flew one trial in tests similar to those of the SST simulation. Both simulations are described in section 2; section 3 lists the tests made, and their results are presented and discussed in section 4. Finally, section 5 relates the simulator tests to the problems of real flight close to V_{ZRC}.

2 DESCRIPTION OF AIRCRAFT AND SIMULATOR

Full descriptions of the two simulations and details of the data used are given in Refs.2 and 3, but only those of direct relevance here are given in Appendix A. The simulator equipment is described in Ref.4.

2.1 SST simulation

The simulation was based on wind tunnel and theoretical data available in December 1965 relating to the Concorde prototype design. The equations of motion of the rigid aircraft were solved in six degrees of freedom on the analogue computer, the aim being an accurate simulation of the aircraft's handling over the speed range 125-225 kt. Autostabilisation was simulated for all three axes, the control laws of the autostabiliser, however, being somewhat less sophisticated than those later used on the Concorde.

The simulator cockpit is shown in Fig.2, mounted on a two degree of freedom motion system. The single seat cockpit used is unrepresentative of that of a large transport aircraft, being rather cramped and having instruments which were not comparable with those in the real aircraft. The pilot's view of the instrument panel is shown in Fig.3; because of unserviceability the visual display shown could not be used and all tests were performed under instrument flight conditions. A "ram's horns" control column replaced the normal fighter-type control stick, and pitch trim was achieved by means of a thumb-operated switch on the left-hand 'horn'. Cockpit motion was provided in pitch and roll, the displacements of the cockpit being directly proportional to the aircraft's computed attitude. The pitch motion was scaled down to 62% of the computed pitch attitude and the roll motion to 45% of the bank angle. As the cockpit is some 6 ft ahead of the pitching pivot, the pilot experienced some incidental vertical motion coupled with the pitching rotation, but this was unrepresentative of the true vertical motion of the simulated aircraft.

Simulated engine noise responded to movements of a single throttle, which was mounted on the right-hand console. For the purposes of this experiment, the throttle angle was pre-set and held constant throughout the tests.

2.2 BAC 221 simulation

The BAC 221 is a single seat research aircraft with a slender wing and is described in detail in Ref.5. It is operated by Aerodynamics Flight Division, R.A.E. Bedford, and pilots flying the simulator were familiar with the real aircraft. The simulation of this aircraft was also based on wind tunnel and theoretical data, as no detailed flight measurements of aerodynamic derivatives were available; the speed range 100-200 kt eas was covered by the simulation. The same simulator cockpit was used for this simulation as for the SST simulation, but on this occasion the instrument content and layout were more like that of the real aircraft, and the fighter-type control stick was fitted (Fig.4). Elevator trim was provided by a thumb-operated switch on the stick. A television display provided a representation of the outside world; a closed circuit TV camera tracks over a scale model of an airfield and surrounding countryside in response to the computed position and attitude of the aircraft, and the picture so produced is projected onto the screen mounted on the front of the cockpit (Fig.2).

The motion system was driven in a way similar to that used for the SST simulation, but scaled to 50% in pitch and to 38% in roll, and engine noise cues were again provided.

3 TESTS MADE

3.1 SST simulation

The simulator was set up to represent a weight of 200 000 lb (90720 kg mass), ISA sea level conditions, and thrust, which was held constant, was chosen to give a zero rate of climb speed (V_{ZRC}) of 156 kt, which permitted speed excursions of up to 30 kt below V_{ZRC} without exceeding the range of validity of the simulation. The chosen V_{ZRC} was not associated with any operational limiting speed, and the thrust level used is in fact less than the maximum obtainable from only two engines.

Two R.A.E. test pilots each flew two simulator trials; the trials were divided into two parts. The first was designed to determine the accuracy to which V_{ZRC} might be established in flight. The pilot was not told the value of V_{ZRC} defined by the mathematical model simulated but merely that it lay between 135 and 170 kt; he was asked to determine V_{ZRC} by performing a series of partial climbs and dives. The second part consisted of recoveries from speed excursions of up to 30 kt below V_{ZRC}, the recovery being considered complete when a positive rate of climb was observed at a steady speed above the V_{ZRC} determined in the first part of the tests. The recoveries generally started from a descent at a steady speed below V_{ZRC}, but some were initiated from a decelerating condition, either in level flight or descending. All manoeuvres were performed under instrument flight conditions as the television visual display was unserviceable. Atmospheric turbulence was not simulated; all tests were made under calm conditions.

The following parameters were recorded on continuous trace pen recorders:- airspeed, altitude, rate of climb, pitch attitude, pitch rate, elevator angle, forward acceleration and incidence.

3.2 BAC 221 simulation

Three conditions were simulated:-

(i) approach configuration (nose drooped and undercarriage lowered), sea level

(ii) clean configuration (nose and undercarriage raised), sea level

(iii) clean configuration 24000 ft (7315 m) altitude.

The weight was 18500 lb (8390 kg mass) for all three conditions, and thrust was fixed at a value giving V_{ZRC} close to 150 kt (actually 146 kt for (ii) and (iii) and 150 kt for (i)). It had been intended to take a V_{ZRC} equivalent to that used in the flight tests of Ref.6 (which was not the true V_{ZRC}, but a value for a throttle setting less than maximum dry thrust, to allow some margin of safety) but in fact the flight V_{ZRC} was closer to 170 kt.

The pilot's briefing was similar to that for the SST simulation, except that V_{ZRC} was to be determined as quickly as possible by any suitable method; partial climbs and glides were not specifically requested. Once V_{ZRC} was determined, recoveries were performed as before, starting from constant speed or decelerating initial states. Three pilots took part in the simulation; each pilot flew one of the three conditions, giving a total of three simulator trials. The recorded quantities were the same as for the SST simulation, except that normal acceleration was substituted for forward acceleration. Trials were again performed under calm atmospheric conditions.

The television visual display, representing an airfield and surrounding countryside, was used for this simulation. This provided a lower limit to the aircraft's vertical freedom, recovery manoeuvres starting 1000-2000 ft (300-600 m) above the ground, but nearly all recoveries ended with at least 500 ft (150 m) of height still in hand. Although condition (iii) represented the aerodynamic effects of flight at 24000 ft (7315 m) altitude (for comparison with the conditions of the flight tests reported in Ref.6) runs were still performed up to 2000 ft (600 m) above the visual 'ground'.

4 PRESENTATION AND DISCUSSION OF TEST RESULTS

4.1 Determination of V_{ZRC}

Previous flight tests with the BAC 221 aircraft[6] had explored two methods for determining V_{ZRC}. One was to attempt to find directly the speed giving level flight for a particular power setting. The determination of V_{ZRC} by this method was difficult, for reasons connected with speed instability in level flight below minimum drag speed, and it was found preferable to perform a series of runs at constant power setting at different speeds near the expected V_{ZRC}, observing the net rate of climb or descent at each speed. The values of speed and rate of climb then gave a graph from which the speed for zero rate of climb could be extracted. This method was also used for the SST simulation.

Instrument deficiencies hampered the determination of V_{ZRC} in the SST simulation. In flying a steady airspeed the pilot had to use the artificial horizon as his only pitch reference, to keep pitch excursions to a minimum. The artificial horizon pitch scale was rather coarse, with pitch markings at 5° intervals, and the attitude required for level flight was close to $12\frac{1}{2}^{\circ}$, midway between markings on the horizon. Small pitch deviations thus passed undetected, reducing the accuracy of speed holding. Also, the scale of the airspeed indicator could not be read to better than one or two knots. These two factors, combined with the low rates of climb experienced at speeds close to V_{ZRC}, affected the accuracy of determination of V_{ZRC}. Fig.5 shows flight path angle as a function of speed, deduced from the equations defining the two simulations; note that for the SST a change of speed of 1 kt close to V_{ZRC} would produce a change of flight path angle of around 0.1 degrees, which is equivalent to a change in rate of climb of only 25 ft/min (0.13 m/sec).

Fig.6 shows a portion of a simulator record taken during a partial climb at around 152 kt. Speed had been held between 152 and 153.5 kt for two minutes, but there were transient variations in the rate of climb from +1 to -3.5 ft/sec (+0.3 to -1 m/sec). Measurements of rate of climb $(\dot{h})$ and airspeed (V) have been taken from these records as shown in Fig.6 for those portions of the trace where the fluctuations in $\dot{h}$ are small and $\dot{V}$ is close to zero; these measurements have been plotted for all the SST trials in Fig.7. Also shown in Fig.7 are the actual trim $\dot{h} - V$ relationship, calculated from the simulator equations, and a least squares fit to the measured points, assuming a quadratic equation. Although the least squares curve gives a good determination of V_{ZRC}, there is appreciable scatter of the measured points about the curve, with errors of up to $1\frac{1}{2}$ ft/sec (0.5 m/sec) in rate of climb or 3 kt in speed.

In the BAC 221 simulation the pilots were asked to determine V_{ZRC} as quickly as possible; they chose to do so by a series of partial climbs and dives as for the SST simulation, bracketing V_{ZRC} and gradually narrowing the speed bracket. Short trim runs were all that were required to establish V_{ZRC} within ±2 kt of the correct value, and this result was achieved in about 2 minutes, but to improve the estimate took considerably longer because of the small change in rates of climb once close to V_{ZRC}. Final results were within 1 kt of the true value for the clean configuration and 2 kt for the approach configuration, though the 1 kt estimates took nearly 10 minutes to establish. The flight instruments did not intrude into the task in this simulation as airspeed could be read to better than ½ kt and, although the scale of the artificial horizon was poorer than that used for the SST simulation, the 'outside world' television display gave an adequate attitude reference.

4.2 Recoveries from flight below V_{ZRC}

The second half of each simulator trial was devoted to the study of recovery manoeuvres from flight below V_{ZRC}. For these tests pilots were asked to reduce speed to a value below V_{ZRC} and then to perform a recovery, the manoeuvre being considered complete when a positive rate of climb was observed at a speed above V_{ZRC}. No particular instructions were given as to the choice of the final speed, but pilots found their choice of speed bounded by two considerations. Firstly, they did not wish to finish up too close to V_{ZRC} in a situation where performance margins were inadequate and there would be further risk of speed falling below V_{ZRC}; some allowance was also necessary for the limits of accuracy of the determination of V_{ZRC} in the first part of the trial. Secondly, although recovery to a speed well above V_{ZRC} would give adequate performance margins, basic energy considerations show that speed increases must be bought at the expense of height losses. The final choice of recovery speed was thus a compromise between minimum loss of height and minimum safe performance margin after recovery, and pilots generally aimed for a speed 5-10 kt above V_{ZRC}.

It should be noted that these tests were performed under ideally calm atmospheric conditions, and that in real flight in the presence of turbulence a further safety margin would be required to ensure positive recovery.

In the SST simulation, recovery was initiated in the majority of manoeuvres from a condition of approximately steady rate of descent and speed. For this class of aircraft there is very little change in trimmed attitude with change of speed, when thrust is constant (at the simulator conditions, a change in speed from 125 to 175 kt gives only 0.6° pitch attitude change), and the attitude prior to recovery was close to $13\frac{1}{2}^{\circ}$ in most runs. This insensitivity of attitude to speed changes is in itself an important factor when considering the likelihood of a pilot inadvertently allowing speed to fall in low speed flight; the fact that pitch attitude, the pilot's most important reference for steady flight, gives virtually no indication of even quite marked speed changes must increase the possibility of inadvertent speed reductions.

From the initial condition of speed approximately stabilized below V_{ZRC}, pilots initiated recovery by a pushover, reducing attitude by about 7°, waited for the speed to rise to about V_{ZRC}, then pulled out, hoping to achieve level flight with airspeed 5-10 kt above V_{ZRC}. Fig.8a shows a typical recovery, from a starting speed 23 kt below V_{ZRC} with the aircraft descending and decelerating slightly; a positive rate of climb is established 10 kt above V_{ZRC}.

