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# A Piloted Flight Simulation of the Westland Lynx

*by*

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# A PILOTED FLIGHT SIMULATION OF THE WESTLAND LYNX

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## SUMMARY

The Aerodynamics Flight Division simulator at RAE, Bedford has been used for a simulation of the Westland Lynx helicopter. The simulation, conducted by RAE in conjunction with Westland Helicopters Ltd., took place about five months before the first flight of the Lynx. Handling features of the helicopter were investigated, including the benefits obtained by stabilisation using duplex lanes, and the problems associated with runaways of the autostabilisation equipment. Potential problem areas were identified and, where possible, solutions investigated.

A brief qualitative comparison of the simulator results with results of flight tests on the actual Lynx has been made, and areas of effective simulation have been identified. The need for improved simulator motion and visual cues for certain phases of simulated helicopter flight is noted.

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* Replaces RAE Technical Report 74099 - ARC 36079.

## CONTENTS

# 1 INTRODUCTION

This Report describes a simulation of the Westland WG13 Lynx helicopter, using the piloted flight simulator of the Aerodynamics Flight Division, Royal Aircraft Establishment, Bedford. The simulation took place about five months before the first flight of the Lynx, which was on 21 March 1971, and studied the predicted flight handling features of the helicopter.

The Lynx is a twin-engine, high performance medium helicopter possessing a semi-rigid (hingeless) main rotor. The semi-rigid rotor has two significant advantages over the more conventional articulated rotor: firstly, the complexity of the main rotor head and control assemblies is reduced, giving a cleaner design requiring reduced maintenance and having improved reliability, and, secondly, the rotor can generate higher control and damping moments than the articulated rotor but at the same time, inherently imparting a greater degree of instability to the vehicle, particularly at high forward speed with extreme aft CG location.

To counter the instability, and to provide automatic control in certain modes of flight, the Lynx is fitted with an automatic flight control system (AFCS). Stabilisation is provided by the automatic stabilisation equipment (ASE) portion of the AFCS acting on the pitch, roll and yaw control channels. In addition, the computer acceleration control (CAC) applies control inputs to the collective pitch channel derived from normal accelerometer signals.

The aim of the moving base simulation was to assess the handling of the helicopter in both stabilised and unstabilised flight to examine whether any fundamental changes to the helicopter or AFCS were necessary, and to investigate the control of the helicopter in the event of system failures within the AFCS.

As a preliminary to this simulation, the Aerodynamics Flight Division simulator was used for the representation of a Westland Wessex helicopter. The simulation techniques required for effective representation to the pilot of helicopter handling behaviour were studied and from this study the areas of validity and the limitations of the simulation were assessed in order to apply limits of confidence to the results of the Lynx simulation. The Wessex simulation has been described in Ref.1; its relevance to the validity of the Lynx simulation is discussed later in the present Report.

The Lynx simulation was prepared and conducted by the Aerodynamics Flight Division of the RAE in close association with staff of the Aerodynamics Department of Westland Helicopters Ltd., (WHL), who contributed to the setting up of the simulation (based on the mathematical model used on the WHL fixed base simulation), and to the monitoring of the piloted tests. The primary objective of the arrangement was to aid design and development progress of the Lynx, and gave WHL the opportunity to make an appraisal of the behaviour of the helicopter and its control system before first flight, based on the experience of their test pilots in handling the moving base simulation. Test pilots from RAE and A & AEE, Boscombe Down also conducted an appraisal of the simulated helicopter.

It is not the author's intention to give in this Report a rigorous account of the simulation experiment; indeed, to do so would be of limited value. Such a Report would be pertinent only to the helicopter at the design and development stage simulated; two years' of development flying have taken the Lynx well beyond this stage, with a number of modifications and improvements incorporated (some associated with problems encountered during the simulator tests). Rather, the aim is to describe the way in which the simulator was used to evaluate handling features of the helicopter, to identify possible problem areas and to investigate, where appropriate, solutions to these problems. Attention will be given to the influence of simulation limitations on the results. Brief mention will be made of subsequent flight tests of the Lynx and the presence or absence of the problem areas encountered in the simulation.

## 2 DESCRIPTION OF HELICOPTER AND SIMULATION

### 2.1 Westland WG13 Lynx - General description

The Lynx is a high-performance helicopter, with a single main rotor, to be produced in Utility and Naval versions. Development testing was initiated with several basic variants, and such a variant (closely similar to the Utility version) was represented in the simulation described in this Report; further description relates to this version. Leading particulars are given in Table 1, and the variant is shown in the photograph and general arrangement drawing of Figs.1 and 2. Power is provided by two Rolls-Royce BS360-07-26 free turbine engines, driving a four-bladed semi-rigid main rotor and four-bladed tail rotor.

The semi-rigid rotor design eliminates many of the bearing components of the conventional articulated rotor, giving reduced complexity and hence a reduction in maintenance requirements. In this application the semi-rigid rotor also gives a substantial increase in the moments transmitted to the rotor hub by tilt of the rotor, thus providing more powerful control and more rapid response than the conventional articulated rotor helicopter, particularly in conditions of reduced rotor thrust.

In comparison with the articulated rotor, the increased rotor moments of the semi-rigid rotor also increase the degree of attitude instability, particularly at high forward speed and with aft CG. (Flight experience subsequent to the simulation appears to show that this destabilising effect is less than expected from previous theoretical studies.)

Automatic Flight Control Systems (AFCS) designed by Elliott Flight Automation Ltd. are fitted to all variants of the Lynx, both to improve stability and control under manual flight conditions, and to provide certain autopilot modes such as heading and height holds, automatic transition to the hover, or sonar hover. This simulation considered only the portions of the AFCS relevant to direct pilot control; tests on the autopilot modes were performed on the fixed-base simulator of Westland Helicopters Ltd.

The control laws simulated here had been established as suitable for the start of a flight development programme from WHL/Elliott work involving systems analysis techniques and confirmation using the comprehensive analogue model on the WHL fixed base simulator. This early work had also led to the inception of the CAC as a means of easing the compromise in basic pitch stability over the flight envelope, by reducing the differences in stability characteristics inherent in the wide ranges of forward speed and longitudinal CG which had to be covered.

A detailed description of the representation of the Lynx on the Aerodynamics Flight Division simulator follows in section 2.3.

## 2.2 The Aerodynamics Flight Division simulator

The elements of the simulator are described briefly below, and shown in block diagram form in Fig.3. A fuller account is to be found in Ref.2; however, a number of changes have been made to the equipment since the publication of that Report. In particular the capability of the cockpit motion system has been increased and is described in Ref.3.

### 2.2.1 The computer

The aerodynamic and kinematic representation of the Lynx was programmed on a 215-amplifier analogue computer. This mathematical model (which is further described in section 2.3) responded to control inputs made by the pilot and to disturbances (winds, turbulence, AFCS malfunctions) introduced by the simulator operator. Computer outputs fed the sources of motion, visual and auditory cues for the pilot, to enable him to fly the simulator and complete the simulation loop. Sixteen computed variables were recorded using two 8-channel pen recorders, and records were also made of the pilot's and operator's commentary.

### 2.2.2 Cockpit interior

The interior of the simulator cockpit is shown in Fig.4a, with a view of a mock-up Lynx cockpit for comparison in Fig.4b. The conventional aircraft control column of the simulator was replaced for this exercise by a cyclic stick from a Wessex; a modified Wessex pedal damper was fitted to the pedals and a collective lever, with adjustable friction clamp, was mounted to the left of the pilot's seat. The geometrical relationship of the pilot to the controls and instruments was by no means correct (due to the smallness of the cockpit and limitations imposed by fixed cockpit structure); however, the force levels and control travels in all axes other than fore-aft cyclic were substantially correct. In this one axis, the available travel was insufficient to reproduce the proposed range of movement for the real Lynx (200 mm at centre of grip instead of 270 mm). The correct control surface-to-stick gearing was represented with a resulting loss of 70 mm of back stick travel, which, for the tests being performed, did not impose any significant limitation on the manoeuvres attempted by the pilots.

Cyclic trim was controlled by a thumb-operated button acting both in pitch and roll planes. Feel forces could be removed either by pressure on a spring-loaded button on the cyclic stick or by operation of a two-position switch on the instrument panel (marked as 'trim release switch' in Fig.4a).

The flight instruments used and their layout were in general similar to those proposed for the Lynx, instruments in the simulator being confined to those relevant to the study of handling behaviour and autostabilisation control.

### 2.2.3 Visual displays

The primary visual display of an outside world was provided by a closed circuit television display, in which a camera tracked over a scale model of an airfield and surrounding countryside in response to position and attitude signals from the computer. The picture thus produced was presented to the pilot on a monochrome monitor mounted above the instrument panel. The angular field of view provided by the display was $45^{\circ}$ in azimuth and $35^{\circ}$ in pitch. Two models were used, one having a scale of 1:2000 covered an area of approximately 12 nm × 4 nm with a maximum altitude of 1500 ft and the other of 1:700 scale with 4 nm × 1.5 nm × 600 ft. The 1:2000 model was used for the greater part of this simulation.

A typical view of the picture presented to the pilot is given in Fig.5.

The cockpit is situated within a dome-shaped room, the walls of which act as a projection screen. A shadow horizon projected on to the walls from above the cockpit was visible through the semi-opaque side windows of the cockpit. It gave peripheral attitude information in pitch and roll to enhance the TV picture. This display is shown in Fig.6 in use in a previous simulation, when it provided the only outside visual display; hence the completely transparent canopy.

### 2.2.4 Motion system

Cockpit motion was available in pitch, roll, heave and yaw as shown in Figs.7a and 7b which gives a view of the cockpit and motion system and details of the ranges of movement available. The motion system was originally designed with two degrees of freedom (roll and combined pitch-with-heave by use of the present heave axis), but, just prior to the Wessex simulation mentioned earlier, was brought up to the present 4-axis standard as described in Ref.3. However, as described in Ref.1 and discussed in Ref.3, operation of the yaw axis was not satisfactory, with unwanted jerks and structural vibrations being felt at each reversal of direction of motion. These spurious motions masked any useful motion cues that might have been derived from the yaw axis and, apart from a few brief tests, yaw motion was not used in this simulation.

The drive laws for the motion system are discussed in Appendix A. In addition to the representation of aircraft movement through space, the motion provided an arbitrary mixture of 1/rev and 4/rev rotor vibrations to enhance the realism of the simulation. The vibration level increased with increasing speed and rotor loading.

### 2.2.5 Auditory cues

Simulated noise incorporating arbitrary representations of engine noise, transmission and gear whine and blade slap was fed into loudspeakers behind the pilot's seat. The engine note varied with torque loading and the blade slap noise increased with increasing rotor thrust.

## 2.3 Simulator representation of the Lynx

The mathematical model of the Lynx was derived from data supplied by Westland Helicopters Ltd., and followed very closely the form of the model used by that firm for their own Lynx simulation as described in Ref.5. The only significant differences between the two representations were that, in this simulation, rotor speed was taken as constant whereas the Westland version could use either constant or varying rotor speed, and differences in the methods of generating body aerodynamics reduced the accuracy of the RAE simulation in extreme flight conditions, though not for normal manoeuvring. The correspondence between the models was so close that only broad description is given here; detailed information can be derived from Ref.5.

Data used was appropriate for the Lynx in its early flying, and the AFCS control laws simulated were those used for initial AFCS development in the flight trials; a number of modifications have since been incorporated.

Fig.8 gives a block diagram of the components of the computation; their content is outlined below.

### 2.3.1 Aerodynamics and kinematics

Aerodynamic forces acting on the main rotor were derived from blade element theory with a compressibility correction on the lift-curve slope. Stall and drag divergence effects were not included. The hingeless rotor was represented by an equivalent articulated rotor with a relatively large offset flapping hinge and a spring restraint about that hinge. Coning of the rotor was taken as quasi-static, and a first-order representation of blade flapping motion was used.

Tail rotor thrust was also derived from blade element theory, though the only blade motion directly computed was the coning angle.

Body forces and moments were derived from wind tunnel test results (in which rotor downwash was not represented) with modifications for the effects of rotor wake angle and velocity.

The kinematic equations were computed in fuselage datum axes, with some approximations in the smaller terms to simplify the computation. Wind effects were added to the computed kinematic velocity components as shown in Fig.8, to provide the aerodynamic velocity components used in generation of the aerodynamic forces and moments.

Artificial turbulence of rms 6 ft/s was fed into the computation when required; the power spectrum of this turbulence is given in Ref.2 and the nature of the turbulence is discussed in section 5.2.

### 2.3.2 Controls and ASE

Movement of the pilot's cyclic, collective and pedal controls provided inputs to the aerodynamic equations, along with contributions from the simulated automatic stability equipment (ASE) and computer acceleration control (CAC). Lateral and fore-aft cyclic stick movements were transformed into appropriate blade angle movements, and the mechanical interlinks from the collective pitch lever which provide additional fore-aft cyclic and tail rotor pitch inputs were represented electronically.

The AFCS control laws and modes of operation are described in Appendix B. The power control actuators, fitted to all four control channels, were simulated simply by a first order lag with time constant of 0.127 second (it has since been established that the time constant for the yaw servo in the aircraft is significantly less than this value).

## 3 VALIDATION - THE WESSEX SIMULATION

Prior to the simulation of the Lynx, the Aerodynamics Flight Division simulator was used for a validation simulation of the Westland Wessex[1]. The aim of this validation exercise was to assess the suitability of the simulator for helicopter handling work; in particular the representation of the helicopter as a mathematical model and the presentation of the relevant operating environment to the pilot were examined.