Too sharp a pull-out at the end of the recovery can have an unfavourable influence on the final speed, as indicated in Fig.8b. The increased lift required to pull out of the dive causes a rise in induced drag so that there is an excess of drag over thrust, even though airspeed is 10 kt above V_{ZRC}. This causes a speed reduction and, although not significant in the recovery shown here, in a not too extreme case could bring airspeed below V_{ZRC} again. The speed at which pull-up commences must obviously be related to the severity of the pull-up to achieve a particular final speed.

In the SST simulation, pilots tended to fly the initial part of the recovery mainly by reference to pitch attitude as displayed on the artificial horizon at the expense of direct attention to airspeed; this may be due to the lack of outside visual cues. In the BAC 221 simulation, where the visual display was operative, the pilots were able to give more attention to airspeed in control of the recovery manoeuvre. They chose to push forward until a reasonable acceleration was observed on the ASI, continued the dive until V_{ZRC} was reached and then pulled out as before. Fig.9 shows recovery manoeuvres performed during the BAC 221 simulation. Figs.9a and b illustrate recoveries starting from flight at initially constant speed and constant height respectively; the manoeuvres end about 8 kt above V_{ZRC}. In the recovery of Fig.9c the pilot used a severe pull-out and as a consequence airspeed dropped just below V_{ZRC}. The pilot was then uncertain whether speed was above or below V_{ZRC}, and tried to increase speed without loss of height; over 35 seconds elapsed before speed again rose above V_{ZRC}, and further height was lost. A second recovery manoeuvre to establish a speed above V_{ZRC} would probably have resulted in a smaller overall height loss than the slow gain of speed shown here, and a condition of improved performance would certainly have been achieved much sooner.

4.2.1 Comparison of height losses during recovery with theoretical predictions

During the recovery manoeuvre the potential energy derived from the loss of height is partly exchanged for kinetic energy to increase airspeed, and partly used to supply the work done against the imbalance of drag over thrust. In Figs.10 and 11 the actual height losses recorded during recovery are plotted for the two simulations against the portion of the height lost, attributable to the kinetic energy change, in raising speed from start to finish of the maneouvre. The portion of height lost due to drag excess (given by the vertical distance between individual points and the 45° line) is seen to increase as the overall height loss increases, as one might expect, as in these cases the aircraft will spend more time below V_{ZRC}. Typically, for the SST, the drag loss is around 30% of the total height loss in the large manoeuvres, and for the BAC 221 it is about 18%.

Pinsker[1] has produced a simple theoretical estimate of the overall height loss during recovery manoeuvres to V_{ZRC}, and, with certain assumptions, relates the height loss to the initial airspeed, mean rate of descent and a drag parameter K. This theory has been extended here (Appendix B, section B.1) to consider recoveries to speeds other than V_{ZRC}. Using the value of K at V_{ZRC} (see Appendix B, section B.2), theoretical values of the total height lost during recovery have been calculated and plotted against actual height lost in Figs.12 and 13. The theoretical expression underestimates the actual height losses for the SST results, the underestimate being greater for the larger manoeuvres. The BAC 221 results show more scatter but are otherwise in good agreement.

Inspection of Fig.5 suggests that to use the value of K at V_{ZRC} might lead to an underestimate of the height loss as the curve of γ against V steepens as V is reduced; the same theoretical calculations have been performed using a value of K, K_m, which takes account of the change of slope (see Appendix B, section B.2). These calculated values are plotted against actual height loss in Figs.14 and 15. The agreement between theory and simulation is excellent for the SST results, but there is again scatter of the point for the BAC 221 simulation and in general a slight overestimate of the height lost.

The theoretical expression for the height lost during recovery is based on a number of assumptions[1], one of which is that the drag characteristics are such that (T - D)/W changes linearly with speed around V_{ZRC}. While this may be approximately true for the aircraft in trimmed conditions (i.e. trimmed (T - D)/W changes linearly with airspeed) it is far from true for the dynamic manoeuvre. Fig.16 shows a recovery manoeuvre from the BAC 221 simulation; the actual (T - D)/W during the manoeuvre is compared with the (T - D)/W assumed in the theoretical expression. The reduction in incidence during pushover gives a reduction in induced drag, and thrust exceeds drag, whereas the assumed variation shows thrust less than drag. During the pull-out the opposite effect occurs. Thus the actual variation of (T - D)/W is somewhat the reverse of that in the theoretical expression. Ref.1, however, was concerned with obtaining an estimate of the magnitude of the height loss during recovery, and for this purpose assumed that the effects of induced drag during pushover and pull-out will cancel each other. This assumption is justified by the very good agreement between theory and simulator test results for the SST simulation, where modest normal accelerations were used in pushover and pull-out. It should be noted that if the recovery manoeuvre starts from an initially descending condition there will be a net positive vertical acceleration required to recover to level flight and hence an adverse overall effect of induced drag, for which the theoretical expression makes no allowance; this effect will normally be small.

The greater scatter of the results of the BAC 221 simulation may be attributed to the more severe manoeuvres performed in that simulation. Incremental normal acceleration during pushovers averaged -0.44 g for the BAC 221, but only -0.20 g for the SST; hence the departure from the assumptions of the theoretical calculations was greater in the BAC 221 simulation.

The higher g levels may have resulted partly from the more rapid response of the BAC 221 compared with the SST and partly from the more powerful visual cues available in the BAC 221 simulation; the pilots were more confident of performing rapid pushovers and pull-outs without fear of overcontrolling, and there were no normal acceleration motion cues to inhibit the use of large g's. In the SST simulation the poor visual reference restrained the pilots to modest pitch rates. Normal accelerations of up to 1 g were used in the BAC 221 simulation; a maximum of 0.4 g was reached in the SST simulation.

Longitudinal accelerations were also higher in the BAC 221 simulation, averaging 3.7 kt/sec compared with 2.1 kt/sec for the SST. However, this greater acceleration was countered by the greater increase in induced drag during the pull-out and V_{ZRC} was still a good speed at which to commence the pull-out.

5 EXTRAPOLATION TO REAL FLIGHT CONDITIONS

There are three problem areas in the use of zero rate of climb speed as a datum for the limits of low speed operation. Firstly, one needs to consider the likelihood of inadvertent speed reduction to or below V_{ZRC} in given flight conditions; secondly, in the context of airworthiness requirements it is important to know with what accuracy one can expect V_{ZRC} to be determined in flight, and thirdly, the magnitude of the height losses to be expected during recovery needs to be determined and the optimum form of the recovery manoeuvre should be established. The simulator tests described here have been concerned with the last two of these areas, and can give very little assistance on the first. It is worth emphasising, however, that although V_{ZRC} is capable of precise definition under a given set of conditions, the approach to V_{ZRC} is not marked by any significant changes (unlike the approach to the stall) and speed can fall below V_{ZRC} without any obvious warning to the pilot, until he tries to maintain level flight at a condition for which performance is then inadequate. Such an event has occurred in flight tests with the BAC 221 and is described in Ref.6. A further factor affecting the probability of speed falling below V_{ZRC} has already been mentioned in section 4.2, where the very small change of pitch attitude with change of airspeed has been described. This lack of appreciation of the approach to V_{ZRC} must be reflected in the choice of speed margins above V_{ZRC} when defining the limits of safe low speed operation.

5.1 Determination of V_{ZRC}

As the zero rate of climb speed is a function of the factors affecting aircraft performance, such as thrust, weight, drag, temperature, altitude, these conditions must be considered when defining and when measuring V_{ZRC}. Flight and simulator tests have shown that V_{ZRC} is best determined by a series of partial climbs and dives, measuring airspeed and rate of climb and obtaining V_{ZRC} from these values of speed and rate of climb. The simulator tests were performed under conditions of constant thrust, weight, temperature, etc., in the absence of atmospheric disturbances, and true values of rate of climb were extracted from the simulator computations and used to determine V_{ZRC}. In practice these conditions would vary and the accuracy of height and rate of climb measurements would suffer from the inadequacies attendant on the measurement of height by pressure systems, particularly for small changes of height or rate of climb. A mean rate of climb, obtained by measuring the time taken for a given change of height, would be used, involving fairly lengthy trim runs at speeds close to V_{ZRC} where the rates of climb are small. Changes in weight due to fuel consumption might cause a significant change in V_{ZRC} during a series of trim runs (for the BAC 221, typically a decrease in V_{ZRC} of about 1 kt/min). Small changes in thrust will also affect V_{ZRC} (1 kt per 25 lb (110 N) of thrust for the BAC 221). Thus determination of V_{ZRC} for a number of configurations and conditions will be somewhat lengthy, and the accuracy of the result will probably be lower than that achieved in the simulator. Also, even when V_{ZRC} is established as a function of the various relevant parameters, uncertainty in the knowledge of conditions at any instant of flight will necessitate a further margin on the value of V_{ZRC} in the definition of safe operating speeds. However, V_{ZRC} will probably be of greatest significance as a take-off performance limitation and at take-off the weight will be known to greater accuracy than at any other instant in flight, reducing the need for a margin for error from this source.

5.2 Recovery manoeuvres

There are two facts one might hope to derive from simulation of the recovery manoeuvre; firstly, the order of magnitude of the height losses experienced during recovery, and secondly the optimum technique for recovery. The simulation tests have shown, by agreement with theory, that the theory of Ref.1 gives a good estimate of the height losses once allowance has been made for the recovery terminating above V_{ZRC} and for the non-linear variation of drag with speed. No particular attempt had been made in these tests to study the optimum recovery technique from the point of view of height loss, but the excellent agreement between simulator and theory for the SST results adds weight to any conclusions that can be drawn from the theoretical expressions for height loss. Ref.1 concludes that the optimum recovery manoeuvre is the most rapid one possible. In practice there will of course be limits to the rapidity that is possible; one such limit is clearly given by the pitch response of the aircraft. Note that recovery manoeuvres in the SST were less severe than those in the more responsive BAC 221. The greater scatter of the BAC 221 results also suggests that when induced drag effects are high, for more violent recoveries, the assumption of Ref.1 of no net effect of induced drag on the height lost may not be as satisfactory and the height loss may be influenced by the detailed form of the pushover and pull-out phases of the recovery. However, such effects would be of minor significance to the general conclusion that height losses are minimised by a rapid recovery manoeuvre.

6 CONCLUSIONS

Two simulations, one of a supersonic transport aircraft and the other of the BAC 221 research aircraft, have been performed in which the problems of flight at or below the zero rate of climb speed (V_{ZRC}) have been investigated. It was found that, in simulated partial climb tests, V_{ZRC} could be determined to within 1-3 kt under the somewhat ideal simulation conditions; the accuracy of such tests in real flight, however, must be expected to be reduced by the effects of a changing weight, thrust etc., and from the difficulties of accurate measurements of low rates of climb when close to V_{ZRC}. Recovery manoeuvres from flight below V_{ZRC} were performed. As was to be expected the loss in height incurred in recovery to a safe speed above V_{ZRC} was largely that explained by simple energy considerations, but since during most of the recovery manoeuvre the aircraft was in a condition where drag exceeded thrust there was an additional height loss attributable to overcoming this excess of drag. In some of the SST manoeuvres this drag loss accounted for up to 30% of the total height loss, but in the more rapid manoeuvres performed in the BAC 221 simulation, around 18% was typical.

A theoretical expression for the height loss during recovery gave very good agreement with the simulator results for the SST simulation; the results for the BAC 221 simulation showed a little more scatter, though still good agreement. The tests suggested that the detailed optimum recovery technique might depend on induced drag effects during pushover and pull-out phases of the manoeuvre but this would only be a refinement to the general conclusions that height losses are reduced by performing a rapid recovery manoeuvre in preference to a slow one.