A number of deficiencies of the mathematical model were found, most of them due to assumption or to errors in the interpretation of data, and were not of relevance to the Lynx experiment. However, one significant error was carried across to this experiment and was not, in fact, discovered until some time after the end of the tests. In the Wessex exercise the representation was simplified by assuming constant main rotor speed considering that aerodynamic torque changes on the main rotor were immediately balanced by increased engine torque without loss of rotor rev/min. The real mechanism is that torque changes result in a change of rotor speed which is detected by the engine governor, giving an engine torque change to restore the rotor rev/min. The assumption in the simulator of constant rotor rev/min is not in itself significant as the percentage change in rev/min is usually slight; however, the assumption of instantaneous change in engine torque is of importance as this transforms the torque change on the rotor into a yawing moment acting on the airframe. In the simulator a change in main rotor torque due, for example, to a collective pitch input, will be transmitted instantly as a yawing moment acting on the fuselage, causing excitation of lateral modes of motion from the longitudinal input. In flight, the yawing moment will be delayed by the dynamics of the rotor, governor and engine and the coupling between modes will be reduced.

Fig.9 shows the response to collective steps in flight and simulator for the Wessex (from Ref.1) - note the immediate build-up in yaw rate in the simulator and the contrasting delay in flight.

A better representation in the simulator would have been to provide a first order lag (to represent the time delay from engine, governor and rotor inertia) between the main rotor torque equation and the fuselage yawing moment equation while still retaining the aerodynamic simplification of constant rotor speed. However, as mentioned earlier, this deficiency of the representation was not discovered until after the Lynx simulation and is relevant to certain problems found in that simulation; these will be discussed later.

In presentation of the handling qualities of the Wessex, behaviour in pitch and roll was thought by the pilots to be representative of the real helicopter, but less realistic was the simulation of yaw and height control. Some difficulty was found in attempting precise control of height near the hover, and throughout the speed range the simulated Wessex appeared to be lacking in directional stability or yaw damping compared with the real vehicle. The former of these problems was attributed to deficiencies of the visual display and inadequate heave motion cues, and the latter again appeared to be associated with lack of motion cues as comparison of flight and simulator traces showed the converse of the pilots' subjective impressions to be true. Unfortunately, as discussed earlier, it was impossible to achieve satisfactory operation of the cockpit yaw motion for the Lynx simulation. In the light of the Wessex tests a good degree of confidence could be attached to results of the Lynx simulation in respect of pitch and roll handling, though care would be needed in the assessment and interpretation of results relating to vertical control at the hover and yaw behaviour.

## 4 CONDUCT OF THE TESTS

Eleven pilots took part in the simulation, giving a total of 70 hours flying in 66 trial sessions. The bulk of this work was performed by the test pilots of Westland Helicopters Ltd. (4 pilots, 48 hours, 41 trials), service test pilots from RAE, Bedford and Farnborough and A & AEE, Boscombe Down providing the remaining contribution.

Preliminary functional evaluation of the simulation was performed by the RAE pilots, then over a 4-week period each of the four WHL pilots spent part of the week at the RAE for the simulator tests. By far the greater part of the tests were conducted at an aft CG condition, the worst from the point of view of pitch stability, and only limited tests were made at the more favourable CG positions. This must be borne in mind when considering the pilot's qualitative assessments of the simulation. Flight up to a maximum speed of 180 kn was studied; the normal maximum cruise speed of the Lynx is 160 kn.

At first, general handling in both stabilised and unstabilised conditions was evaluated, including the effect of AFCS failures. The simulator operator was able to feed in failures of any combination of lanes and channels, the failure in each lane giving either a zero demand signal, or full demand in either direction.

From this general assessment, areas of particular interest were established, and further attention given to these areas. Testing did not follow a rigid programme; no detailed investigation of satisfactory areas was pursued, and in some problem areas the tests were very much ad hoc, and were continued only until some changes had been investigated, or the reasons for the problem had been better defined. For this reason, description of the test results will in places be general, and in some cases very qualitative, the purpose of the simulation being to examine handling problems and not just to establish the overall handling characteristics of the helicopter.

## 5 TESTS MADE - EVALUATION AND RESULTS

As mentioned earlier, the simulation did not follow a rigid programme, but, after a general evaluation, used ad hoc tests to investigate possible problem areas. This makes presentation of the tests in any logical structure somewhat difficult; description will be directed firstly towards possible limitations of the simulation, then to handling without ASE or CAC, stabilised flight, and AFCS failures. There will inevitably be overlaps among these areas in the somewhat lengthy description that follows, and some points of discussion will necessarily appear out of order, because of their bearing on the tests being described.

Pilots' comments and opinions have been extracted from tape recordings made during the tests and from reports written by several of the pilots subsequently to the tests. Two of these reports are given in Appendix C.

### 5.1 Some simulation aspects of the tests

Inevitably, as the simulator provides only a partial synthesis of the real-life environment, some consideration must firstly be given to any limitations imposed by the simulation on the validity of the results. Some guidance can be drawn from the results of the Wessex experiment; that simulation showed problems in yaw control and in height judgment near the hover, due to limitations and deficiencies of the motion and visual systems, while representation of pitch and roll behaviour was judged to be satisfactory.

The Lynx simulation gave similar problems in yaw and height control during initial piloted tests, the problems of yaw control were severe enough to detract from evaluation of the remaining aspects of the helicopter's stability and control characteristics, even with the ASE engaged. There were possible aerodynamic reasons for this control difficulty as well as simulator ones; the fuselage has a large side area ahead of the CG which provides a destabilising weathercocking moment for which the fin does not entirely compensate, though of course, the tail rotor provides a further large contribution to directional stiffness. Because of the yaw problems experienced in the Wessex simulation and pending confirmation of the Lynx airframe contributions the simulation was modified for much of the testing by removal of the body contribution to yawing moment to permit evaluation of the rest of the helicopter's behaviour. Later in the programme the problems of yaw control were further investigated and will be described later.

Accurate control of height near the hover was not possible, apparently due to the inadequacy of visual and motion cues generated by the TV display and motion system. Some improvement was obtained for limited tests by increasing the gain of the motion drive equations (see Appendix A, section A.4) but these revised motion laws were unsuitable for the remainder of the flight envelope; for convenience, for the bulk of the tests, laws of a form usable in all flight regimes were programmed, and care was used in the interpretation of results from tests where precise height control was required at low speed.

Although the size, overall shape and layout of the simulator cockpit were not representative of the Lynx, pilots were able to accept this deficiency for the purpose of evaluating handling characteristics. The closeness of the TV display and instrument panel was a source of adverse comment, and the obvious deficiencies of the display (poor definition, small field of view, intrusive line structure of the picture) were criticised. Where these deficiencies were thought to have affected the evaluation, this has been noted in the following text.

The motion was regarded by the pilots as being a valuable feature of the simulation, with the exception of the yaw axis, which had mechanical deficiencies giving jerky operation of sufficient severity to destroy the value of useful cues in this axis. Yaw motion was used for very few of the tests described here. In other axes the motion improved the realism of the simulation and provided cues of AFCS failures to which reaction was instinctive.

In section 3, description has been given of a deficiency in both the Wessex and Lynx simulations whereby changes in main rotor torque were assumed to be transmitted directly to the fuselage, rather than through the time delay of rotor speed decay and compensating engine response. In this simulation, in approximately level flight conditions this deficiency is of little significance. Fig.10a shows the position of the theoretical stability roots of the stabilised aircraft. The full equations of motion of the stabilised Lynx as simulated are of 22nd order (obtained by considering the simulator equations in perturbation form); only roots likely to be of relevance to aircraft handling are shown in the diagram, and for convenience the negative half of the imaginary axis has been omitted. Roots are shown for the stabilised aircraft in level flight at 120 kn at the aft CG condition, both for no time delay in the equation between body yawing moment and main rotor torque (i.e. as simulated) and for a first-order time delay of 1 second. The relationships between the values of the roots and the period and damping of the modes corresponding to those roots are shown in the subsidiary diagram. This figure of 1 second was chosen arbitrarily to illustrate the effects of the time-delay on the stability roots. The full mechanism of the delay - rotor speed decay, governor action, engine response, rotor speed restoration - is far more complex than a first-order system, and highly amplitude-dependent. A representation of such a system would be beyond the scope of this Report (and could provide a complete simulation in itself); the calculations given here should give a guide to the effects of delay rather than provide absolute values.

There is negligible movement of the roots with change of time delay (apart from the root directly associated with the time delay, which moves towards an infinite negative value with reduction in the time delay). Although the stability roots are virtually unaltered, the response characteristics will be changed as described for the Wessex in section 3 and shown in Fig.9 - inputs which produce a change in main rotor torque will produce more rapidly the associated yawing moments and hence yaw response of the fuselage.

In banked flight, however, and particularly in turns to the left, the picture is significantly altered. Fig.10b shows the effect of variation of the time delay on the roots for a $45^{\circ}$ banked turn to the left, at 100 kn with ASE and CAC engaged. Of special significance is the fact that a root which is virtually neutrally stable with a time delay of 1 second becomes unstable with no delay (i.e. in the condition simulated). Note also that if an infinite time delay is assumed (i.e. changes in main rotor torque are completely uncoupled from the fuselage yawing equation) the root is stable. At $60^{\circ}$ bank (Fig.10c) the effect is even more pronounced; with infinite time-delay there are no unstable roots, at 1 second delay there is a root with a time to double amplitude ($T_2$) of 2 seconds, while in the condition simulated the root is even more strongly unstable with a $T_2$ of only 0.87 second.

The reasons for this marked change in the pattern of the roots can be understood by reference to the pitch law of the ASE (see Appendix B). This derives its stabilising action from terms which have a pitch attitude signal as their source. The dominant characteristic of the unstabilised helicopter is an unstable pitching mode which increases in severity with aft movement of the CG and increase in forward speed; the pitch channel of the ASE acts directly against this mode by means of the pitch attitude-derived signals. In a banked turn, however, the pitching plane of the aircraft is inclined to the earth axis system, and the pitch attitude change resulting from pitching about the helicopter's Y-body axis is correspondingly reduced by the cosine of the bank angle (pitch attitude $\theta$ is related to body rate of rotation in pitch (q) and yaw (r) and bank angle $\phi$ by the equation $\dot{\theta} = q \cos \phi - r \sin \phi$ .) Furthermore, the torque change produced by pitching will, through the engine and governor response, produce yawing of the fuselage; in a left-hand turn this yawing will be of such a sign (left yaw from upward pitching) that the pitch attitude change will be further reduced. There will come a combination of speed and bank angle at which the pitching and yawing will produce no change of pitch attitude and the pitch channel of the ASE will no longer be opposing the dominant pitch instability of the unstabilised helicopter.

In the simulator, this effect was found when, at certain conditions of forward speed (normally above 100 kn and at aft CG) and banked turn to the left, a rapid pitching and yawing divergence occurred, from which the pilot was rarely able to recover. At the time of the tests, a full explanation was not reached; the lack of pitch attitude change was appreciated but the significance of the torque representation was not appreciated. By assuming that main rotor torque changes are instantaneously transmitted to the fuselage the severity of the effect has been magnified; if one assumes a time delay of even one second the divergence is much less severe. This is still only an approximation to the real-life situation where, as noted earlier, the mechanism of engine and rotor speed changes is not a simple first-order process but a complex and amplitude-dependent system for which the calculations given earlier provide only an illustration of effects rather than a determination of actual values.

A further complication in the simulator arose from the fact, described in Appendix A, section A.1, that the pitch drive law of the motion system was also based on a pitch attitude signal instead of on body pitch rate terms. Thus in a direct analogy with the pitch channel of the ASE, the pilot was deprived of the pitching cues which would have alerted him to the divergence and enabled him to apply instinctive corrective control movements, and his attempt to control the divergence was therefore much less effective.

In summary, in left-hand turns at speed, and particularly at aft CG, the effectiveness of the pitch channel of the ASE is degraded by virtue of its reliance on a pitch attitude signal, which is not in the pitching plane of the helicopter, and is further weakened by the yaw coupling resulting from torque changes due to the pitching. In the simulator the severity of this effect was significantly exaggerated for two reasons; firstly the yaw coupling was over-severe, and secondly the pilot was deprived of the cues which would have aided his control of the problem.

## 5.2 Handling with ASE and CAC disengaged

It should be noted here that the CAC channel of the AFCS is considered as a basic aircraft function rather than a channel of the ASE. 'Unstabilised flight' would therefore normally indicate a flight condition with ASE disengaged, but CAC still active. However, the simulator tests also evaluated the simulated helicopter in its fully unstabilised state, and the following sub-section applies to the simulation in that condition.

An early criticism of the simulated helicopter, applying to both stabilised and unstabilised flight, was that the fore-aft trim rate of the cyclic stick was far too slow. The rate chosen for the Lynx at that time was one giving full travel through the trim range in 35 seconds, in both axes. This had been reproduced, approximately, in the simulator, but due to the criticisms received, the system was changed after a very few trials to give a travel time of 11 seconds (equivalent to 15 seconds for the real Lynx because of the missing fore-aft movement in the simulator: section 2.2.2). At a later stage the lateral trim time was also revised to a value of 17 seconds. At the time of writing this Report, travel times of 17 seconds in each axis have been adopted on the real helicopter.

Turning now to the more specific problems of handling in an unstabilised condition, the most significant characteristic of the unstabilised simulator was a pitch instability which increased in severity with increase in forward speed and aft movement of the CG. Fig.11a shows the theoretical effect of forward speed on the stability roots at aft CG (only roots likely to be relevant to pilot's control of the helicopter are shown - the stability equations are actually of 11th order) and Fig.11b demonstrates the theoretical effect of CG movement on the roots at 180 kn. The conditions described as *forward* and *aft* CG are the design limits for the CG range, and *mid* is midway between these two positions. At aft CG at 180 kn, there is an unstable root corresponding to a mode with a time to double amplitude ($T_2$) of close to ½ second. The severity of this mode is reduced by forward CG movement to give a $T_2$ of 5.2 seconds at forward CG, or by speed reduction, with a $T_2$ of 4 seconds at 70 kn at aft CG.