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Appendix A

AIRCRAFT DATA AS USED IN THE SIMULATIONS

A.1 SST simulation

A full description of the data used appears in Ref.2.

Weight	200 000 lb (90720 kg mass)
Pitching inertia	4.19×10^6 slug ft^2 (5.68×10^6 kg m^2)
Reference wing area	3856 ft^2 (358.2 m^2)
Reference wing chord c_o	90.75 ft (27.66 m)
cg position for these tests	52.5% c_o
Thrust used in these tests	45890 lb (204 130 N)
Zero rate of climb speed V_{ZRC}	156 kt
K (defined in Appendix B)	0.306

A.2 BAC 221 simulation

Ref.3 provides a detailed list of data used.

Weight	18500 lb (8390 kg mass)
Pitching inertia,	
clean configuration	5.07×10^4 slug ft^2 (6.87×10^4 kg m^2)
approach configuration	5.41×10^4 slug ft^2 (7.34×10^4 kg m^2)
Reference wing area	490 ft^2 (45.5 m^2)
Reference wing chord	25 ft (7.62 m)
cg position for these tests,	
clean configuration	161 in (4.09 m) forward of datum
approach configuration	159 in (4.04 m) forward of datum
Thrust used,	
clean configuration	4311 lb (19175 N)
approach configuration	4986 lb (22178 N)
Zero rate of climb speed,	
clean configuration	146 kt eas
approach configuration	150 kt
K clean configuration	0.309
approach configuration	0.175

Appendix B

B.1 Height lost during recovery manoeuvre from below V_{ZRC}

Pinsker has shown[1] that the height change ΔH during a manoevure from a speed $V_o - \Delta V_o$ to a speed V_o is given by

$$\Delta H = -\frac{\Delta V_o}{2g}(2V_o - \Delta V_o) - \int_o^{t_R} \frac{D - T}{W} V(t)\, dt \qquad (1)$$

where t_R = duration of the manoeuvre
T = thrust
D = drag at time t
$V(t)$ = airspeed at time t.

The first term in the expression for ΔH is due to the exchange of potential and kinetic energy, and the second term to the work done against the excess of drag over thrust.

It is then assumed that, if V_o is the zero rate of climb speed V_{ZRC}, the drag versus speed characteristics of the aircraft can be assumed linear within the range of interest and can be described by the equation

$$\frac{T - D}{W} = \Delta V \frac{K}{V_o} \qquad (2)$$

where $\Delta V = V(t) - V_o$ and K is a constant.

It is further assumed that $V(t)$ can be replaced by the mean speed $V_o - \Delta V_o/2$ and that ΔV can be represented by a mean value $-\Delta V_o/2$. Then

$$\Delta H = -\frac{\Delta V_o}{2g}(2V_o - \Delta V_o) + \int_o^{t_R} \frac{K}{V_o}\left(-\frac{\Delta V_o}{2}\right)\left(V_o - \frac{\Delta V_o}{2}\right) dt$$

$$= -\frac{\Delta V_o}{2g}(2V_o - \Delta V_o) - \frac{K}{2V_o} \cdot \Delta V_o \left(V_o - \frac{\Delta V_o}{2}\right) t_R \quad . \qquad (3)$$

If we take the mean vertical velocity $\dot{H}_m = \Delta H/t_R$ we can rearrange equation (3) to give

$$\Delta H = -\frac{1}{2g}\,\frac{V_o\,(2V_o - \Delta V_o)}{1 + \frac{K}{4\dot{H}_m}\cdot\frac{\Delta V_o}{V_o}\cdot(2V_o - \Delta V_o)} \quad . \qquad (4)$$

However, in the simulator tests, recoveries were made to speeds above V_{ZRC} and it is possible to modify the theory of Ref.1 to allow for this. Let recovery be from speed $V_o - \Delta V_o$ to speed $V_o + \Delta V_1$. Equation (1) now becomes

$$\Delta H = -\frac{(\Delta V_1 + \Delta V_o)}{2g}\,(2V_o + \Delta V_1 - \Delta V_o) - \int_o^{t_R} \frac{D - T}{W}\,V(t)\,dt \qquad (5)$$

and $V(t)$ is replaced by the mean speed $V_o + (\Delta V_1 - \Delta V_o)/2$ and ΔV by $(\Delta V_1 - \Delta V_o)/2$. Substituting in equation (5) and rearranging as before gives

$$\Delta H = -\frac{1}{2g}\,\frac{(\Delta V_1 + \Delta V_o)\,(2V_o + \Delta V_1 - \Delta V_o)}{1 + \frac{K}{4\dot{H}_m}\cdot\frac{\Delta V_o - \Delta V_1}{V_o}\cdot(2V_o + \Delta V_1 - \Delta V_o)} \quad . \qquad (6)$$

The speeds here are true airspeeds; if we wish to write the equation in terms of equivalent airspeeds we must use the relationship $V_{eas} = V_{tas}\sqrt{\sigma}$. Hence, with speeds in eas, we have

$$\Delta H = -\frac{1}{2g\,\sigma}\,\frac{(\Delta V_1 + \Delta V_o)\,(2V_o + \Delta V_1 - \Delta V_o)}{1 + \frac{K}{4\dot{H}_m\sqrt{\sigma}}\cdot\frac{\Delta V_o - \Delta V_1}{V_o}\cdot(2V_o + \Delta V_1 - \Delta V_o)} \quad . \qquad (7)$$

B.2 Evaluation of K

The equation of motion along the flight path can be written, for small flight path angles, as

$$m\dot{V} = T - D - W\gamma \quad .$$

Hence for unaccelerated flight

$$W\gamma = T - D$$

i.e.

$$\gamma = \frac{T - D}{W} \quad .$$

Now from equation (2)

$$\frac{\Delta V}{V_o} K = \frac{T - D}{W}$$

$$= \gamma$$

therefore

$$K = \left(\frac{\gamma}{\frac{\Delta V}{V_o}}\right) .$$

For the conditions simulated, γ was not linear with V (Fig.5), so K was taken from the slope at V_o of the graph of trimmed flight path angle versus airspeed, i.e.

$$K = V_o \left[\left(\frac{\partial\gamma}{\partial V}\right)_{\dot{V}=0}\right]_{V=V_o} .$$

An alternative value of K was also used, taking some account of the non-linear variation of γ with V; this value, K_m, was obtained from the slope of the γ - V curve at the mean speed of the recovery manoeuvre, V_m, i.e.

$$K = V_o \left[\left(\frac{\partial\gamma}{\partial V}\right)_{\dot{V}=0}\right]_{V=V_m}$$

where $V_m = V_o + (\Delta V_1 - \Delta V_o)/2$.

SYMBOLS

D	aircraft drag
g	unit of normal acceleration = acceleration due to gravity
h	height
$\dot{h}$	rate of climb
ΔH	height change during recovery manoeuvre
$\dot{H}_m$	mean rate of climb during recovery manoeuvre
K	drag factor, defined in Appendix B
K_m	value of K at $V = V_m$
K_o	value of K at $V = V_{ZRC}$
m	aircraft mass
T	aircraft thrust
t	time
t_R	total recovery maneouvre time
V	airspeed
V_m	mean recovery speed, $= V_o + \frac{\Delta V_1 - \Delta V_o}{2}$
V_R	rotation speed
V_{ZRC}	zero rate of climb speed
V_o	$= V_{ZRC}$
V_1	take-off decision speed
ΔV_o	defined by:- speed at start of recovery manoeuvre $= V_o - \Delta V_o$
ΔV_1	defined by:- speed at end of recovery manoeuvre $= V_o + \Delta V_1$
$\dot{V}$	forward acceleration
W	aircraft weight
γ	flight path angle
σ	relative air density

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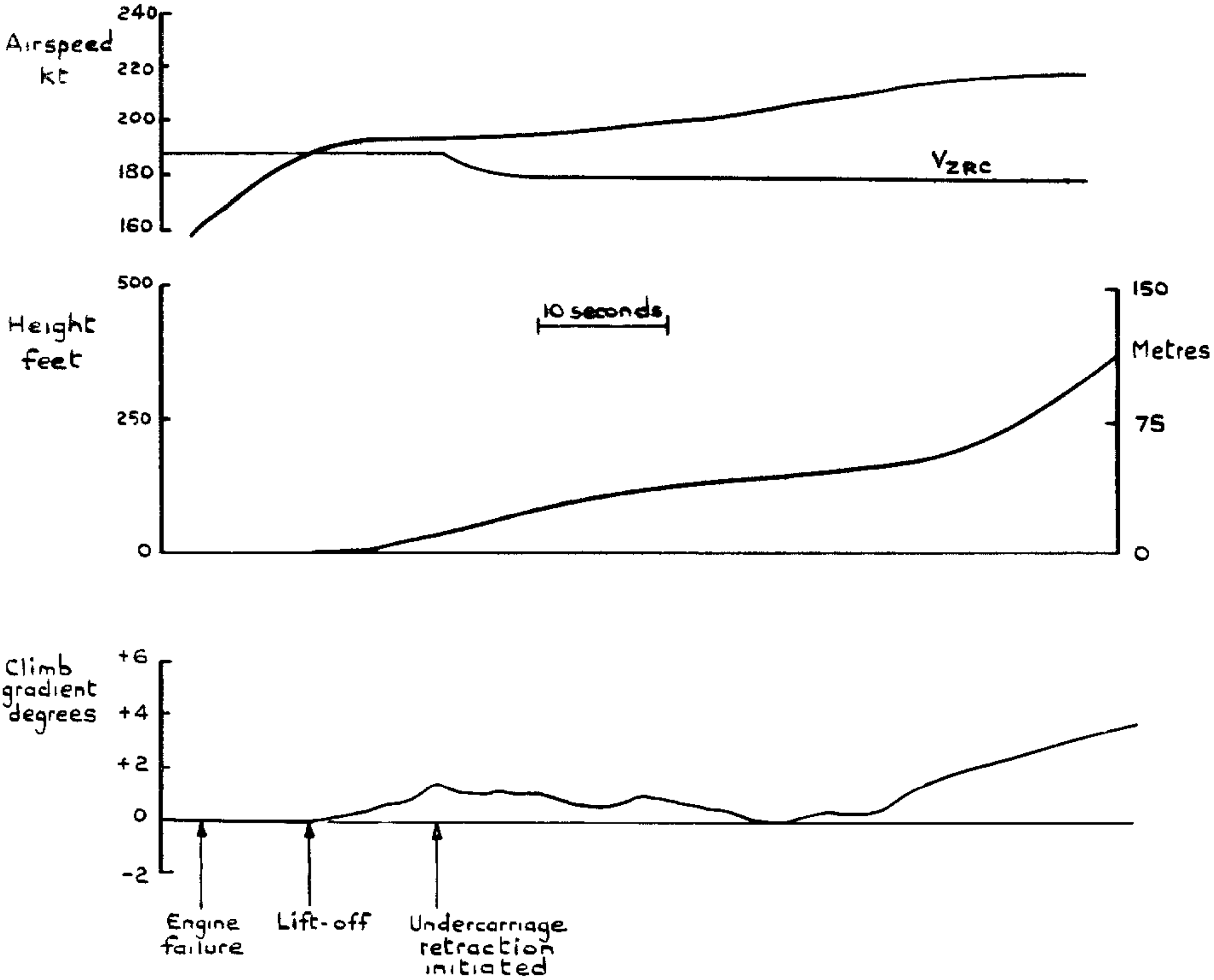

Fig.1 Premature lift-off from the simulation described in reference 8

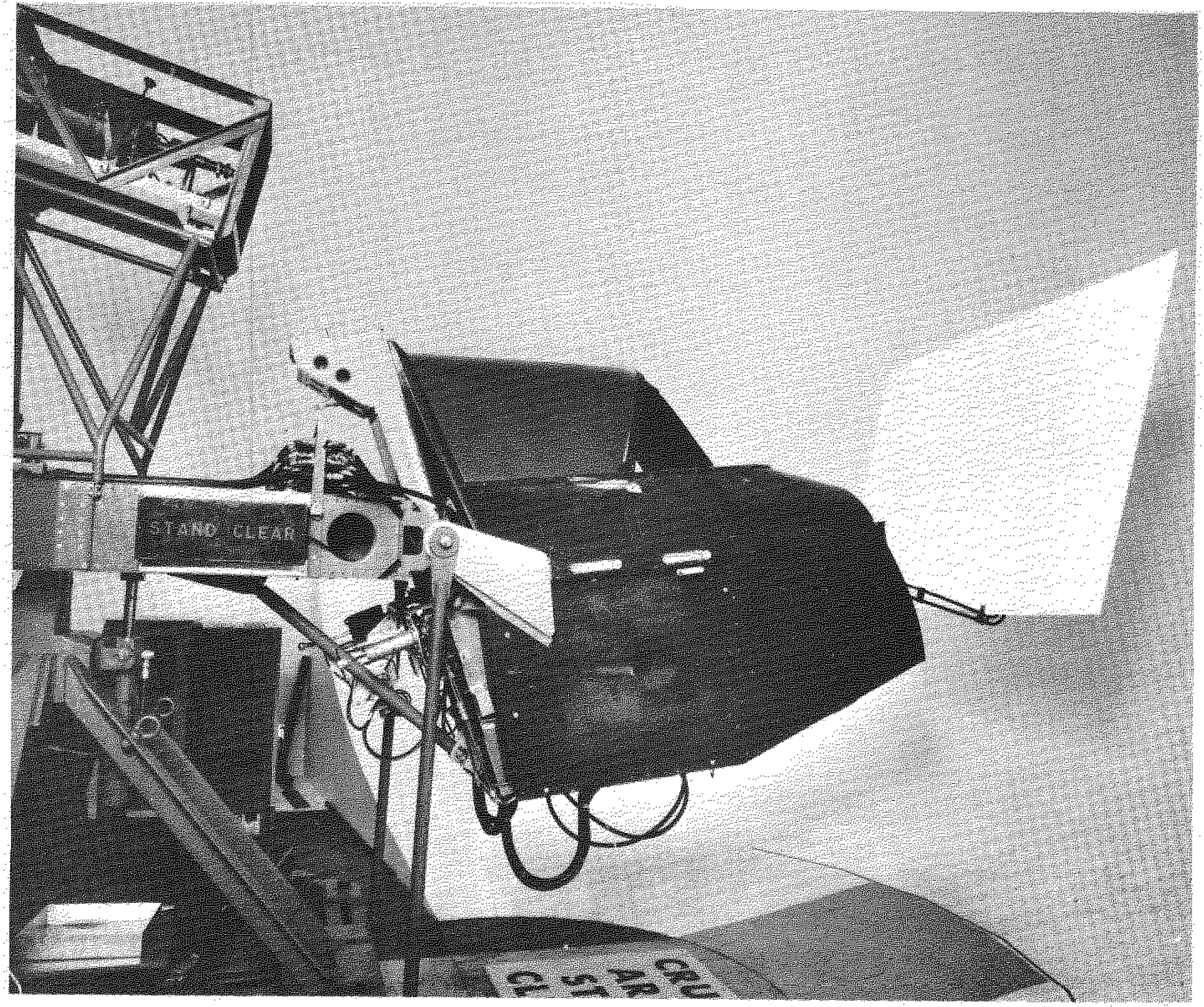

Fig.2. General view of simulator cockpit

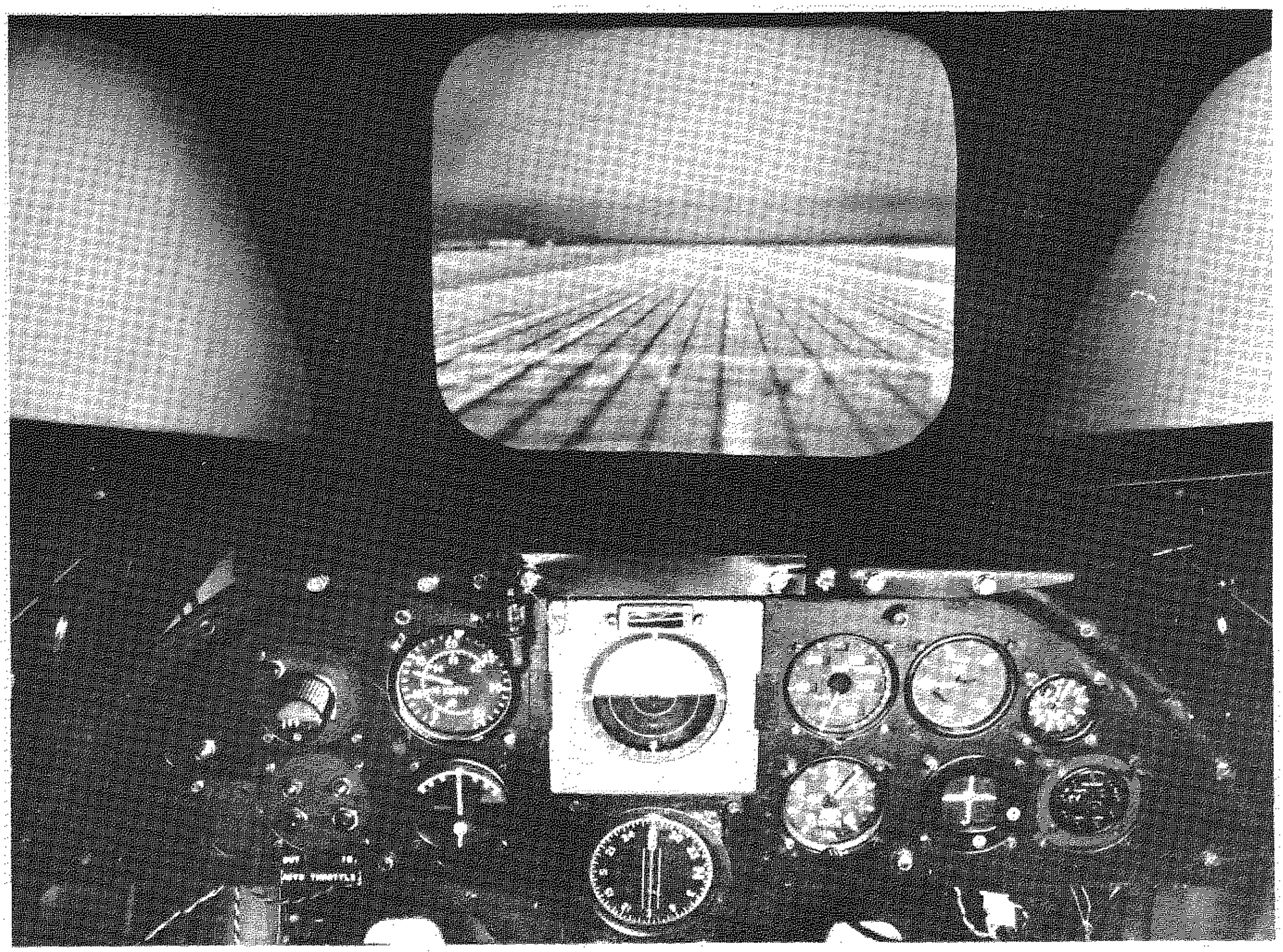

Fig.3. Instrument panel, SST simulation

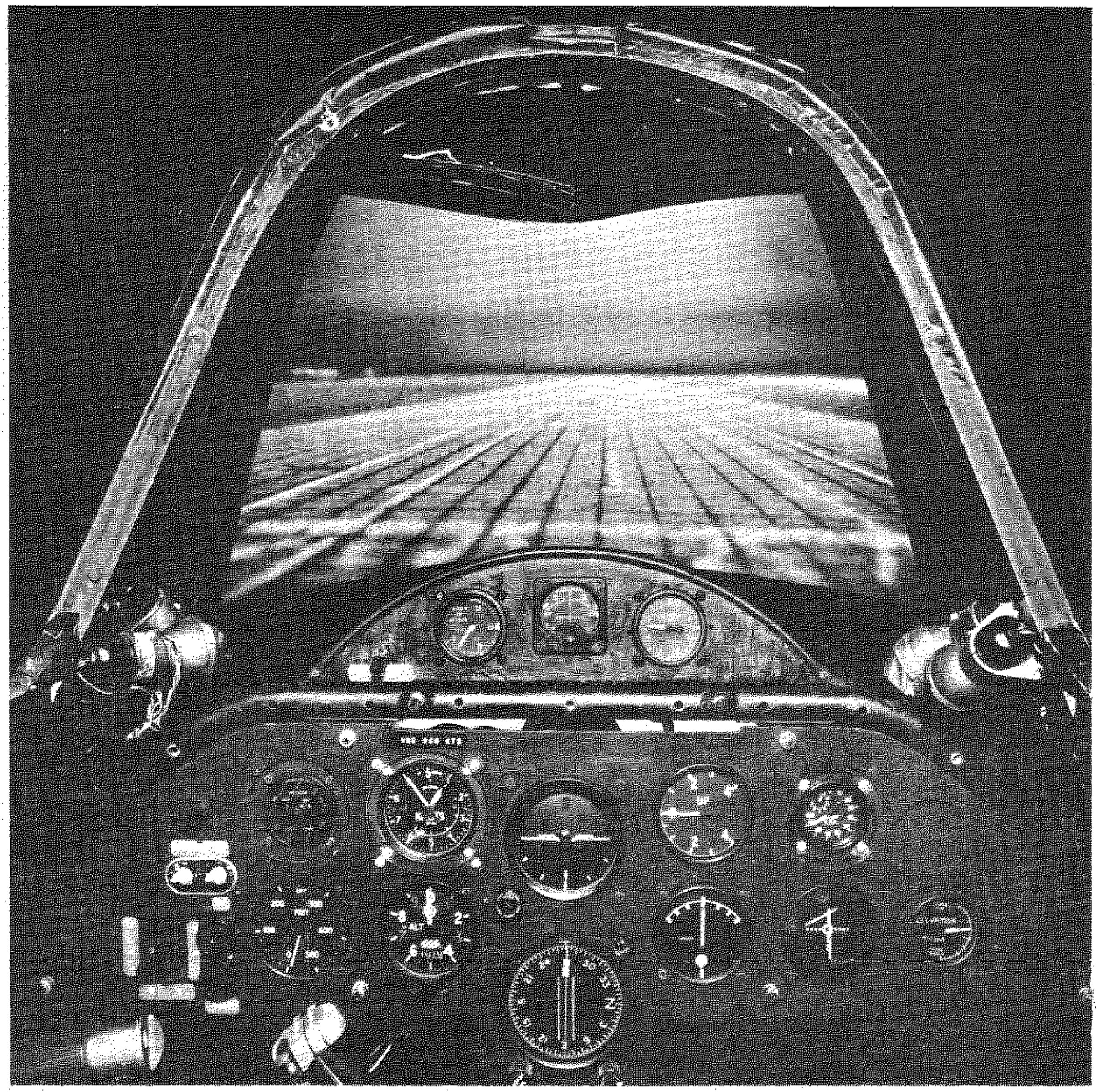

Fig.4. Instrument panel and visual display, BAC 221 simulation