The pilot's assessment of pitch control was that at aft CG in calm conditions, control was not too difficult up to 80 kn, but becoming progressively harder at higher speed, and being described as 'precarious' at 180 kn. A further complicating factor was that collective pitch changes produced a significant pitching moment which required a compensating cyclic movement to prevent attitude change, and it was in controlling the pitching changes resulting from collective inputs that greatest difficulty was experienced. It was felt that unstabilised flight at aft CG was an unacceptable condition for normal operation (though, of course, as the ASE and CAC systems are both duplex, unstabilised flight is not envisaged for normal operation).

In brief tests at mid CG, a significant improvement in control was experienced; not only was the severity of the instability reduced (Fig.11b), but the pitch coupling from collective inputs was also lessened, both effects giving reductions in the pilot's work-load.

In turbulence (rms 6 ft/s), although there was some increase in workload, it was only a small addition to an already high workload. The turbulence used in the simulator has been criticised for its uniformity, there being very few large gusts, and even over quite short periods of time the average velocity is zero giving little cumulative disturbance. An improved turbulence representation is at present being developed[6] for the simulator to overcome the deficiencies of the present system; had there been a more intermittent component in the turbulence used in this simulation, there might have been more effect on the pilot's workload as each disturbance would require corrective action.

These points are illustrated in Figs.12a-c; Fig.12a shows simulator records of flight without ASE or CAC at aft CG at around 160 kn in calm conditions. Constant longitudinal cyclic activity is apparent, which contrasts with stabilised flight where no pilot action is required to maintain trim conditions over quite long periods of time. Also noticeable is the large trim change required to compensate for the collective pitch reduction. Lateral cyclic activity is less, though some coupling between longitudinal and lateral motions was apparent to the pilots. In turbulence (Fig.12b), there is an increase in longitudinal cyclic activity, but attitude excursions are little different.

Fig.12c shows the effect of CG position on pitch control. All three sets of traces are from the same trial and are of flight at around 150 kn in calm conditions with CAC and pitch ASE disengaged. For the aft and mid traces the roll and yaw channels were engaged, but were disengaged for the forward CG case. There is an obvious improvement in the mid case compared with CG aft; stick activity is reduced considerably, and pitch excursions are smaller and less rapid. Further improvement at forward CG is less apparent, though there are periods of quite a few seconds over which no pilot action is necessary to keep pitch attitude within reasonable limits.

Mention has already been made of the pitching moments generated by collective inputs; this occurred in spite of an interlink between the collective lever and the cyclic pitch control system, although this was incorporated primarily to deal with steady state trim changes in climb and descent at constant speed, and not to cope completely with transient collective changes. Yaw rates resulting from collective inputs were also noticed (again there is an interlink, present for steady state trim reasons rather than for transient response) but were associated with the incorrect engine speed representation discussed earlier. A pitch-to-roll coupling was also present; the unstable pitching mode involved a fair amount of roll, the ratio of roll rate to pitch rate contributions being close to 1:1 at 180 kn. However, pilots appear to be more tolerant of a roll rate than of the same amount of pitch rate, and the bank angle variations due to this mode attracted negligible criticism in comparison with the pitch attitude behaviour.

In fact, roll control of the simulator without ASE was quite crisp and pleasant, with negligible deficiencies throughout the speed range; analogy was drawn with the well-liked roll characteristics of the Westland Scout helicopter. Only a small amount of pitching was generated by roll inputs, but control of this pitching tended to reflect back into roll and prevent precise attitude holding; if the pitch stabiliser was engaged on the simulator, this intrusion into roll control was removed. Turns at 80 and 180 kn are shown in Figs.13a and b; at 80 kn control of bank angle appears smoother than at 180 kn, where there is also more longitudinal activity (note that 180 kn is higher than the design maximum cruise speed of 160 kn).

Although roll control was satisfactory, the associated yawing behaviour possessed a number of deficiencies. Even with the destabilising fin/body term removed, as discussed earlier, the yaw response was significantly underdamped. The yaw rate trace at 180 kn shows an almost continual oscillation, which is in part associated with the incorrect coupling from pitching moments due to the engine representation used, but, irrespective of this coupling, damping is inherently low as shown by the large and poorly damped oscillation resulting from rudder inputs at 80 kn. Control of yaw in an unstabilised condition was very difficult, partly due to the poor yaw damping, and partly due to the lack of motion cues in yaw, which prevented the pilot from responding early to disturbances, and from assessing the sufficiency of the corrective actions that he applied. In turbulence, the yawing mode was continually excited in an oscillation over which the pilot could not exercise any effective control. Because of the poor yaw behaviour, movement of the slip ball during turn entry and exit was erratic, and suppression of slip was difficult (and again hindered by the lack of motion cues). Re-introduction of the fin/body term caused further deterioration of the yaw stability and control behaviour.

At the hover, pilots found that precise control of height was very difficult. The collective lever was a powerful controller of vertical motion, and in the absence of clear visual and real-life motion cues it was not possible to apply collective control sufficiently finely to adjust small rates of climb or correct small height errors. There was frequently a tendency to set up a fairly slow vertical oscillation by overcorrecting with each collective input (Fig.14a). A minimum of collective lever friction was required to avoid further aggravation of the problem.

Yaw control near the hover was also very difficult; Fig.14a shows quite high rates of yaw being generated. Unfortunately the pedal position trace was not available for this flight, but Fig.14b shows similar yaw activity near the hover for another trial, with the corresponding pedal movement. The reasons for this behaviour are in part very similar to the height control problems; inadequate visual and missing motion cues prevent the pilot from exercising fine control over yaw inputs. Associated with this is the further simulator deficiency of incorrect coupling between collective inputs (and hence torque changes) and yawing, so that the height control problem also reflects into yaw. Although these simulator faults were a major influence on the yaw control difficulty, the low yaw stability and damping and high yaw control power were in themselves contributors to the problems.

To give a general summary of the simulated helicopter without ASE or CAC the major problem was one of pitch control, with lesser problems in yaw and in height control near the hover, and with roll control providing virtually no difficulties. The severity of the pitch divergence increased with increasing forward speed and aft CG movement. At aft CG in this fully unstabilised condition, the helicopter as simulated was thought to be unsuitable for normal operation; at very high speed, a considerable workload was required just to maintain straight and level flight, and in an emergency situation speed reduction would be necessary before manoeuvring could be attempted with any degree of safety. With forward CG movement, the problem was much less severe.

Movement of the collective lever produced marked coupling in pitch, of a degree again increasing with speed and aft CG movement. At the hover, control of height was imprecise due to poor motion and visual cues. Yaw control was poor throughout the speed range, in part due to inadequate yaw stiffness and damping, but mainly due to deficiencies of the representation - lack of cockpit motion in yaw, limited visual cues and discrepancies in the simulation of engine torque effects.

### 5.3 Handling with ASE and CAC engaged

Stabilisation was provided by the ASE in three control channels, plus CAC in the collective channel, giving in the simulator a stability equation of 22nd order. Roots are shown in Figs.15a and b (again only roots likely to be of direct concern to the pilot are plotted - there are a number of other roots further to the left of those shown) demonstrating the effects of forward speed and CG position. The dotted lines joining the marked data points are rather tentative, particularly near the origin where combining of the roots along the real axis to produce imaginary roots may not be quite as shown.

The two oscillatory roots towards the top marked 'a' and 'b' in Figs.15a and b are predominantly associated with lateral motion, combining roll, slip and yaw in varying proportions; oscillatory root 'c' is primarily a pitching mode. The leftmost roots on the real axis, which combine at certain conditions to give a well-damped oscillatory mode, are for modes involving pitching and vertical motion. Of special note is the unstable root at 180 kn aft CG, which is primarily associated with slip, and will be discussed later.

General impressions of the simulation of the stabilised Lynx were of a helicopter pleasant to fly in the greater part, with crisp pitch and roll control and no cross-coupling between the axes. Problems were encountered in yaw, and again in height control near the hover; also tight pitch attitude control at speed produced slight oscillatory control problems. Further discussion of the simulator with ASE and CAC will, where possible, consider each axis of control in turn, though inevitably there will be some association between axes.

Considering first the collective control, similar problems to those encountered in unstabilised flight in obtaining fine height adjustments at low speed were again met; this is not really surprising, as the problems appear to be due to the inadequacy of visual and motion cues and not to deficiencies of the simulated aircraft. Any improvement that was achieved was largely due to the extra attention available because of the reduced workload in other axes. Limited tests were performed with increased motion cues, and appeared to help the pilot achieve better control; however, the motion system travel available restricted the use of these revised laws to very modest manoeuvres.

At speed, collective inputs still caused significant pitch changes. Figs.16a and b show quite large collective inputs in the simulator at 120 kn at aft CG; in Fig.16a the pilot has taken corrective action against the pitch change induced by the collective input (upward pitching from up collective) - a substantial retrimming of the cyclic stick is required. In Fig.16b, the pitch change is not opposed, and the nose drops about 16°. Pilots considered that this coupling between collective inputs and pitch was disturbing, particularly when performing a simulated autorotation, when the full lowering of the collective required considerable back stick to prevent dropping of the nose.

However, the coupling is also used with effect as an additional source of pitch stabilisation. Because of the precarious nature of pitch control in unstabilised flight at aft CG, sufficient protection must be provided against failures of the pitch channel of the ASE. With the duplex pitch system proposed, a runaway of one lane would be opposed initially by the second lane, but after even a short time at certain conditions this lane could reach its full authority and the helicopter would then be effectively in an unstabilised state in the pitch channel until pilot intervention brought the working pitch channel back within its authority. Increasing the pitch authority does not solve the problem, as the authority of a runaway is also increased.

In the collective channel, the CAC, detects normal acceleration of the helicopter and applies collective pitch, proportionately, in the sense to oppose the normal acceleration. When the normal acceleration is associated with pitching, the action of the CAC will produce a collective pitch input which, by virtue of the coupling between collective inputs and pitching motion, gives a pitching moment in opposition to the disturbing motion. As the coupling is more severe at higher speed, and the g associated with pitch changes also increases with speed, there is an automatic increase in effectiveness of the CAC to match the increase in severity of the unstable pitching mode through the speed range. The CAC should therefore also provide some alleviation of the effects of turbulence on the helicopter at high speed.

The stability improvement introduced by the CAC is not in itself (in the absence of the pitch channel of the ASE) adequate to give satisfactory handling qualities, throughout the whole speed and CG range, but the range of acceptable flight conditions is extended and the inherent pitch instability is reduced; for example, at 120 kn at aft CG the $T_2$ of the pitch mode is increased from 2 seconds for the unstabilised helicopter to nearly 7 seconds by the addition of the CAC. With the pitch channel engaged, the CAC still provides some improvement in stability at high speed and also gives added protection in the pitch runaway situation.

The pitch channel of the ASE provides both attitude and rate inputs for stabilisation (though 'rate' is in fact derived from an attitude term). Fig.17 shows the response of the simulator to $1^{\circ}$ steps of longitudinal cyclic stick, at the hover and at 160 kn; there is little change of pitch response with forward speed, as the dynamics imposed by the ASE law are more significant than those of the basic helicopter. In general, pilots had little criticism of pitch handling; attitude changes were crisp and precise, with the stick providing almost pure attitude control for small inputs, but more of a rate response for larger inputs. Fig.17 shows that in response to a step input the pitch rate response is almost triangular returning to zero rate in a little over 1 second, with negligible change subsequently.

Two factors interfered with the quality of pitch control; the first was the high level of coupling from collective lever inputs, and has already been discussed. The second was a slight tendency for pilot-induced oscillations (PIOs) to occur when attempting to exercise tight control of attitude. This occurred mainly at high speed, and only with certain of the pilots. In Fig.18, the pilot was attempting to aim the helicopter at a point in his visual field; during the aiming task some large collective inputs were made, to provide a disturbance to the task. A tendency towards PIOs is shown, as underlined on the pitch rate trace, particularly during the collective movements (because of the strong collective/pitch coupling) but also at other times. The oscillation has a period of close to $1\frac{1}{2}$ seconds (i.e. imaginary part of the root is about 4 $\text{seconds}^{-1}$) and would appear to be associated with the oscillatory mode marked 'c' in Figs.15a and b. This mode is, however, well-damped (less than $\frac{1}{4}$ cycle to half amplitude) whereas the PIOs appear undamped. Some explanation for the tendency may be derived from referring to the step inputs in Fig.17. Pitch rate rapidly builds up in response to the input, and just as rapidly decays to give the new steady attitude; the time from maximum pitch rate to steady attitude is little over $\frac{1}{2}$ second. On attempting to change attitude, the pilot is aware of the rate generated by his input but it is not immediately apparent that this rate is going to decay, and the instinctive reaction is to oppose the pitch rate with a return of stick towards the original position. This also forces a return of pitch attitude, and hence requires another control input to reselect the required attitude; this cycling is likely to continue until the pilot exercises a slightly looser control in pitch, and allows the natural damping of the oscillatory motion to stabilise the attitude, rather than adding his own unwanted (and in fact destabilising) attempts to provide damping of the mode.

As mentioned earlier, the tendency to excite PIOs was slight, very much pilot dependent, and only present when tight attitude control was attempted. It was found that increasing the control sensitivity greatly accentuated the tendency, as did increasing the magnitude of the motion cues.