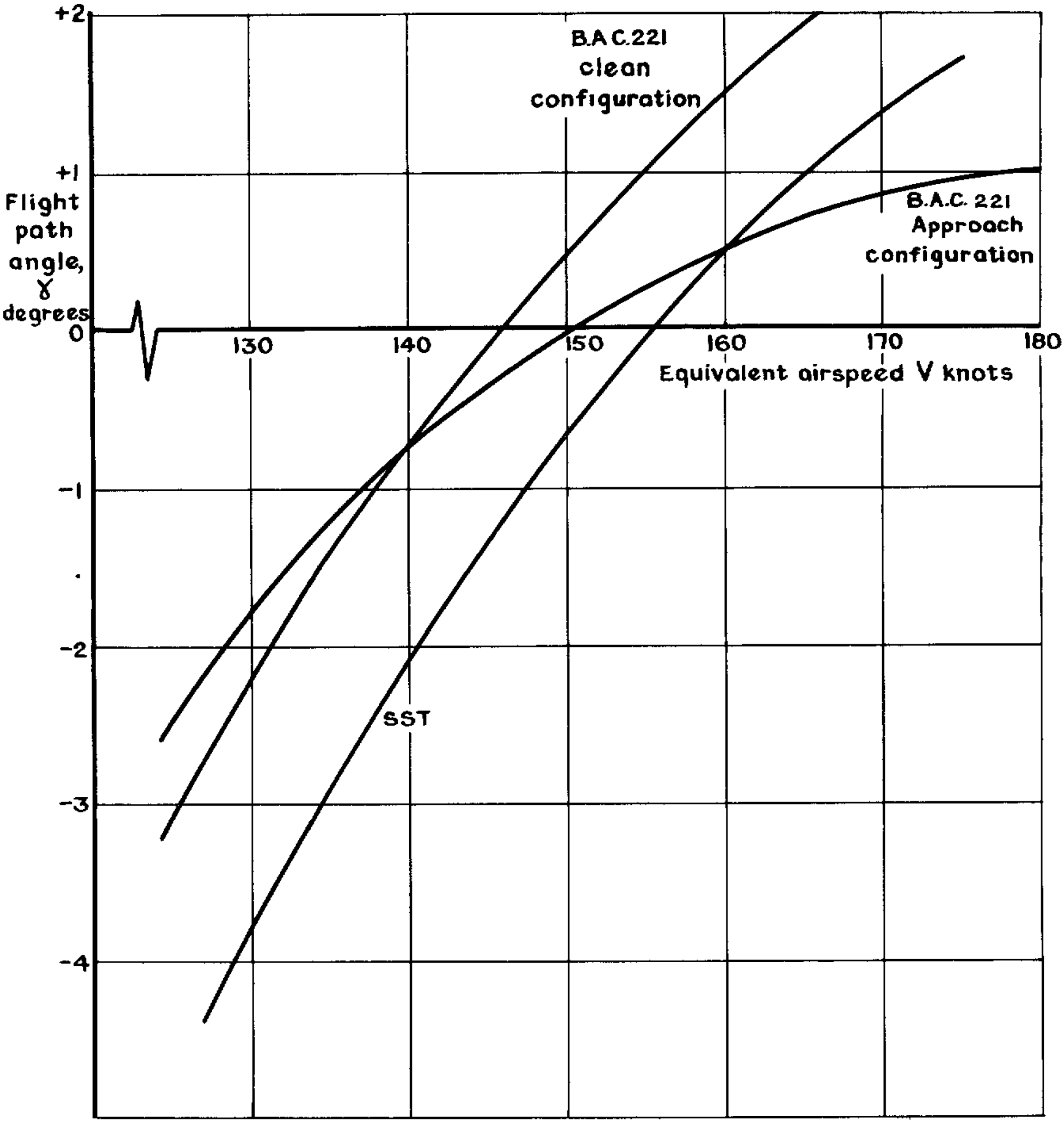

Fig. 5 Trimmed flight path angle versus equivalent airspeed, thrust constant

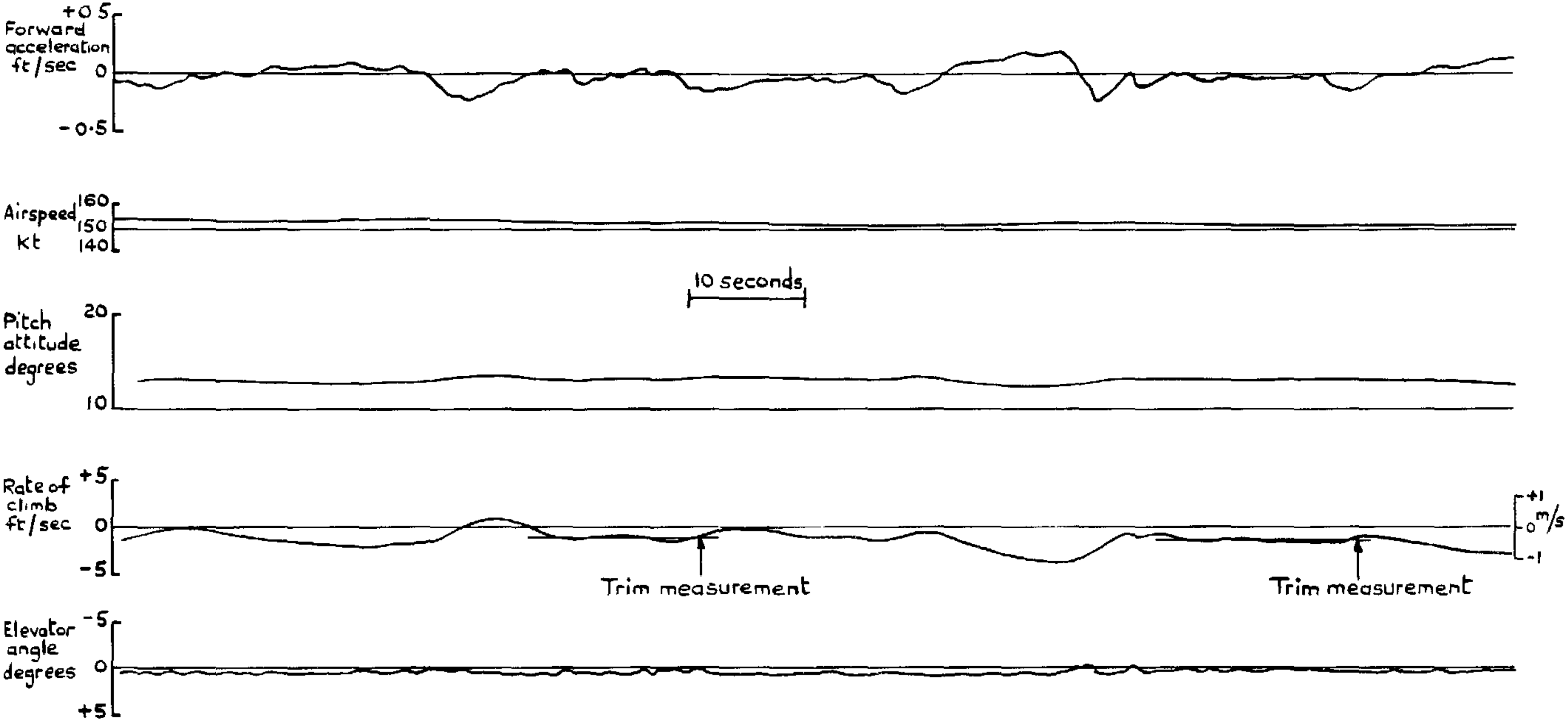

Fig.6 Partial climbs, SST simulation

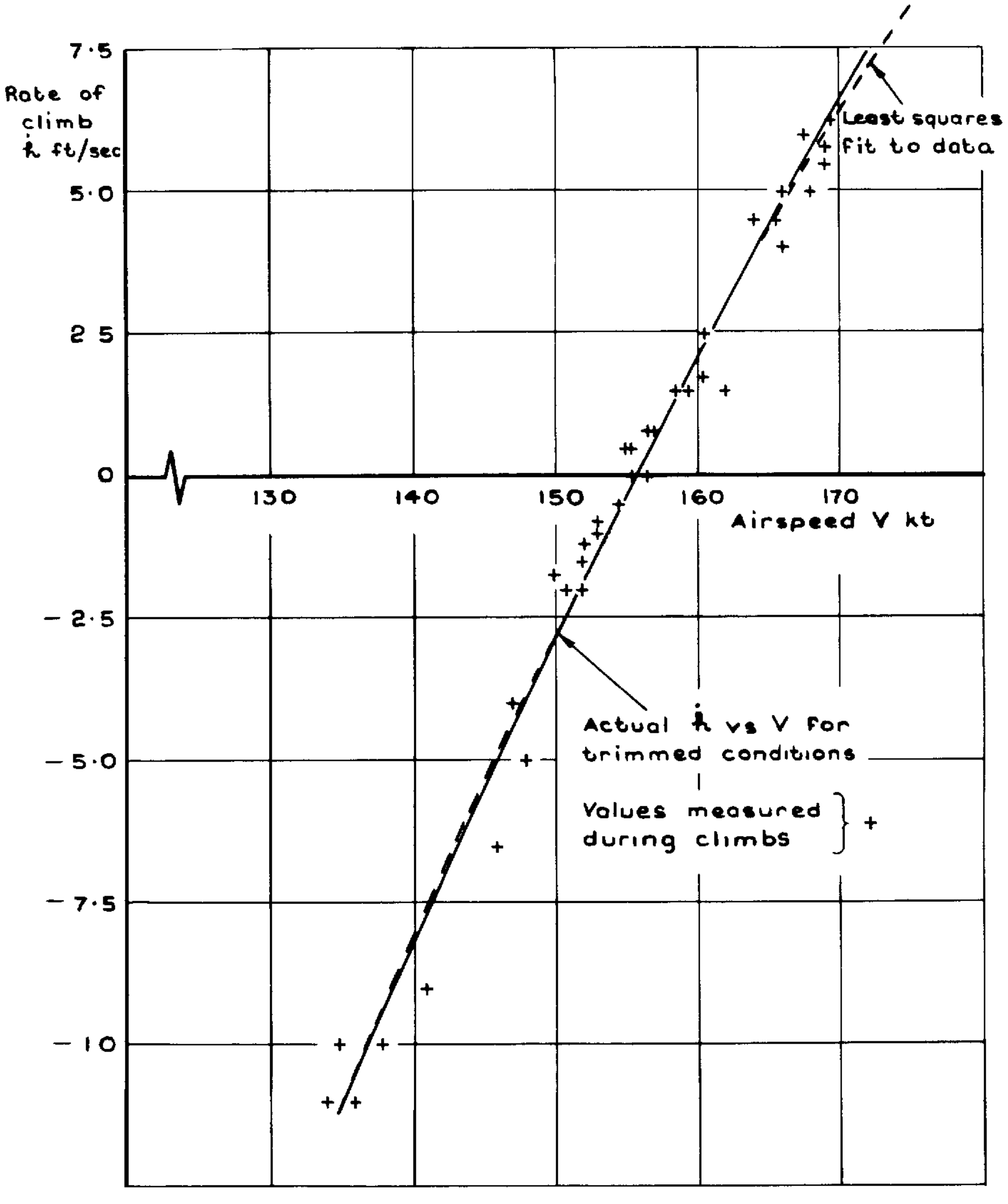

Fig 7 Rate of climb vs airspeed in partial climbs, SST simulation

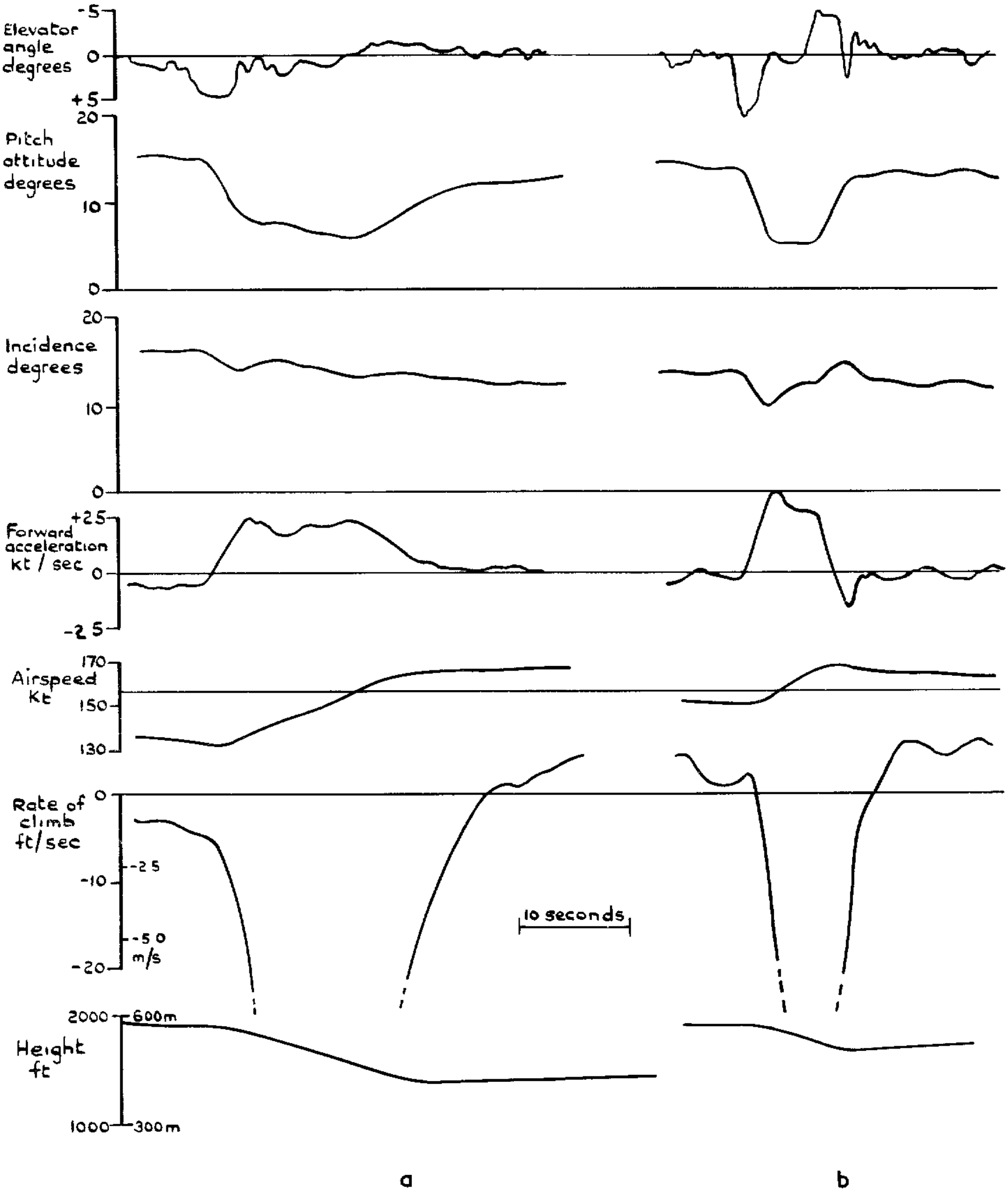

Fig. 8 a & b Recoveries from below zero rate of climb speed, SST simulation

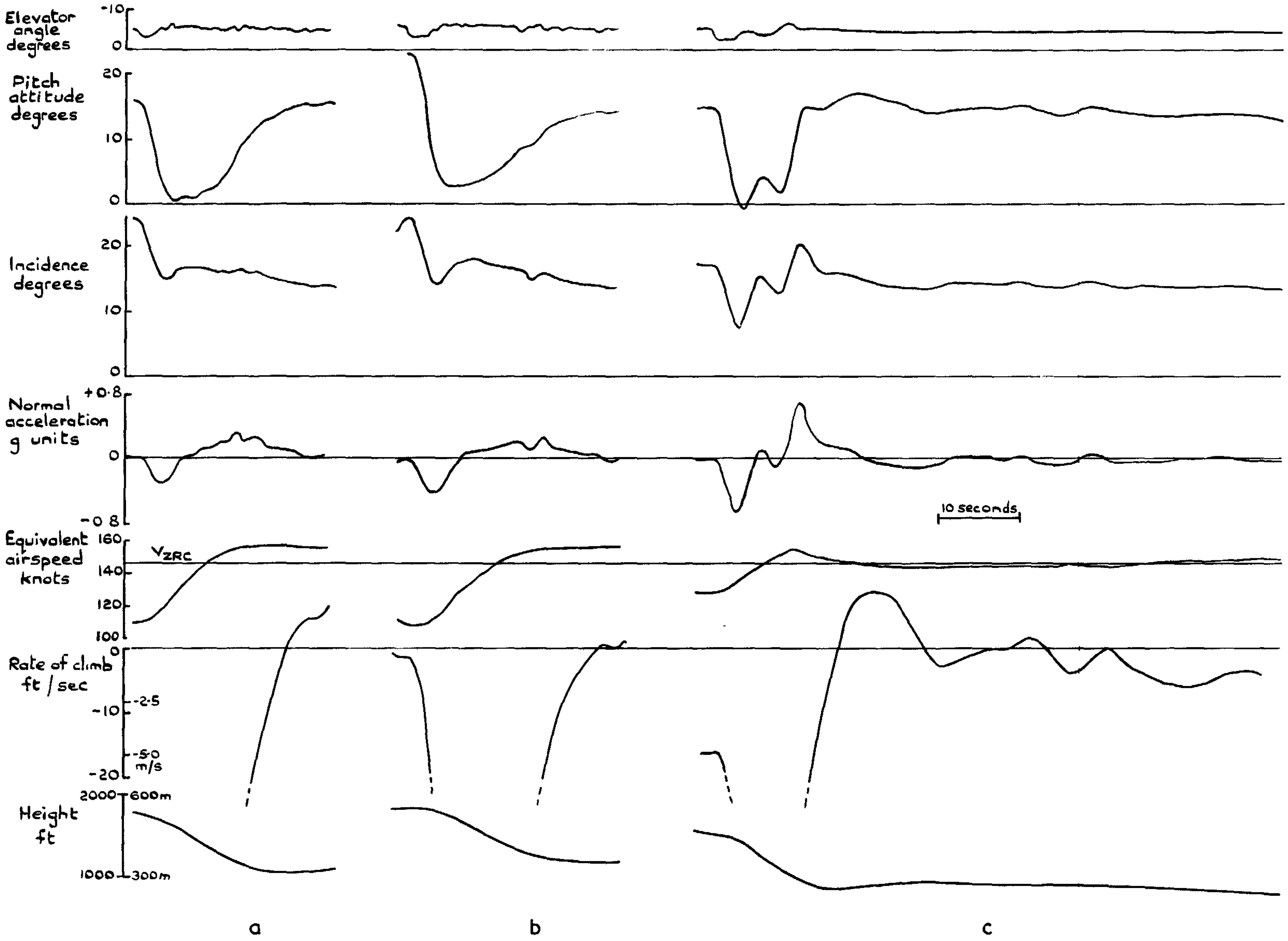

Fig. 9 a-c Recoveries from below zero rate of climb speed, BAC 221 simulation

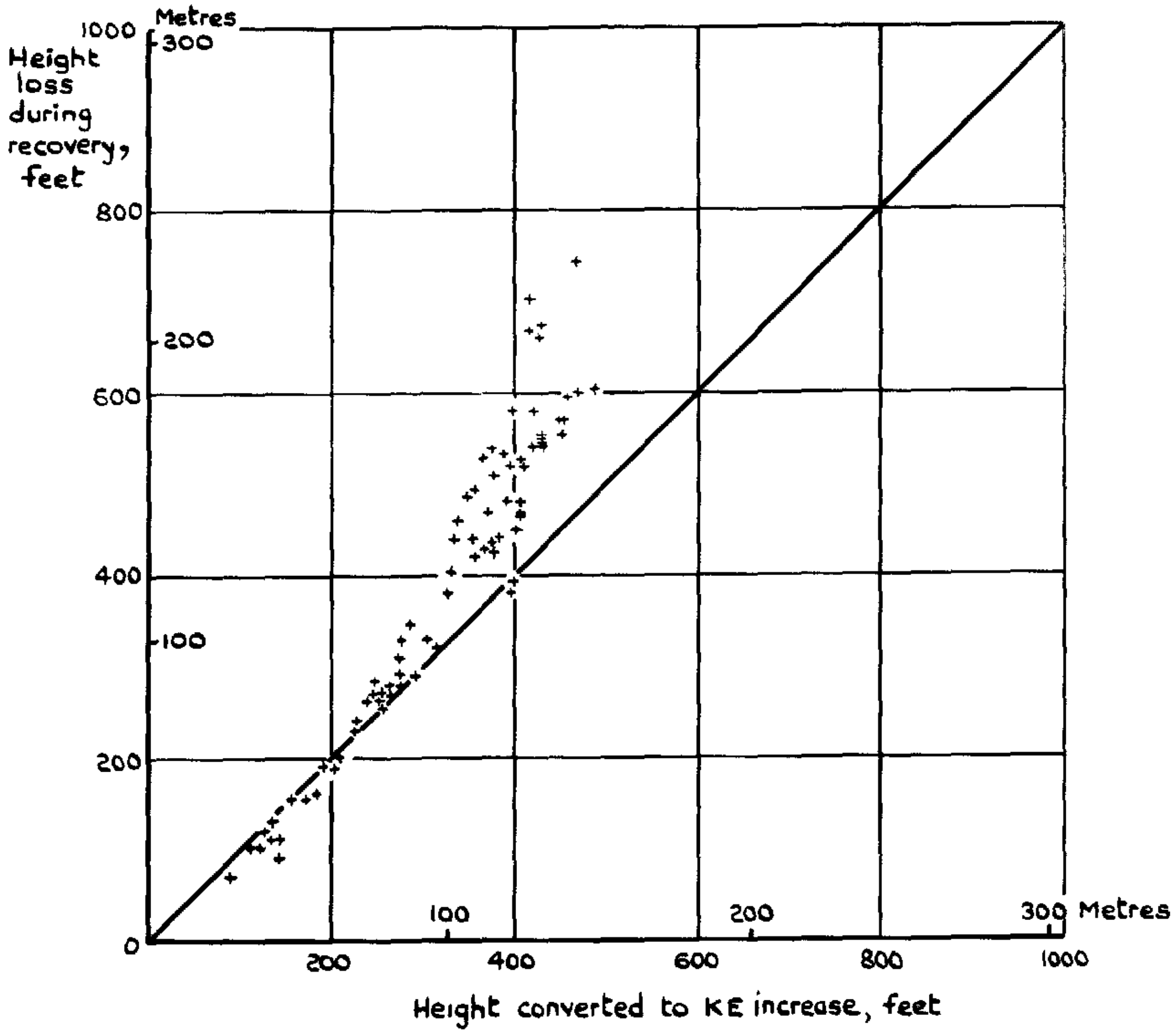

Fig.10 Height loss during recovery v height converted into increase in kinetic energy, SST simulation