The ability to predict the extent to which PIOs might be induced in real flight depends quite finely on the accuracy of the representation of control power and pitch stability in the simulator and on the validity of the motion cues provided. Ways were sought to suppress the PIO tendency, in case it was repeated in flight. Changing gains within the pitch law of the ASE was not too successful; quite large gain changes were needed to give effective suppression (e.g. doubling of the damping term), and such changes would be undesirable because of their influence on the whole of the pitch control task. An alternative change was to introduce a first-order lag in either the stick or the attitude (but not the 'rate') terms of the pitch law; either was effective in suppressing the PIO tendency. A lag of about ½ second on the attitude term was sufficient to prevent overcontrolling, with only a very slight degradation of the crispness of pitch response; alternatively, a one-second lag on the stick term took the edge off the sharpness of the pilot's inputs without changing the stability roots of the helicopter. Awareness of the effectiveness of these palliatives was thus available if a PIO problem were to occur in flight.

Yaw control was influenced by two simulator deficiencies, the lack of yaw motion and the error in torque representation giving undue coupling between torque changes and yawing. Besides these unintentional or unavoidable deficiencies, there was a real problem associated with the low directional stability of the helicopter, as shown by the mode in Fig.15a which eventually becomes unstable at high speed. Directional stability was not good throughout the whole speed range; Fig.19a shows turn reversals in the simulator, pedals fixed at 150 kn, where large and erratic fluctuations of sideslip are evident. Because of the simulator deficiencies, control of these fluctuations was very difficult, but the basic problem lay with the lack of stability which led to the sideslip variations. Changes in the yaw channel of the ASE were tried in order to suppress the sideslip excursions; Fig.20 shows the effect of these changes on the unstable root (note the highly expanded scale compared with Fig.15; note also that the speed of 180 kn is above the maximum cruise speed of 160 kn).

The law proposed for the yaw channel of the ASE was of the form (see Appendix B):-

$$\theta t_A = 0.3\left(\frac{2s}{1 + 2s}\right) r$$

where $\theta t_A$ was the demanded tail rotor pitch angle (degrees) and $r$ was the fuselage yaw rate (degree/s). Variation of the washout time-constant had little effect on the instability (see Fig.20 for 4 seconds time-constant instead of 2 seconds) and increasing the gain of the law increased the instability (Fig.20 shows the roots for a gain of 0.6 instead of 0.3). It is not altogether surprising that these variations of yaw damping did not suppress the instability; the unstable oscillation is a long period one involving slip rather than yaw, i.e. a lack of directional stiffness, not damping.

A marked improvement was obtained when the effect of feeding a signal from a laterally-mounted accelerometer, at the CG, to the yaw pedals was tried. The yaw law now became:-

$$\theta t_A = 0.3\left(\frac{2s}{1 + 2s}\right) r + k\,\frac{\Sigma Y}{mg}$$

where $k$ was a gain value and $\Sigma Y/mg$ represents the signal detected by the lateral accelerometer, in $g$ units (see Appendix B). Fig.19b shows turn reversals following on directly from those of Fig.19a, with the addition of the lateral accelerometer term in the yaw channel of the AFCS (gain k = 16 degree/g). Sideslip variations are virtually suppressed. Pilots commented favourably on the improved stiffness in yaw, with little need to attempt co-ordination of turns. A gain of 11 degree/g was found to be adequate, and the roots for this value are shown in Fig.20 - the mode is now stable. Because of the simulator deficiencies, this gain might be found to be unnecessarily high in real flight conditions.

### 5.4 ASE and CAC failures

The operation of the duplex ASE is described briefly below, and applies also to the CAC; a fuller account is given in Appendix B.

Each channel of the ASE consists of two lanes, each engaged (and disengaged) by a push-button (Figs.4 and 21). The control position demanded by each lane is shown on a pair of indicators, the association between lanes and push-buttons being by the lane identification numbers 1 and 2 marked on both buttons and indicators. With both lanes of a particular channel engaged, the resulting control movement is the average of that demanded by the two lanes, each lane being effective over half the total authority.

With only one lane active, full authority and full sensitivity are restored to that lane. Failure is apparent to the pilot by non-synchronisation of the two lane indicators for a particular channel (e.g. pitch indicators in Fig.21) - and of course by any resulting helicopter response. The defective lane must be identified by the pilot and disengaged by the appropriate lane button.

Pilots had some criticisms of the indicator display. One anomaly was that a nose-down runaway in pitch was indicated by a forward movement of the lane needle, as was an upward runaway of a collective lane. However, this runaway, by virtue of the pitching response from collective inputs, gave a pitch response in the opposite sense to that obtained during a similar movement of the pitch needle. This led to some confusion as to which needle was associated with a failure causing pitching motion. A second problem was that if one lane ran away to its full authority, the second lane would tend to run to the opposite authority limit (this was particularly true in pitch); both needles for a channel would be at their limits and the defective lane could not readily be distinguished (though corrective action taken by the pilot through the flight controls should bring the active lane back within its working range).

The failures examined were of runaways to the maximum authority position of one or both lanes of each channel, with, in general, the lanes being approximately at mid-range before failures. Simultaneous failures of more than one channel were also tried. Description of the tests made will again be given for each channel in turn.

As might be expected, runaways in roll presented no significant problems; the simulator without ASE has already been shown to be satisfactory in roll, so loss of some roll stabilisation provided little degradation. Also, the roll rates generated by the failures were not sufficiently high to require rapid pilot intervention. It was quite easy to compensate for the runaway and restore the helicopter to level flight before disengaging the faulty lane. Fig.22 shows a number of roll runaways; in Fig.22a a runaway of a single lane is shown, with no pilot intervention. A steady roll rate of around 3½ degree/s is generated after a transient rate of about three times that value. Fig.22b shows a similar failure (given to the pilot without prior warning) to which the pilot responds in little over half a second; the bank angle excursion is $6^{\circ}$ at the start of intervention, and does not exceed $10^{\circ}$. In Fig.22c an unrealistically severe runaway is shown in which the AFCS channel is trimmed to 50% authority to the left (by means of the trim wheel on the control panel); a single lane runaway to the right then occurs, so that the failed lane moves through $\frac{3}{4}$ of the total available travel whereas the still active lane only has $\frac{1}{4}$ of the travel available in the required direction. A much higher roll rate than that of Fig.22a is developed, but even though the pilot does not intervene to correct the runaway for almost 5 seconds, control is quickly regained; the peak bank angle was around $45^{\circ}$.

A runaway during a $30^{\circ}$ banked turn is shown in Fig.22d; even though the pilot does not intervene for about 3 seconds, the bank angle increases by only $15^{\circ}$ and level flight is rapidly regained.

Surprisingly, in view of the problems associated with yaw control in the simulator, runaway of a yaw lane generated no difficulties; a small yaw rate develops but it is rapidly damped out without pilot intervention. Yaw failures were not studied in detail, but on the few occasions they were used the pilots described the effect as innocuous or even failed to notice the runaway.

CAC runaways were not very disturbing, when the pitch channel was engaged. A single lane runaway gave an increment in normal acceleration and, at speed, a change of pitch attitude, but led to no problems requiring immediate pilot action. Runaways are shown in Figs.23a and 23b; with no pilot intervention an attitude change of $4^{\circ}$ occurs at 160 kn, though at the hover there is no pitch attitude change. In Fig.23c a runaway is controlled with no difficulty and the faulty lane disengaged. The remaining lane is then subjected to a runaway and, now having full authority and being unopposed by a second lane, provides a greater disturbance than that generated by the first failure; there is still no significant handling problem.

As would be expected, runaways of the pitch channel of the ASE are of greater significance. The responses of the simulated helicopter to runaways of a single pitch lane at the hover and at 160 kn are shown in Fig.24. The response resulting from the runaway is very much dependent on the travel available to the still-active lane. In the nose-down runaway shown in Fig.24a the active lane (lowest trace) does not reach the authority limit and the pitch rate generated by the runaway is rapidly cancelled. In Fig.24b, as in Fig.24a, the active lane is trimmed slightly nose-down but this time the runaway is in a nose-up sense. The lane reaches its authority limit, after which damping of the disturbance is obtained only from the aerodynamics of the helicopter, plus the CAC. The pitch attitude generated is far higher in this case. Runaways at 160 kn are shown in Fig.24c and d; the effect of the authority limit is more clearly demonstrated here. In Fig.24c the limit is not reached and the pitch rate is counteracted; in Fig.24d, however, the active lane starts to act against pitch rate, but reaches its limit. The helicopter is now effectively without stabilisation in pitch, and pitch rate diverges as the unstabilised helicopter is unstable in pitch at this speed. Figs.24a-d are for the helicopter with the CAC engaged. Fig.24e shows a nose-down runaway at 160 kn with the CAC disengaged, for comparison with Fig.24c; without the extra stabilisation provided by the CAC the active lane now reaches full authority in the nose-up direction and pitch rate diverges.

Figs.25 and 26 provide examples of runaways experienced by the pilots in the simulator. For the runaways in Fig.25, the pilot was warned that the runaway was about to occur, and deliberately delayed his intervention to counteract the runaway for as long as he thought safe; for those in Fig.26 no warning was given and the pilot's natural reaction to the runaway is shown.

At 140 kn (Fig.25a) no intervention is necessary; the active lane stays within limits and the pitch rate damps out. At 160 kn no intervention is required for a nose-down runaway (Fig.25c); when the pilot does intervene, pitch attitude is rapidly restored. For a nose-up runaway (Fig.25b) the active lane saturates and pitch rate begins to build up further, requiring intervention by the pilot to suppress the instability. Once the pilot takes corrective action he helps to bring the active lane off the authority limit and its damping contribution is restored. In the particular run shown the pilot waited for 1½ seconds before applying forward stick. Note that he did not disconnect the faulty lane until the attitude had been resotred to normal; note also that disconnection of the faulty lane in itself provides another disturbance (which is more easily controlled as the pilot is aware that disengagement provides this disturbance). This technique was generally adopted by the pilots, i.e. first control the disturbance resulting from the runaway, without attempting to determine or disconnect the faulty lane; then, when under control, diagnose and disconnect the lane and control the second disturbance. It was found preferable not to use the stick trim system during control of the failure, so that on disconnection all that was needed to restore the aircraft to trim conditions was to release the force that the pilot had applied to counter the disturbance.

At 180 kn (Fig.25d) the pilot was still able to wait for 2 seconds after a nose-down runaway before applying back stick; the nose dropped a long way during the disturbance and a 'g' change of 1 g occurred, but the attitude was quickly restored once the pilot intervened; there is a slight residual oscillation possibly caused by the pilot endeavouring to hold an out-of-trim position of the cyclic stick.

The records in Fig.26 are of pitch runaways of which no warning was given to the pilots. The nose-down runaway of Fig.26a occurred in turbulent conditions at the hover. The pitch attitude change is restrained at $7^o$ (compared with $11^o$ for no pilot intervention - Fig.24a) and attitude is then rapidly restored to the original trim condition. The normal acceleration variations shown are associated with collective lever inputs being made to hold height, and not directly with the pitch response. In the runaway of Fig.26b the pilot's action has been firstly to oppose the runaway and reduce the pitch attitude to a safer level, and then after a few seconds to return attitude to the starting value. A similar reaction is shown in the runaway at 180 kn of Fig.26c. For this runaway the active pitch lane of the ASE was also recorded; the lane rapidly reaches the authority limit, but is brought back into the working range when the pilot takes action against the runaway. Fig.26d shows a simultaneous runaway of both pitch lanes at 180 kn - an extreme case as this is above the normal maximum cruise speed, and the duplex system should avoid such simultaneous failures. The pilot is still able to control the situation, though rapid intervention is required (about 0.6 second after the start of the runaway compared with 1.4 seconds for the single lane failure) and the cyclic stick is for some time on the forward stop; the pitch attitude change during the runaway is no worse than that for the single lane failure, due to the more rapid intervention.

It is worth emphasising the point, illustrated in Fig.24a and b, that if the ASE channels are trimmed off-centre in one direction, a runaway of one lane in the other direction will provide a greater disturbance, and will be opposed by a lane with effectively reduced authority, than would be obtained with lanes initially trimmed to centre. With speed changes there will be some tendency for the trim position of the pitch lanes to move (and CG movement due to change of fuel or load state will also cause a very small trim shift) so it is important that the position of the lanes be monitored and where necessary restored to the centre of their range by means of the trim wheel, or the helicopter will be exposed to failures of potentially greater severity.

To summarise, the only ASE runaways requiring early pilot intervention were those of the pitch lanes of high speed; all other runaways could be left for a number of seconds before taking corrective action, and there were no significant problems in restoring trim conditons. In pitch, at aft CG and above about 160 kn, the response to pitch runaways was eventually divergent due to saturation of the remaining active pitch lane, and more rapid pilot action was required. However, even at maximum speed and with a double lane failure, rapid corrective action brought the situation under control (though any further delay might lead to there being insufficient forward cyclic stick travel to recover the helicopter after an aft runaway until the faulty lane had been disengaged).

## 6 SUMMARY OF SIMULATION RESULTS AND COMPARISON WITH REAL FLIGHT

In this section the results of the simulator tests are compiled; a general description is first given, followed by a list of problem areas of the simulation. These are then compared qualitatively with information available from flight tests of the Lynx.

### 6.1 Simulation results

Once the trim rate of the cyclic stick had been increased, pitch and roll control of the stabilised helicopter at aft CG attracted little criticism; the only troubling feature was the tendency of some pilots to excite pilot induced oscillations (PIOs) when attempting certain precise attitude tasks. Otherwise, attitude control in both axes was satisfactory. Collective pitch lever movements produced marked pitching changes which in some tasks interfered with pitch attitude control. At the hover, fine height control was not found possible. The most significant deficiency of the stabilised helicopter as represented on the simulator was the lack of directional stability, particularly at high speed. The pitching instability encountered in banked turns to the left at high speed was also disturbing, and at the time of the simulation was not properly understood.