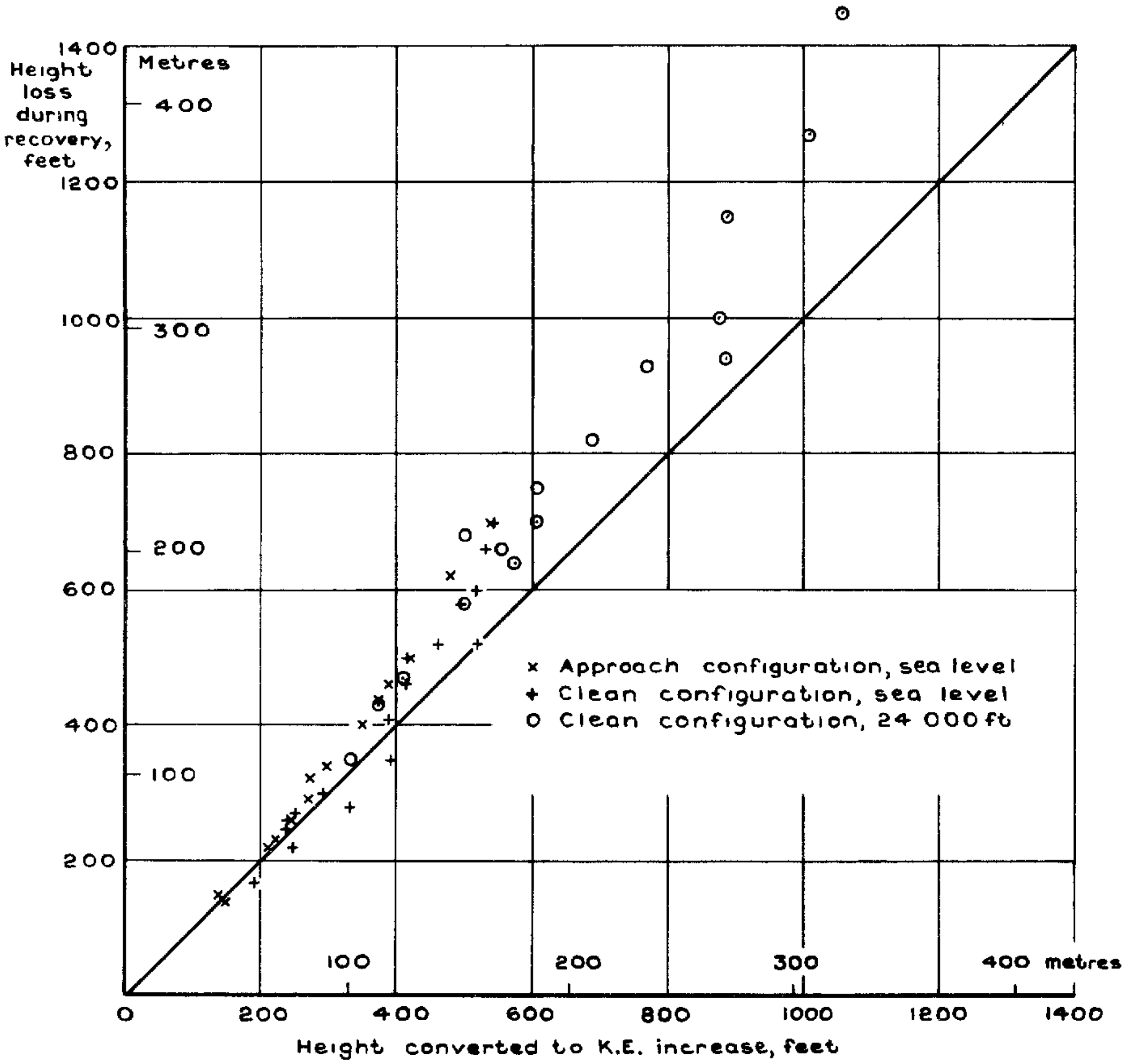

Fig. 11 Height loss during recovery v height converted into increase in kinetic energy, B A C 221 simulation

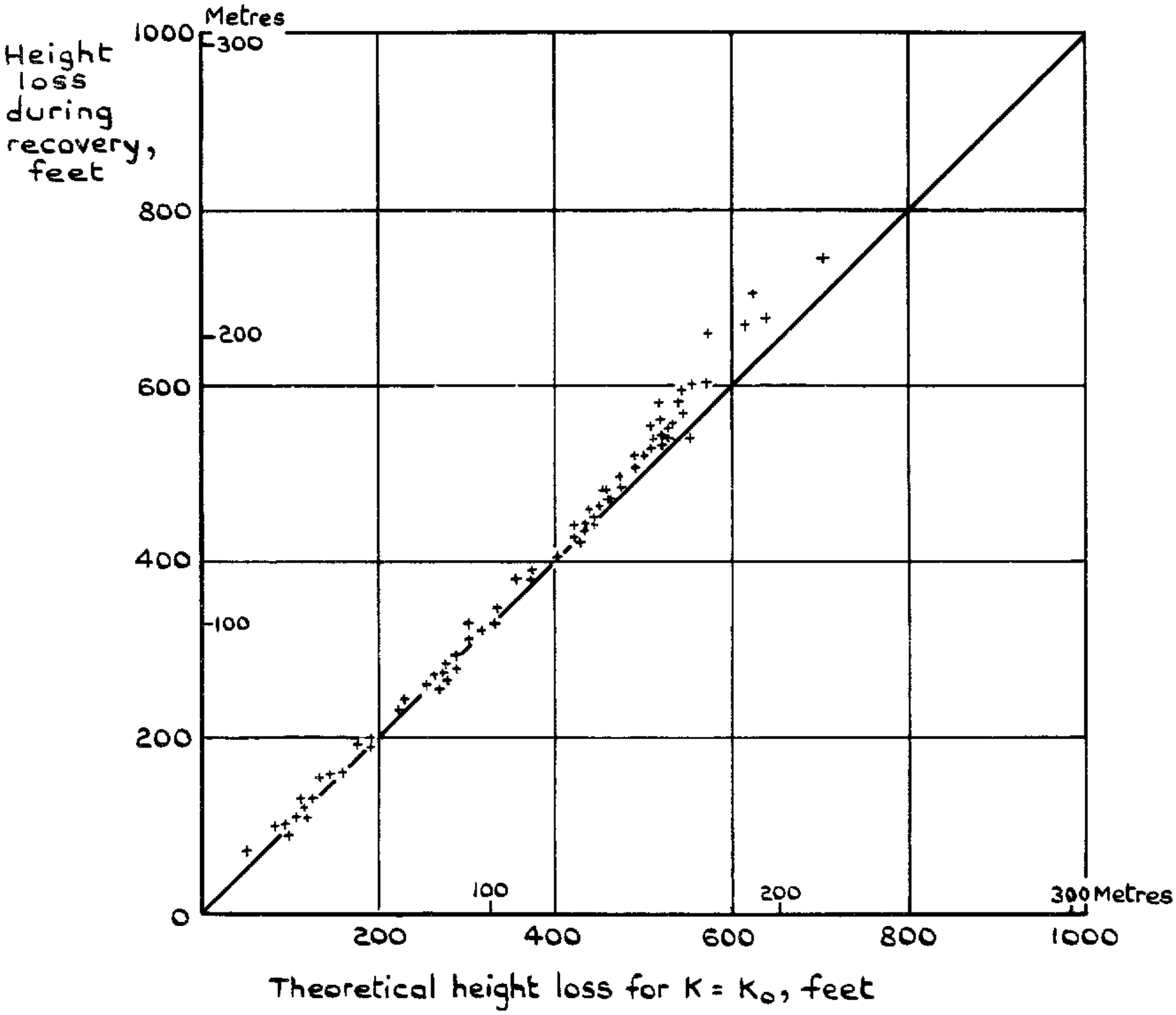

Fig.12 Height loss during recovery v theoretical height loss using K at V_{zRC} SST simulation

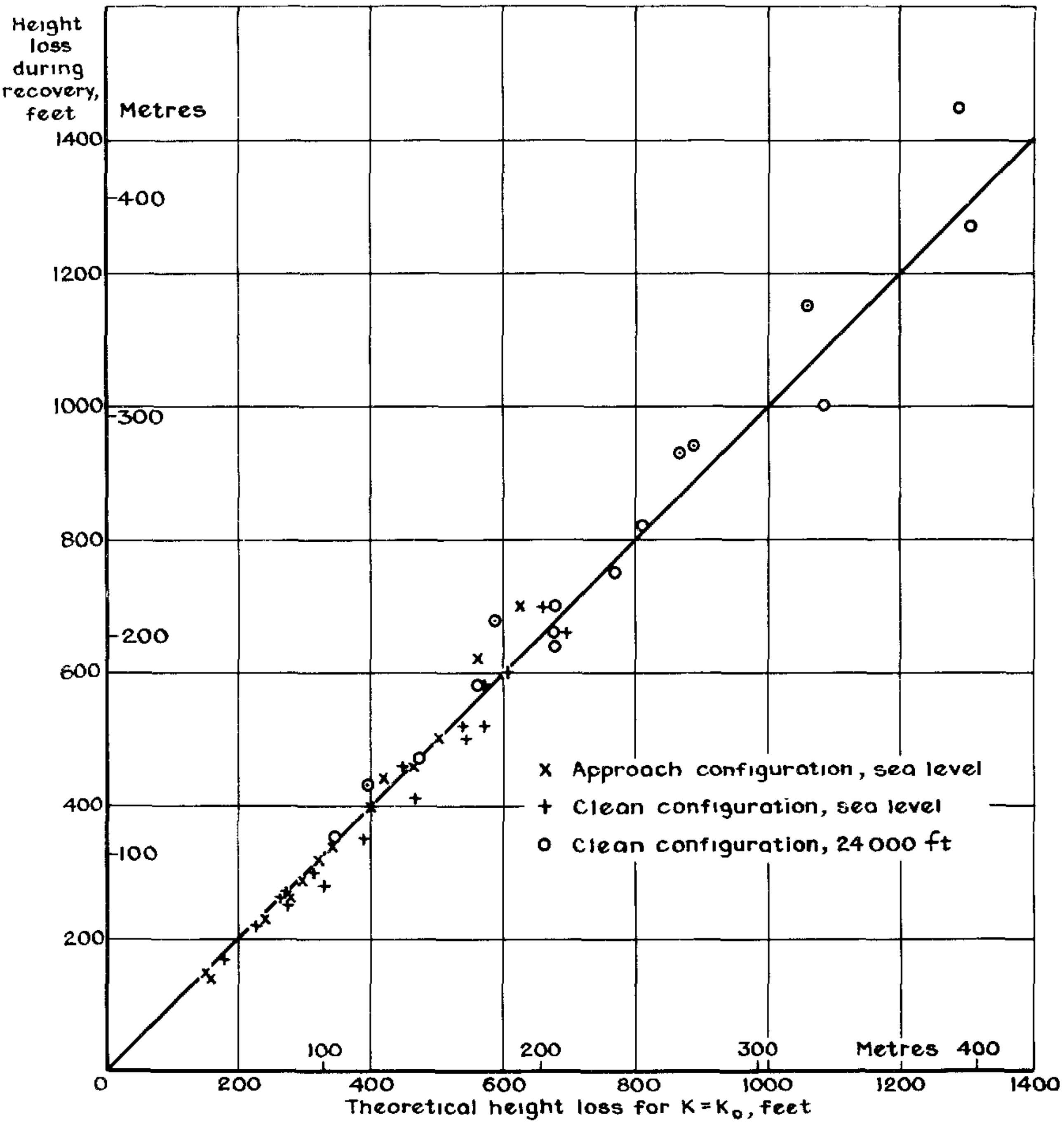

Fig 13 Height loss during recovery v theoretical height loss using K at V_{zrc}, BAC 221 simulation