The helicopter without ASE or CAC showed no significant deficiencies in roll behaviour, a further deterioration in yaw control due to lack of yaw damping, and an increase in the pitching motions generated by collective pitch inputs. Pitch control became progressively more difficult with increasing speed due to the increasing pitch instability. At the maximum speed simulated (180 kn) control was described as precarious. Some alleviation of the instability was obtained by the addition of the CAC.

Runaways of the ASE produced no unexpected or severe problems. The most critical case was of pitch lane runaways at high speed; however, satisfactory control was still retained even in runaways at maximum speed. The importance of keeping the ASE lanes trimmed as near as possible to the centre of their range, to prevent failures of increased severity, was noted. This can hardly be considered a problem area as the purpose of the pitch channel of the ASE is to combat the instability of the helicopter - it is almost inevitable that pitch runaways at maximum speed will provide the design limiting case and that control of these runaways will therefore be the most demanding task.

There was some criticism of the indicator display of the ASE in that after a runaway the failed lane was not always readily identified; occasionally the wrong lane was disconnected. However, careful diagnosis always identified the correct lane.

In the limited tests at mid and forward CG positions, significant improvements in pitch stability and ease of pitch control of the unstabilised helicopter were evident. There was also some improvement in the yaw behaviour. It is worth re-emphasising the fact that the great majority of the simulator tests were performed at aft CG and therefore at the condition of greatest instability of the unstabilised helicopter.

To summarise the problems encountered in the simulation, and, where possible, give potential solutions to the problems, we have:-

(a) The cyclic stick trim rates originally proposed were found to be unacceptably low and were increased from 35 seconds for full travel to 15 and 17 seconds for longitudinal and lateral trim respectively.

(b) Collective pitch inputs at speed produced marked, and occasionally disturbing, pitch attitude changes; these were most significant for the helicopter without ASE or CAC.

(c) Fine height control at the hover was not found possible; this could have been due to an oversensitive collective pitch control but it was thought that deficiencies of the TV visual display and restricted motion travel were the most probable cause, as shown by the earlier Wessex validation simulation.

(d) There was a PIO tendency from some pilots when attempting precise attitude tasks. Slight modification of the pitch law of the ASE alleviated this tendency.

(e) Pitch control of the helicopter without ASE or CAC became progressively harder with increase of speed; however even at maximum speed at aft CG control was still possible though requiring continuous pilot attention. Forward movement of the CG gave very significant improvement in pitch control. Addition of the CAC also was beneficial in reducing the severity of the pitch divergence at high speed.

(f) A pitch and yaw instability was encountered in left-hand turns at moderate to high speed; analysis subsequent to the simulation has revealed a deficiency in the representation of yawing moments acting on the fuselage due to torque changes. This misrepresentation greatly exaggerated the inherent reduction in stability that is provided from the ASE in banked turns when the pitch signal is dependent on an attitude gyro. Incorrect motion cues fed to the pilot also reduced his early awareness of the instability.

(g) At high speed the simulated helicopter, even with the ASE engaged, showed poor directional stability. Without the yaw channel of the ASE there was also a reduction in yaw damping and control was imprecise. Lack of yaw motion of the simulator cockpit was an undoubted major contributor to this deficiency (again demonstrated by the Wessex simulation), but the lack of directional stability of the stabilised helicopter was evident in analysis of the stability roots of the helicopter. There were doubts as to the validity of the simulator data, and as to the exaggeration of the problem that was provided by the lack of simulator yaw motion, but a potential solution of the problem was provided by the addition of a lateral acceleration term in the yaw channel of the ASE, which contributed an effective increase in the directional stiffness of the helicopter.

### 6.2 Comparison with real flight

At the time of writing this Report, Lynx helicopters have been flying for about two years. Comparison with the points raised in the simulator tests has been drawn from comments received from test pilots and staff of Westland Helicopters Ltd., and from a report on a brief evaluation of the Lynx carried out by the British and French Service test establishments (A & AEE, CEV) approximately one year after the first flight of the Lynx.

As in the simulator, pitch and roll handling of the stabilised Lynx with the AFCS state simulated have shown minimal undesirable handling features, and the crisp response in both axes has been well liked. Yaw stability has provided some problems, particularly in descending flight.

Comparing flight and simulator more specifically, point by point:-

(a) Cyclic stick trim rates for the Lynx were increased to 17 seconds for full travel, close to the simulator values.

(b) Collective pitch movements produced the marked pitching coupling found in the simulator and would have had a degrading effect on the ability to perform accurate instrument flying, apart from the influence on normal handling. The collective-to-cyclic interlink has now been modified from the state used in the simulation to improve the handling in this area.

(c) No problem has been found in controlling height at the hover, confirming the need for improved motion and visual cues for this phase of simulated helicopter flight.

(d) There has been no significant PIO problem, though some mention has been made of a small residual pitching oscillation evident when attempting to maintain constant attitude at high speed.

(e) The helicopter has been flown throughout the speed range without autostabilisation; control at maximum speed is possible though difficult. The benefit obtained from the CAC has been shown, and most flying of the 'unstabilised' Lynx is in fact performed with the CAC engaged.

(f) There has been no evidence of a pitch-yaw instability in turns at high speed. There is, however, occasionally a tendency for a long period pitching motion to develop, possibly due to the weakened pitch attitude law obtained in a turn. The simulator, due to deficiencies in the representation, here gave false indication of a possible problem.

(g) Yaw stability has been limited in some conditions and particularly during descending flight. Aerodynamic solutions to the problem have been tried, in the form of additional fin area, with some limited success. Introduction of a lateral accelerometer term in the yaw channel of the ASE has also been tried briefly, and shows useful potential. The problems of yaw control have not been as severe as those found in the simulator, however; in particular the difficulty of directional control of the simulated helicopter without ASE at the hover has not been found, again re-emphasising the need for yaw motion before effective control of this axis of motion can be achieved in the simulator.

Study of ASE runaways had not begun at the time of writing this Report, so no comparison was possible in this area.

## 7 CONCLUSIONS

The Aerodynamics Flight Division simulator at RAE, Bedford has been used for a simulation of the Westland Lynx helicopter. The simulation took place about 5 months before the first flight of the Lynx. Handling features of the helicopter were investigated, including the benefits obtained by stabilisation, and the problems associated with runaways of the autostabilisation equipment. Potential problem areas were identified and, where possible, solutions investigated.

Comparison has been drawn between the simulator results and results of flight tests on the actual Lynx; section 6 lists this comparison in detail. With the exception of three areas, there was a strong similarity in results. One area of poor comparison was due to an invalid simplification of the equations used in the simulation; the other two areas again highlighted the need for improved simulator motion and visual cues for certain phases of simulated helicopter flight, a conclusion which had previously been established in a validation simulation of the Westland Wessex.

## Acknowledgment

The author wishes to express his thanks to the staff of the Aerodynamics Department of Westland Helicopters Ltd., who assisted in the preparation and operation of the simulation described in this Report, and to the test pilots of WHL, RAE and A & AEE who performed the evaluation of the simulated helicopter.

## Appendix A

## MOTION DRIVE EQUATIONS

The aim of the motion drive equations is to give the pilot an impression of vehicle motion as closely related as possible to that which he would receive in real life, as he relies to a considerable extent on the motion cue received for control of an aircraft, particularly when the vehicle's stability is poor. Description of the laws used in the Lynx simulation is given below; a fuller explanation of the philosophy behind the form of the drive laws is given in Ref.4.

### A.1 Pitch motion

This axis of motion was used simply to reproduce pitch motion of the aircraft, with a law of the form

$$\theta_{c/p} = K\theta_{a/c}$$

where $\theta_{c/p}$ is the pitch angle of the simulator cockpit*

$\theta_{a/c}$ is the pitch attitude of the aircraft

and $K$ is a constant, dependent on the range of simulator motion available and the range of aircraft motion that it is desired to represent.

In this simulation a value of 0.4 was used for $K$, which was dictated by the requirement to allow large pitch attitude manoeuvres during investigation of AFCS runaways.

A considerable improvement can be made on this form of pitch motion law by considering the way in which motions are sensed by the pilot's vestibular apparatus of the inner ear. In simple terms these motion sensors consist of two orthogonal sets, one set detecting linear acceleration, the other sensing a mixture of rotational accelerations and rates. If one now considers the use of motion relative to the functions of these motion receptors it can be seen, for example, that the pitch axis of motion can be used to provide a rotational cue and also, by reorientation of the pilot with respect to the gravity vector, an acceleration cue. Taking first the rotational cue in isolation, one could reproduce pitch rotation by relating pitch rates $q$ of simulator and vehicle by

$$q_{c/p} = q_{a/c}$$

---

* Throughout this Appendix the subscript c/p will be used to represent motion of the simulator cockpit, and a/c to represent motion of the vehicle being simulated.

However, this would produce an inherent linear acceleration cue in the simulator, due to reorientation with respect to gravity. This is avoided by considering the initial motion cue to be of greatest significance, and washing out the subsequent motion so that attitude changes of the aircraft produce no long term attitude change of the simulator cockpit. This results in a law of the form (introducing a gain to keep the motion within limits):-

$$q_{c/p} = K\left(\frac{\tau s}{1 + \tau_s}\right) q_{a/c}$$

i.e.

$$\theta_{c/p} = K\left(\frac{\tau}{1 + \tau_s}\right) q_{a/c}$$

where $\tau$ is a time constant and $s$ is the Laplace operator.

The second use of the pitch axis is for representation of fore-aft translational acceleration, and here the relationship could be

$$\sin \theta_{c/p} = \frac{\Sigma X_{a/c}}{mg}$$

where $\Sigma X_{a/c}$ is the sum of the forces (excluding gravitational) acting along the aircraft's X body axis, $m$ is the aircraft mass, and $g$ is the gravitational constant.

However in the converse of the previous argument for rotational cues, this linear acceleration cannot be felt without rotation of the cockpit and hence generation of spurious rotational cues. The philosophy used is that rotational cues take priority over the translational cues and only the longer term translational cues (which can be generated without rapid rotation of the cockpit) are used, by use of a filter of the form:-

$$\sin \theta_{c/p} = \left(\frac{1}{1 + \tau s}\right) \frac{\Sigma X_{a/c}}{mg}$$

Using the small angle approximation for $\sin \theta_{c/p}$ and introducing a gain $K$ in this term for scaling purposes, we get the full pitch law of

$$\theta_{c/p} = K_1\left(\frac{\tau_1}{1 + \tau_1 s}\right) q_{a/c} + K_2\left(\frac{1}{1 + \tau_2 s}\right) \frac{\Sigma X_{a/c}}{mg} \qquad \text{(A.1)}$$

This law was not used in this simulation, though it was evaluated in the previous simulation of the Wessex, and has been used in all subsequent simulations on the Aerodynamics Flight Division simulator; however, explanation of this form of law is given here as it highlights a major deficiency of the law of the type

$$\theta_{c/p} = K\theta_{a/c}$$

when applied to banked flight. As the pilot is seated in the plane of symmetry of the aircraft his rotational sensors will respond to pitch rate, which is a quantity also defined in the vehicle's plane of symmetry. Pitch attitude $\theta$ however, is defined in a plane normal to the earth's surface and is related to pitch rate by the equation

$$\dot{\theta} = q \cos \phi - r \sin \phi$$

where $\phi$ is bank angle and $r$ is yaw rate.

With the law used in the simulator the pilot senses $\dot{\theta}$ , whereas in flight the relevant parameter is $q$ , and in banked flight these quantities are no longer equal and, if $r$ is small, the cue felt by the pilot will be degraded by $\cos \phi$ . The significance of this was not appreciated at the time of the simulation, and in particular, as described in section 5.1 a situation occurred in which a pitch rate was associated with a negative yaw rate in a left-hand turn so that the terms on the right-hand side of the above equation tended to cancel leaving the pilot *(in the simulator)* with no sensation of the pitch rate which, in flight, would be felt directly.

Because of this deficiency, the improved law of equation (A.1) has been used in all subsequent simulations.

## A.2 Roll motion

The form of law used in roll has a direct analogy with the pitch motion law of equation (A-1). It was:-

$$\phi_{c/p} = K_3 \left(\frac{\tau_3}{1 + \tau_3 s}\right) p_{a/c} - K_4 \left(\frac{1}{1 + \tau_4 s}\right)\left(\frac{\Sigma Y_{a/c}}{mg} + \frac{\ell_p \dot{r}}{g}\right)$$

where $p_{a/c}$ is aircraft roll rate, $\ell_p$ is the distance of the pilot ahead of the aircraft CG and $\Sigma Y_{a/c}$ is the sum of the forces (excluding gravitational) acting along the aircraft's Y-body axis. The additional term $\ell_p \dot{r}/g$ introduces the linear acceleration felt by the pilot during yawing acceleration due to his displacement from the CG.

The values used were $K_3 = 0.25$, $K_4 = 0.5$, $\tau_3 = 1.5$ seconds, $\tau_4 = 1$ second.

## A.3 Yaw motion

Brief tests were made using a law of the form

$$\psi_{c/p} = 0.5\ \psi_{a/c}$$

where $\psi$ is heading angle, but yaw motion deficiencies prevented normal use of this axis.

## A.4 Heave motion

Because of the ability of the aircraft to sustain an acceleration along its Z-body axis (e.g. in a co-ordinated turn) and the inability of the simulator motion system to produce a sustained vertical acceleration on the pilot, washout of second order is required in the heave law.

The ideal heave motion law of

$$\ddot{h}_{c/p} = -\left(\frac{\Sigma Z}{m} + g - \ell_p\dot{q}\right)$$

where $h_{c/p}$ is the vertical displacement of the simulator cockpit, $\Sigma Z$ is the sum of the forces (excluding gravitational) acting along the aircraft's Z-body axis and the $\ell_p\dot{q}$ allows for the pilot's position relative to the CG, is degraded to

$$\ddot{h}_{c/p} = -K_5\left(\frac{\tau_5 s}{1 + \tau_5 s}\right)\left(\frac{\tau_6 s}{1 + \tau_6 s}\right)\left(\frac{\Sigma Z}{m} + g - \ell_p\dot{q}\right)$$

i.e.

$$h_{c/p} = -K_5\left(\frac{\tau_s}{1 + \tau_5 s}\right)\left(\frac{\tau_6}{1 + \tau_6 s}\right)\left(\frac{\Sigma Z}{m} + g - \ell_p\dot{q}\right)$$

In this simulator, as the pitch axis is carried on the heave arm and the action in heave is itself a pitching motion, it is necessary to provide an additional term to the pitch axis to compensate for the pitching due to the heave law. Some structural problems were encountered when rapid heave changes were fed to the motion system and as a result the gain that could be used in heave was much lower than would have been desired. Values used were $K_5 = 0.2$, $\tau_5 = \tau_6 = 0.5$ second. This difficulty was emphasised by the ability in a helicopter to apply rapid changes of vertical acceleration directly by action of the collective lever; in a conventional aircraft, vertical acceleration is derived through pitching of the aircraft and, with the exception of accelerations imposed by turbulence, the accelerations have a lower frequency content.

For brief hovering tests an increased gain of $K_5 = 0.6$ was used, giving improved heave cues, but this was not suitable for use during normal manoeuvring flight.

Simulated rotor vibration was fed into pitch and heave axes as a mixture of 1/rev and 4/rev oscillations, attenuated by forward speed and rotor thrust.

# Appendix B

## AUTOMATIC FLIGHT CONTROL SYSTEM (AFCS) - AUTOSTABILISER LAWS

### B.1 Laws

The AFCS provides both autostabilisation during manual flight and automatic control of the helicopter in certain flight modes (e.g. autopilot holds, automatic hover). The second of these functions was not simulated here, where the concern was handling qualities as presented to the pilot, but the autostabilisation capability of the AFCS was represented in some detail.

Autostabilisation was provided in the pitch, roll and yaw ASE channels and the control laws are given below:-

Pitch:
$$B_{1A} = 0.1\left(\frac{s}{1 + s/16}\right)\theta + 0.12\left[\theta + 19.5\,(\eta_F - \eta_{F_0})\right]_{L\pm5^\circ}$$
$$+\ 0.12\left[\theta + 19.5\,(\eta_F - \eta_{F_0})\right]$$

| | | |
|---|---|---|
| where | $B_{1A}$ | is the demanded cyclic pitch angle (in degrees) |
| | $\theta$ | is the fuselage pitch attitude (degrees) |
| | $\eta_F$ | is the fore-aft cyclic stick position, expressed as the proportional distance forward from the fully aft position relative to the full travel available. |
| | $\eta_{F_0}$ | is a datum cyclic position, similarly defined |

and $[x]_{L\pm5^\circ}$ indicates that the term takes the following value:-

$$\begin{array}{llcl} \text{if} & x \leqslant -5^\circ & [x]_{L\pm5^\circ} = & -5^\circ \\ & -5^\circ < x < 5^\circ & [x]_{L\pm5^\circ} = & x \\ & 5^\circ \leqslant x & [x]_{L\pm5^\circ} = & +5^\circ \end{array}$$

The first term derives from pitch attitude a cyclic signal which approximates to pitch rate; the remaining terms provide attitude stabilisation.

The authority of the pitch law was limited to ±3.16° of cyclic pitch of the rotor blades. The stick position terms in the law served the dual purpose of allowing a trim change of pitch attitude without too much erosion of the pitch law authority in one direction, and also of giving an increased pitch response to compensate for the increased damping applied by the law.

During the simulation, the pitch law was modified by the inclusion of a lag on the $(\eta_F - \eta_{F_0})$ terms or on the $\theta$ terms within the same brackets, with a number of values of the lag time-constants being evaluated. Details are given in the main text.

Roll:

$$A_{1A} = -0.1\left(\frac{s^2 + 8s + 64}{s^2 + 32s + 64}\right)\left(\frac{s}{1 + 0.1s}\right)\phi - 0.15[\phi]_{L\,-8^\circ}^{\;\;+6^\circ} - 0.1\left(\frac{\tau_\phi s}{1 + \tau_\phi s}\right)\phi + \frac{12}{1 + 0.5s}(\eta_L - \eta_{L_0})$$

| | | |
|---|---|---|
| where | $A_{1A}$ | is the demanded cyclic pitch angle (degrees) |
| | $\phi$ | the fuselage bank angle (degrees) |
| | $\eta_L$ | the proportional lateral cyclic stick position from fully left |
| | $\eta_{L0}$ | is a datum lateral cyclic position |
| | $\tau_\phi$ | is a time-constant with value 5 seconds below 60 kn, 1 second above 60 kn |

The law provides roll attitude stabilisation over a limited bank angle ($-8^\circ$ to $+6^\circ$); outside this region rate stabilisation is provided, which, as in the pitch law, is derived from a bank angle signal. The first term has an additional filter, $\left(\frac{s^2 + 8s + 64}{s^2 + 32s + 64}\right)$, designed to suppress a rotor flapping resonance condition. The $\tau_\phi$ term, having a long time-constant below 60 kn, reinforces the attitude term at low speed, whereas above 60 kn the reduced time-constant causes the term to weaken its attitude effect and contribute some additional roll damping. The stick terms, as in the pitch law, compensate in the control response for the increased damping. The authority used was $\pm 1.91^\circ$ of blade angle.

Yaw:

$$\theta_{t_A} = 0.3\left(\frac{2s}{1 + 2s}\right)r + K\frac{\Sigma Y}{mg} + [\theta_{t_H}]$$

| | | |
|---|---|---|
| where | $\theta_{t_A}$ | is the demanded tail rotor pitch angle (in degrees) |
| | $r$ | the fuselage yaw rate (degrees/s) |
| | $K$ | a constant |
| | $\Sigma Y$ | the sum of the forces acting along the aircraft Y-body axis (excluding the gravitational component) |
| | $mg$ | the aircraft weight |

and $[\theta_{t_H}]$ a heading hold term, only present when the heading hold mode of the autostabiliser is engaged.

$\frac{\Sigma Y}{mg}$ represents the signal that would be detected by a lateral accelerometer placed at the aircraft CG. This term was not included for initial simulator tests but was later introduced to improve lateral stability.

The heading hold mode of the autostabiliser as proposed for the Lynx was more complicated than could be simulated, including trimming of the yaw pedals, a facility not available on the Aero Flight Simulator.

The proposed law at the time of the simulation was

$$\theta_{t_H} = 0.2r + \theta_{t_{AP}}$$

and

$$\theta_{t_{AP}} = 0.4r + 0.7\ (\psi_\varepsilon - \psi_0) + 0.1 \left(\frac{\psi_\varepsilon - \psi_0}{s}\right)$$

where $\psi_\varepsilon$ was the heading change occurring from the time of engagement of heading hold,

and $\psi_0$ was a datum heading change, controlled by a knob on the AFCS controller.

When $|\theta_{t_{AP}}| > 1^\circ$, the pedals were moved in the sense to reduce its value, until $|\theta_{t_{AP}}| < 0.75^\circ$.

The law was simulated here by neglecting the pedal trimming and taking the above law as appropriate to $|\theta_{t_{AP}}| < 1^\circ$ , i.e.

$$\theta_{t_H} = 0.6r + 0.7\ (\psi_\varepsilon - \psi_0) + 0.1 \left(\frac{\psi_\varepsilon - \psi_0}{s}\right)$$

A further simplification was taken by generating $\psi_\varepsilon$ as

$$\psi_\varepsilon = \int r\,dt\ ,$$

integration starting at the time of engagement, i.e.

$$\theta_{t_H} = 0.6r + \left(\frac{0.7s + 0.1}{s^2}\right) r - \left(\frac{0.7s + 0.1}{s}\right) \psi_0$$

Authority of the yaw channel was ±3.64 degrees.

Collective:

The computer acceleration control (CAC) had a law

$$\theta_{0_A} = -1.5 \left(\frac{1}{1 + 0.01s}\right) \Delta n$$

where $\theta_{0_A}$ is the demanded collective pitch angle (in degrees) and $\Delta n$ is the incremental signal detected by a vertical accelerometer at the aircraft CG (in g units), i.e.

$$\Delta n = -\frac{\Sigma Z}{mg} - 1 ,$$

where $\Sigma Z$ is the sum of the forces (excluding gravitational) acting along the aircraft Z-body axis.

Authority of the collective channel was $\pm 2.14^\circ$.

In each of the four channels, the control angle demanded by the autostabiliser was added to the pilot's demanded control angle, the sum of these two angles being subjected to the actuator lag of 0.127 second to give the actual blade movement. In addition the main rotor cyclic pitch angles required for the aerodynamic computations were related to the respective servo actuator outputs through a control phase angle of $15^\circ$:-

$$B_1 \text{ at blade} = (B_1 \text{ servo}) \cos 15^\circ + (A_1 \text{ servo}) \sin 15^\circ$$
$$A_1 \text{ at blade} = (A_1 \text{ servo}) \cos 15^\circ - (B_1 \text{ servo}) \sin 15^\circ$$

There were also interlinks from the collective lever to the longitudinal cyclic and yaw control systems, upward collective movement giving forward cyclic and left yaw inputs.

## B.2 Control of autostabiliser modes

The ASE and CAC control and indicator panels are shown on the left-hand side of the cockpit in Fig.4a and drawn in Fig.21. Each of the four channels is duplicated, with the two lanes of each channel (lanes 1 and 2) having individual engage/disengage buttons (marked 1 and 2). The indicator panel contains eight indicator needles, in two groups of 4, with one needle for each lane indicating the control signal for that lane. Yaw and roll needles move across the face of the instrument, collective and pitch move vertically. Thumbwheels for pitch and roll trim and a knob for heading hold trim, feeding respectively $\eta_{F_0}$ , $\eta_{L_0}$ and $\psi_0$ in the AFCS control laws, are mounted adjacent to the lane buttons. The thumb-wheels are used to trim the AFCS null indicators to the centre of their travel so that maximum range of movement in each direction is obtainable.

If both lanes in any one channel are operational, the resultant control demand is the average of the two lane demands, i.e.

$$\theta_{\text{CHANNEL}} = \tfrac{1}{2}\,(\theta_{\text{LANE 1}} + \theta_{\text{LANE 2}})$$

In the event of faulty operation of one lane, the remaining lane will continue to operate as normal, but with halved authority and gain. If only a single lane is engaged, full authority and gain are preserved, e.g.

$$\theta_{\text{CHANNEL}} = \theta_{\text{LANE 1}} \text{ for LANE 2 disengaged}$$

The indicator panel indicates faulty lane operation by uncoupled behaviour of the appropriate pair of lane needles; the pilot is left with the diagnosis of the faulty lane and disconnection by the appropriate lane button. In the simulator, faults introduced by the operators could also be signalled to the pilot by illumination of a warning lamp to the right of the torquemeter.

Two switches on the cyclic stick were linked to the ASE system. Operation of a button gave disconnection of all pitch, roll and yaw lanes, leaving the CAC engaged, and operation of a rocking switch caused engagement or disengagement of the heading hold system.

## Appendix C

## PILOT'S REPORT - WG13 SIMULATION AT RAE, BEDFORD

*M.C. Ginn*, Test Pilot, Westland Helicopters Ltd.

### C.1 Introduction

The WG13 has been simulated on the RAE handling simulator with motion, and TV and shadow visual cues. This Report covers the 'flying' by the first of four pilots, who were each to spend a nominal week at Bedford. A programme of pitch and roll axis tests at 80-180 kn in 20 kn increments, and at the hover were to be made, in full autostabiliser, CAC only, and full manual control. The comments on the tests which follow will show areas where repeats will not be needed, and others where new tests are suggested. In fact, no tests were made at 100 kn, due to pressure of work.

### C.2 Pulse inputs

Pulse inputs were made at all speeds except 100 kn and the hover, and recorded. It is considered that they need not be repeated in an academic form, but only sampled as desired by subsequent pilots for qualitative comment. With full stabilisers, the returns to datum were generally very good, and good at 180 kn. With CAC only, up to 140 kn a long period oscillation usually resulted from pitch and roll pulses, but at 160 kn and above a direct divergence was seen. In full manual, at 80 kn, the roll pulses resulted in a return to datum, and pitch pulses lead to a divergence opposite to the input. At higher speeds an increasingly rapid divergence was caused.

### C.3 Runaways

Pitch, roll and CAC runaways were tested at 80, 120, 140, 160 and 180 kn in three forms:-

(a) Both stab lanes engaged and nulled: single runaway.

(b) Both stab lanes engaged and trimmed 50% off null: single runaway adverse to trim.

(c) Both stab lanes engaged and nulled: double runaway to simulate effect of runaway when operating on single stab lane following failure.

In addition single CAC runaways were tested when operating with CAC only. The pilot intervened when pitch angles of about ±35$^{\circ}$, or bank angles of 60$^{\circ}$ were reached. In general pitch lane runaways at high speed (case (a)) required intervention in 1½ to 2 seconds. All other case (a) runaways could be left for more than 2½ seconds. When unannounced runaways were given, attitude excursions were generally limited to ±5° with ease, except case (c), where ±20° could be expected.

It was noted that failure diagnosis was not quite as rapidly carried out with the double 4 needle indicators as expected. Furthermore, a forward movement of a longitudinal needle on the righthand instrument (pitch channel) caused a nose-down aircraft rotation, while a similar movement on the lefthand instrument (collective channel) caused a nose-up aircraft rotation. Despite this fact, a systematic approach to the diagnosis produced the correct answer every time.