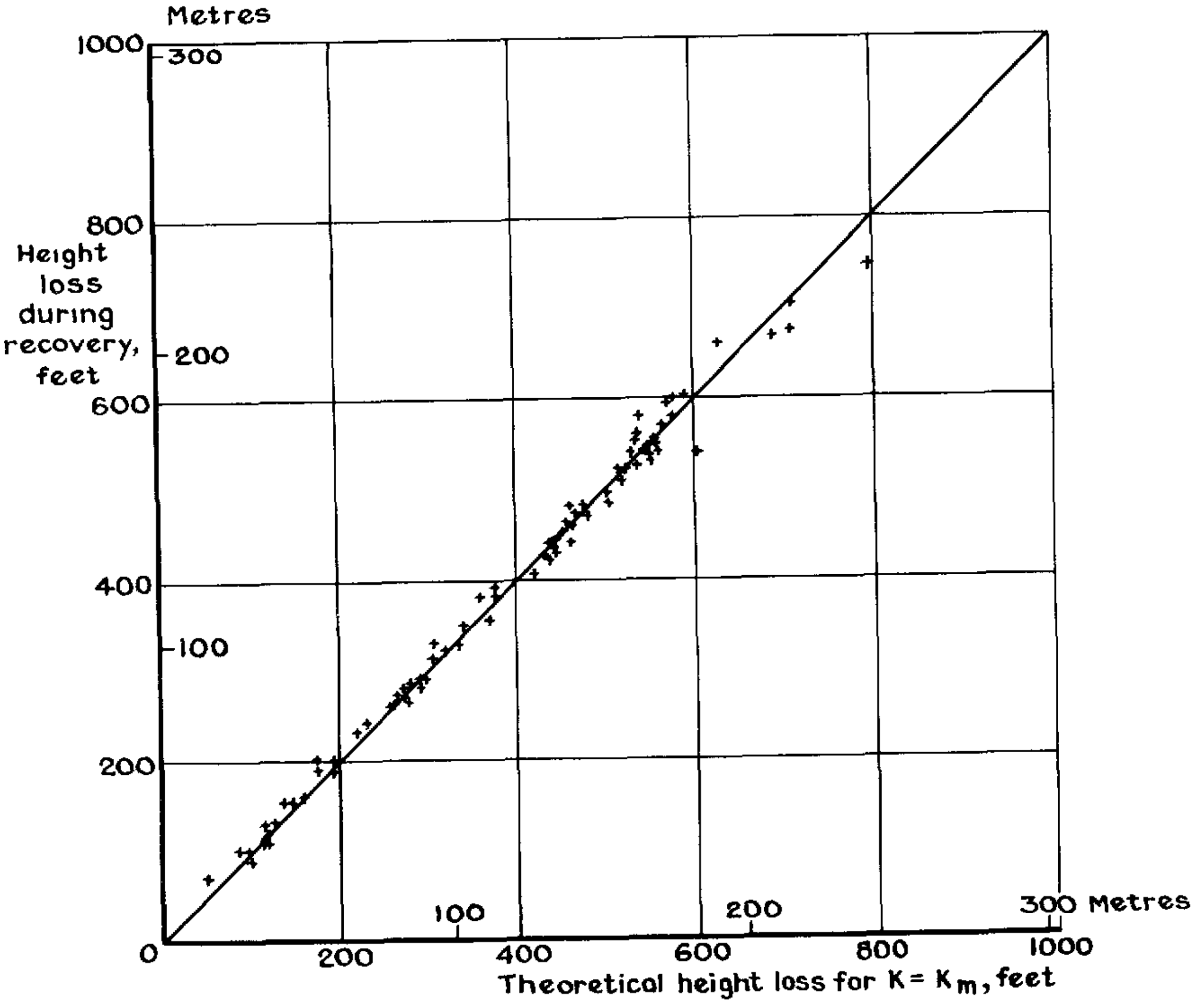

Fig. 14 Height loss during recovery v theoretical height loss using mean K, SST simulation

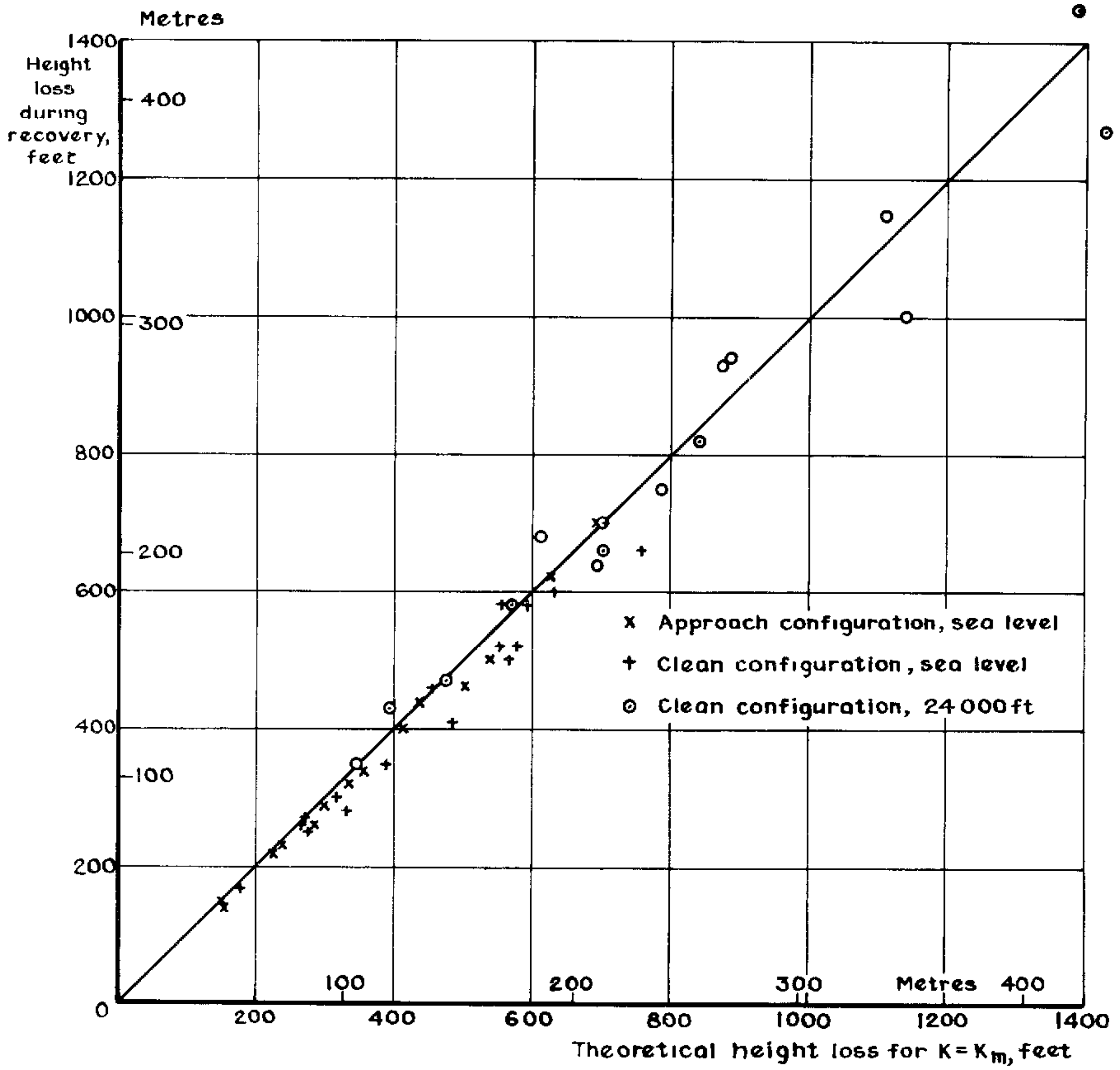

Fig. 15 Height loss during recovery v theoretical height loss using mean K, BAC 221 simulation

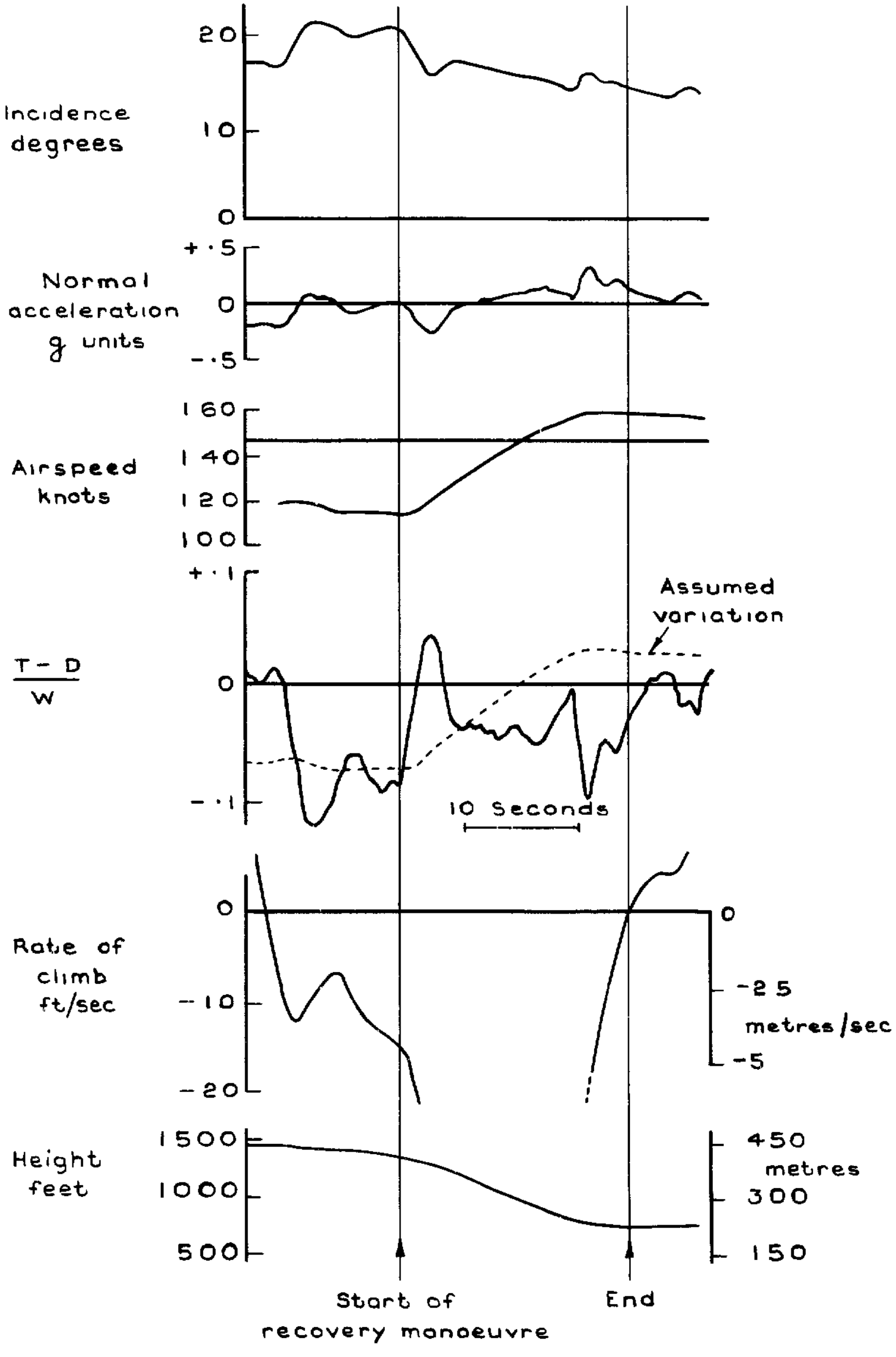

Fig.16 Recovery manoeuvre, showing $\frac{T-D}{W}$ variation

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