### C.4 Saturation in large amplitude changes

Within the vision and motion limits of the simulator, little saturation was seen. By offsetting the pitch trim, it was possible to saturate in a nose-up manoeuvre, yet remain at say +15° on the TV picture. Attitude holding was not very difficult. Also decelerations of typically, 160 to 60 kn in 12½ seconds were possible by holding +30° (saturated) on the VGI, with no difficulty.

### C.5 Collective pitch movement

CP movements proved just as disturbing in pitch (also slightly in roll and yaw) as seen on the WHL simulation; up movement generally caused more trouble than downward. With full stabilisation, a stick movement which varied with speed was needed, to stay at a chosen attitude: sometimes even to stay out of saturation. In practice the CP movement proved a very useful pilot task in pitch for other assessments, such as evaluation of PIO. In CAC only, and full manual flying, CP movements were a more obvious problem. At speeds above 140 kn, CP movements had to be gentle to avoid the risk of losing control. The gearing of the collective control was considered satisfactory in forward flight, with 1% alterations of torque possible, yet with a fairly small total travel to autorotation.

### C.6 Instrument flying

The simulator was flown without TV (due to a fault) to test instrument flight capacity. CAC only and full manual were flown. It should be pointed out that the yaw axis simulation was not considered fully reliable. In particular, the contribution of the fin and body was de-stabilising. Tests involving 'full manual' were generally flown with the fin and body term deleted; this cut down the number of crashes significantly. It is considered that in future, the yaw stabiliser could be left engaged (heading hold off) for 'full manual' flying, rather than have the pilot subjected to possible spurious yaw problems. Instrument flying, with turns up to ±15° bank, ±1000ft/min height changes, was carried out. The situation at 180 kn in full manual was that in emergency, the pilot would retain control, but would be well advised to slow down to 120 kn. With CAC engaged, flight up to 180 kn was generally inaccurate, but otherwise satisfactory for limited use. However, it was felt that control could be lost by exceeding 20° bank, or making fast CP movements. Also the use of full power was likely to be very upsetting at medium speeds.

### C.7 Roll control

Within the simulator limits, in which turns of more than 30° bank were not practicable, the roll control, autostabiliser, and beeper trim were all satisfactory. The response of the aircraft in roll to yawing in forward flight was positive, and gentle with stabilisers engaged. The yawing caused by rolling was more complex. For instance when rolling left, the slip ball stayed central (feet off) but on reversing the rate back to wings level, the slip ball would go out well to the right.

### C.8 PIO

It became apparent, as the other tests were made, that there was some overcontrolling in pitch. Four tests were made at all speeds tested, to examine this feature more closely:-

(a) Tracking an aiming point on the TV outer glass screen onto a feature of the displayed terrain.

(b) Making CP movements while tracking as at (a) above.

(c) Operating the trim release switch, and then recovering from the ensuing oscillation.

(d) Attempting to force the oscillation at its natural frequency.

Although the pilot frequently felt that there was no PIO present, examination of the stick position trace showed bursts of undamped oscillation of short period during test (a). The effect was worse at 80 kn than 160. Test (b) was never free from PIOs.

Five runs were made with altered parameters, with stabs engaged:-

(e) Attitude term in stabiliser halved. This had no effect at 80 kn or at 160 kn. The stabiliser appeared sloppier, but pulse inputs were acceptable. Test (c) caused loss of control.

(f) Heave gain doubled This increased motion and made the PIOs worse.

(g) Pitch attitude ratio doubled 0.8 of aircraft attitude was applied to the cockpit, in addition to doubled heave gain. This further worsened the PIO. Both these motion changes were retained for the following runs, to highlight any improvement.

(h) Repeat with stabiliser attitude term halved No clear improvement.

(i) Stabiliser damping doubled This gave a very definite improvement at 80 kn, but little improvement at 160 kn. However, 80 kn had been the worse point. Test (d) at 80 kn showed there to be no possibility of forcing the oscillation. Test (c) was greatly improved.

## C.9 Hover

Difficulty was experienced on previous tests in holding a steady height. The pilot's task was eased before the tests here as follows:-

(a) Heave gain increased
(b) TV model changed to large scale (4 miles total length)
(c) Hovering done close to model of 100ft high ATC tower
(d) Heading hold installed (selectable on/off)
(e) Verbal warning of rearwards and lateral velocities on exceeding 3-5 knots.

A certain amount of learning was required, but eventually good hovering was obtained with all systems working. The minimum attainable collective movement caused a 100ft/min rate of climb or descent. In real life, with ground effect, such movements would result only in a change of steady height, until an OGE hover is reached. In full manual (fin and body term out), hovering was satisfactory. To avoid coupling yaw and collective oscillations, great concentration was needed.

The collective overall gearing was found to be roughly $2^{\circ}$ per 1000ft/min climb. It is considered that with real 'g', with real (i.e. more distinct) vision of surrounding scenery, and with ground effect, the collective sensitivity should be satisfactory on the real helicopter. However, this test was made with minimum collective friction. The situation could deteriorate drastically in the presence of friction. Approaches and transitions to the hover were easy, with heading hold in.

## C.10 Conclusions

(a) Single runaways were satisfactory in pitch, roll and collective, and only came below 2.0 seconds max delay at 160 kn and above in pitch.

(b) Other abnormal runaways were manageable by an alert pilot.

(c) The stabiliser was generally satisfactory in pitch and roll, and manoeuvres involving saturation were fairly easily controlled. Pulse inputs were recorded satisfactorily.

(d) Collective pitch effects on control in pitch was most disturbing; they demanded a stick movement when stabilised, but had very adverse effects on control with the stabiliser off.

(e) Instrument flying was satisfactory, but with CAC only it was inaccurate and tiring at high speed.

In full manual control at 180 kn, control was precarious and gentle manoeuvres only were feasible. Only stabilised flight was felt acceptable for routine operation.

(f) The simulation showed a distinct tendency to a PIO, whose general feel was present even in full manual.

(g) Hovering was considered acceptable within the limits of the simulation.

(h) Further tests:-

The following further tests should be made:-

1 Flight with each stabiliser channel (both lanes) disengaged singly, in turn.

2 The effect in pitch of CP changes in the hover.

3 The unpleasantness of pitch control at high power at medium speed should be investigated.

4 The PIO should be further tested with altered motion cues.

## Appendix D

## PILOT'S REPORT ON THE 'LYNX' SIMULATOR AT RAE, BEDFORD, NOVEMBER 1970

*Flt. Lt. A. P. Bell*, RAF, Test Pilot, A & AEE, Boscombe Down

### D.1 Introduction

D.1.1 This Report gives brief pilot impressions and some control response and stability data for the WG13 (Lynx) flight simulator at the Royal Aircraft Establishment, Bedford.

### D.2 Conditions relevant

### D.2.1 Aircraft mathematical model

The mathematical model used in this simulator included all known aerodynamic derivatives and characteristics of the Lynx as supplied to RAE by Westland Aircraft Ltd.

### D.2.2 Cockpit

The cockpit was not representative of the Lynx, but included normal helicopter controls and instruments. An ASE control panel and null indicators were fitted, and these were similar to those proposed for pre-production aircraft.

### D.2.3 Visual and motion cues

The cockpit provided pitch, roll and heave motion cues, and the visual presentation was in the form of a television screen. The picture for this was provided by a servo operated television camera operating over a three-dimensional 2000 to 1 scale model of the countryside. Additionally a simulated horizon was projected onto the interior wall of the spherical building housing the simulator. This could be seen through the frosted perspex of the cockpit canopy and gave additional attitude cues. '4R' and 'IR' rotor vibration was also simulated, and the 'IR' level increased with increasing 'g'. These vibrations were however, of Wessex frequency, and not representative of the Lynx.

### D.2.4 Limitations of the simulation

D.2.4.1 The following were not simulated:-

(a) Ground effect in the hover.

(b) Variable atmospheric density.

(c) Rotor speed fluctuations and engine response.

(d) Blade stall.

D.2.4.2 In addition to those points already mentioned the following aspects of the simulator were not representative:-

(a) Cyclic control ranges were restricted due to the small dimensions of the cockpit. The control gearing was however, correct.

(b) Heading hold was of a simple type engaged and disengaged by buttons on the cyclic stick, and with no open loop facility on the yaw pedals.

(c) Heading changes of more than $45^{\circ}$ from the centre-line of visual display resulted in loss of visual reference.

(d) Cyclic and collective handgrips were of Wessex type.

## D.3 Tests made

D.3.1 Longitudinal static stability at fixed collective pitch.

D.3.2 Longitudinal dynamic stability.

D.3.2.1 At aft and mid CG.

D.3.2.2 With and without the computer acceleration control (CAC).

D.3.3 Cyclic control response.

D.3.3.1 With and without ASE.

D.3.3.2 With and without CAC.

D.3.4 ASE runaways

D.3.5 Effect of two proposed modifications to the ASE

D.3.5.1 A lag term in the stick canceller circuit to reduce a possible tendency for some pilots to encounter pilot-induced oscillations (PIOs).

D.3.5.2 A lateral accelerometer to provide a coordinated turn facility.

## D.4 Results of tests

### D.4.1 Longitudinal static stability

Fig.* 1 gives graphs of stick position and pitch attitude against speed in three configurations: rear CG, collective pitch 43%; mid CG pitch 53%, and rear

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* Figures are not included in the present Report.

CG minimum pitch. 43% pitch gave about 150 kn in straight and level flight. Gradients of these curves are in the correct sense and stabilisation of a selected speed was easy. The rearward stick movement needed to prevent nose-down pitch on entering autorotation from the cruise was about 17%.

### D.4.2 Longitudinal dynamic stability

Fig.2 gives some examples of the behaviour of the unstabilised model in pitch. These tests were done with the ASE roll channel engaged after a brief check had shown that very little pitch to roll dynamic coupling existed. The test with mid CG and CAC engaged was in fact repeated with the roll channel disengaged and gave similar results. The model was also flown ASE out up to 180 kn without undue difficulty.

### D.4.3 Cyclic control response

#### D.4.3.1 Pitch, ASE out

Following nose-up step cyclic inputs of between 3 and 5% at speeds between 60 and 130 kn pitch attitude and pitch rate increased rapidly. The rate of increase of normal acceleration appeared to have reached a maximum 2 seconds after the input. Pitch rate after one second was between 10 and 15°/second and the time to attain 20° nose up was about 2 seconds. Response with the CGC out appeared to be marginally faster than with it in.

#### D.4.3.2 Roll, ASE out

Response to step inputs was linear with no pitch coupling. Fig.3 gives the roll rate obtained with varying cyclic inputs between 80 and 120 kn. Following a small input the roll rate remained effectively constant; after larger inputs some disymmetry was evident with a tendency for the roll rate to continue increasing following an input to the left and to decrease following an input to the right. Rate of roll with a one inch input (about 8%) was 16°/second in both directions.

#### D.4.3.3 Pitch ASE in

Figs.4 and 5 show the response of the model to cyclic fore and aft inputs at about 140 kn, ASE in, with and without CAC. Response with CAC was more deadbeat than without. Approximately one inch of rearward stick displacement produced a nose-up attitude change of 6° after 10 seconds with an overshoot to 13° after 1½ seconds. Peak pitch rate of 13°/second was reached ¼ second after the input.

Aft inputs on the cyclic stick at high speed were always accompanied by a rapid drop in indicated torque and a pronounced yaw to the left. It was difficult to assess the 'g' applied during these manoeuvres without an accelerometer.

### D.4.4 ASE runaways

Single channel ASE runaways were injected unannounced at high forward speed and during tactical low flying. The CAC was engaged during these tests. These produced a pitch or roll reaction that was easily controlled by the pilot. Deciding which channel in the two channel system was defective was not particularly easy, as the null indicators generally showed full deflection of both series actuators one in each direction. The faulty channel could be identified by noting the direction of the attitude change at the moment of failure. Thus if the aircraft had pitched nose up, and No.1 pitch showed full deflection nose up and No.2 pitch ASE showed full deflection nose down, then No.1 pitch channel was at fault. After cancelling the faulty channel ASE performance with the remaining one operating was unchanged. The motion and visual cues available in the simulator were sufficient to warn the pilot that a failure had occurred if in straight and level flight at the time of failure, but if it occurred in manoeuvring flight then it was less easy to detect.

### D.4.5 Steep turns and general manoeuvring

The limitations of the simulation as listed in section D.2.4 reduced the amount of useful testing that could be done in these areas. One major problem was encountered; if a steep turn to the left at 45° angle of bank and high speed was attempted, with ASE in or out, a violent divergent pitch-up occurred which usually resulted in loss of control. No definite explanation for this phenomenon has yet been produced. Apart from this the model was easy to manoeuvre, and target tracking at low altitude appeared easy. In view of reports that pilot induced oscillations had been observed by some pilots when changing speed, an attempt was made to reproduce this but without success. A proposed modification to eliminate this tendency was tried. This involves introducing a lag of approximately one second in the stick canceller term in pitch. Little difference in handling could be detected during the short qualitative assessment. Another proposal is that a lateral accelerometer should be fitted to feed signals into the ASE yaw channel to give a balanced turn facility. This gave a noticeable improvement although it did not eliminate sideslip altogether.

## D.4 Conclusions

The object of this simulation of the Lynx is to assist the designers in their task of optimising firstly the aerodynamic characteristics of the aircraft and secondly the performance and functioning of the autopilot system. Several problems have been encountered, notably the divergent pitch-up characteristic of the model in steep left turns (see section D.4.5), but it is not known whether these deficiencies are due to inaccuracies in the aerodynamic model and are therefore not representative of the full size aircraft, or whether the aircraft itself will be limited by some other factor such as blade stall, which is not simulated, before reaching these critical areas. In other respects such as static and dynamic stability, control response and ASE failure cases, the performance of the model is acceptable, and in some cases good.

Control response with and without ASE appears satisfactory with little or no pitch to roll coupling. The computer acceleration control is effective in improving the dynamic longitudinal stability of the model without ASE, and has the effect of giving more deadbeat response to cyclic inputs with the ASE engaged. Response to single ASE failures is entirely acceptable. The yaw characteristics of the model were not investigated due to lack of time and no yaw ASE malfunctions were tried. Some form of coordinated turn facility is obviously desirable in any modern helicopter of this class, and the lateral accelerometer appears to be an acceptable solution.

Although no-one would suggest that simulation is infallible, this exercise has pin-pointed areas of interest or potential hazard, and as such the results from it will be useful in guiding further design work and ultimately flight testing of the full size aircraft.

## Table 1

## WESTLAND LYNX: LEADING PARTICULARS

| | |
|---|---|
| Overall length (rotors turning) | 49 ft 9 in (15.16 m) |
| Main rotor diameter | 42 ft (12.80 m) |
| Minimum height (tail rotor stopped) | 11 ft 3 in (3.43 m) |
| Maximum all-up weight | 8000 lb (3630 kg) |
| Maximum cruise speed | 160 kn (296 km/h) |
| Power plant: | Two Rolls-Royce BS 360-07-26 forward drive free power turbine engines with maximum continuous rating of 750 shp per engine. |

Particulars are appropriate to the basic variant as simulated, but do not necessarily reflect the values for production versions of the helicopter.

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| No. | Author | Title, etc. |
|---|---|---|
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| 2 | D.H. Perry<br>L.H. Warton<br>C.E. Welbourn | A flight simulator for research into aircraft handling characteristics.<br>ARC R & M 3566 (1966) |
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| 7 | - | Lynx helicopter - summary letter report on the CEV/A & AEE flight assessment of the prototype aircraft, XW837.<br>A & AEE Ref.APF/173/014, 5 April 1972 |

Fig.1 Westland Lynx

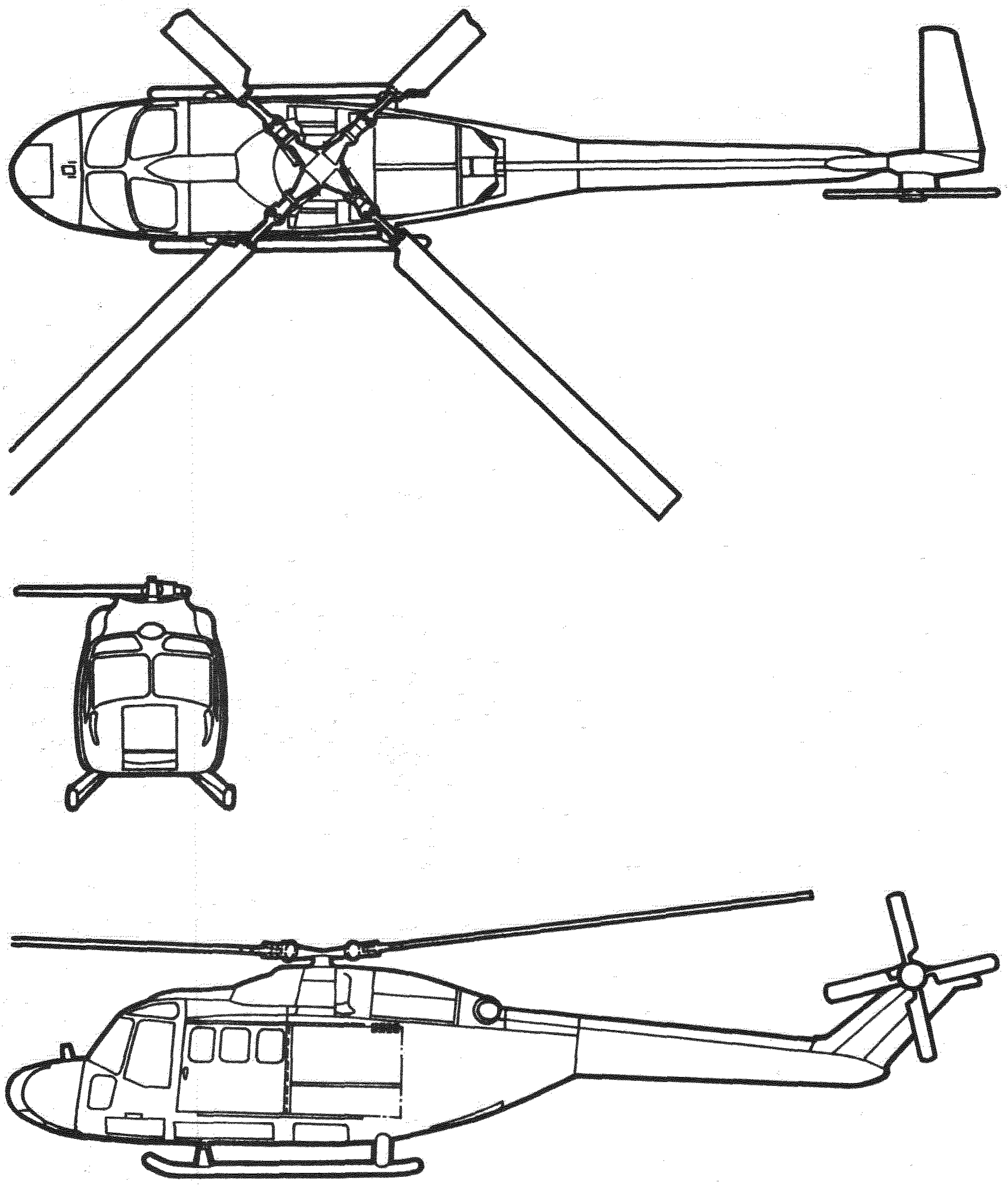


Fig.2 Lynx general arrangement

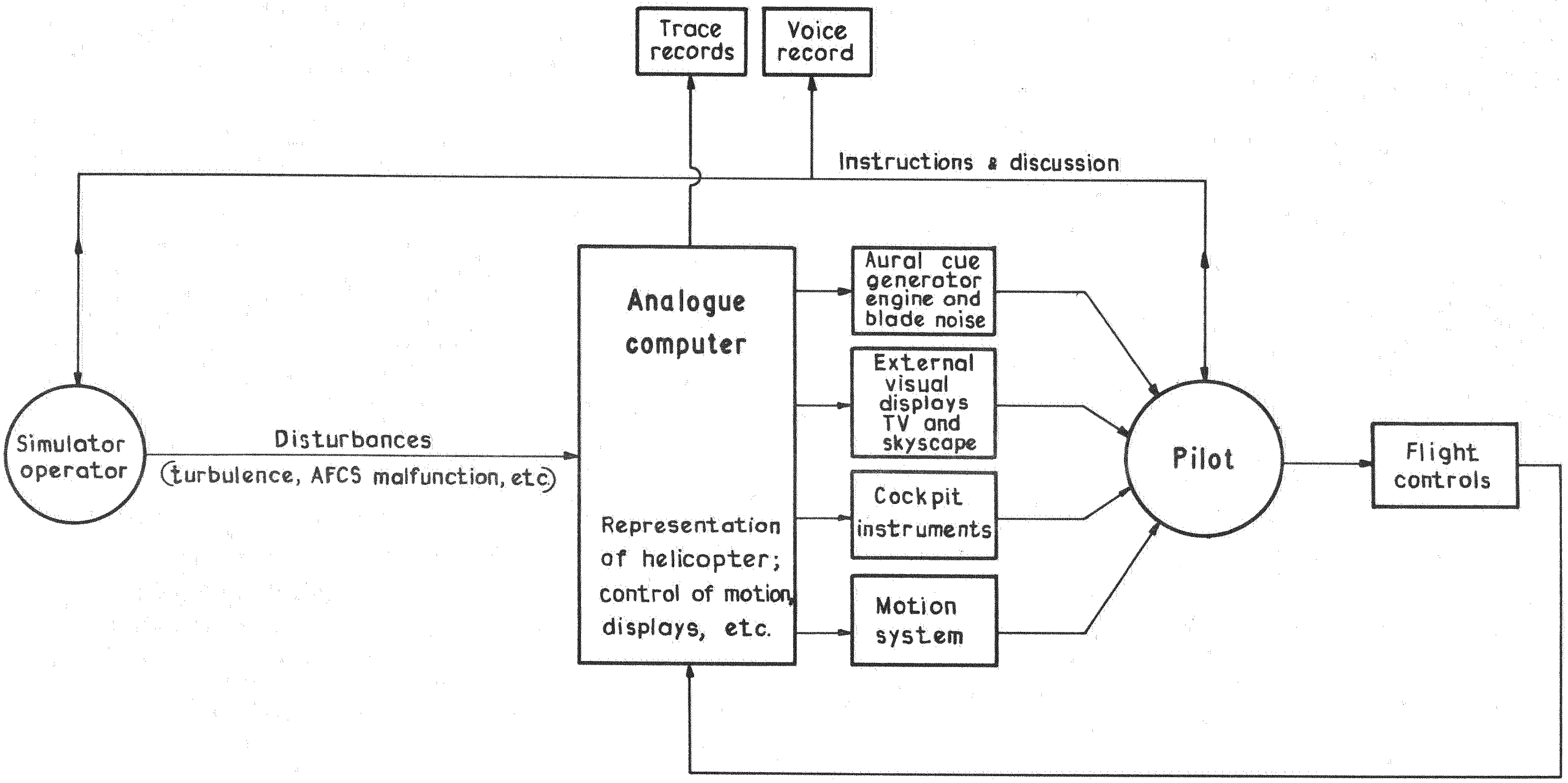


Fig.3 Block diagram of simulator

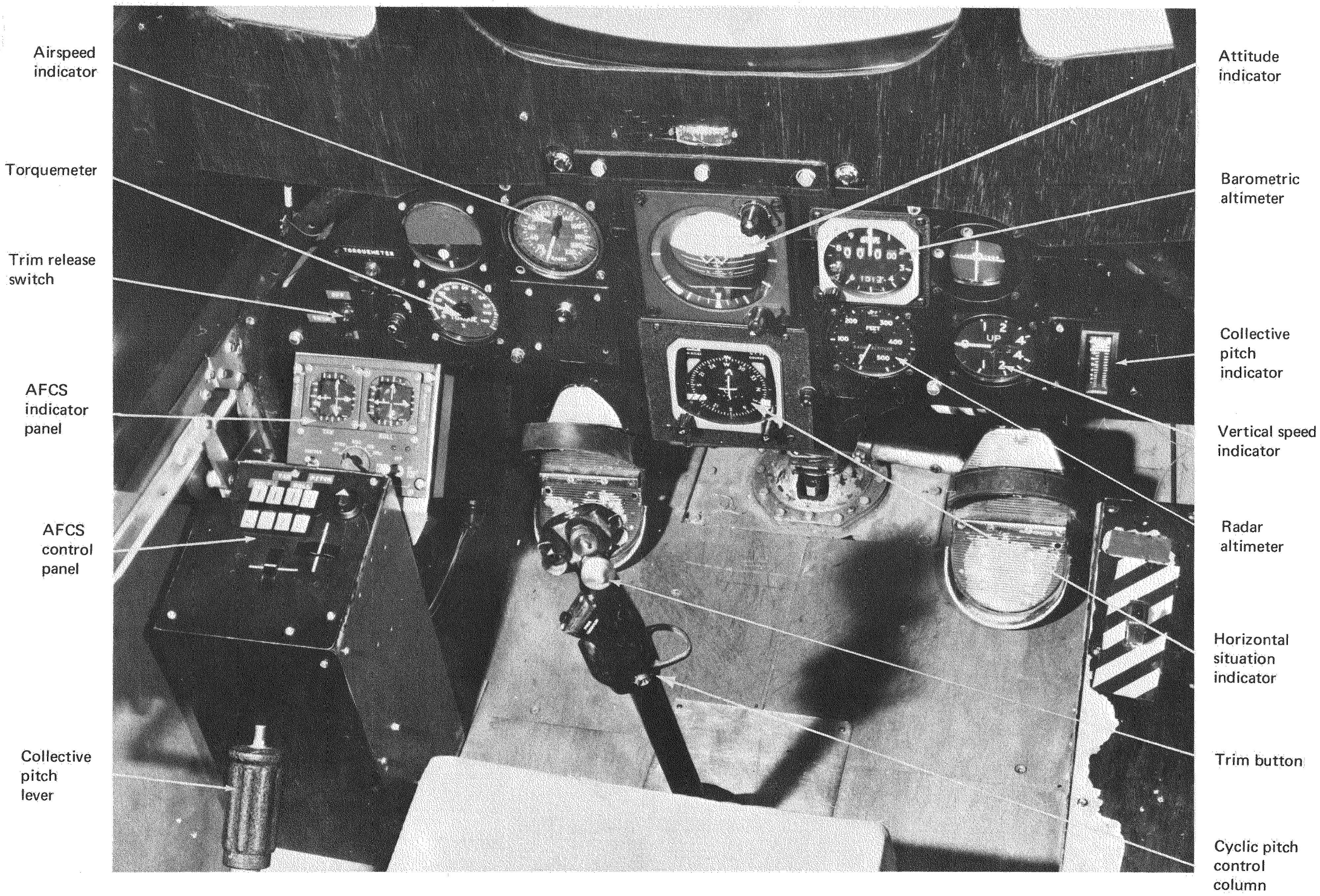


Fig.4a Cockpit interior — simulator

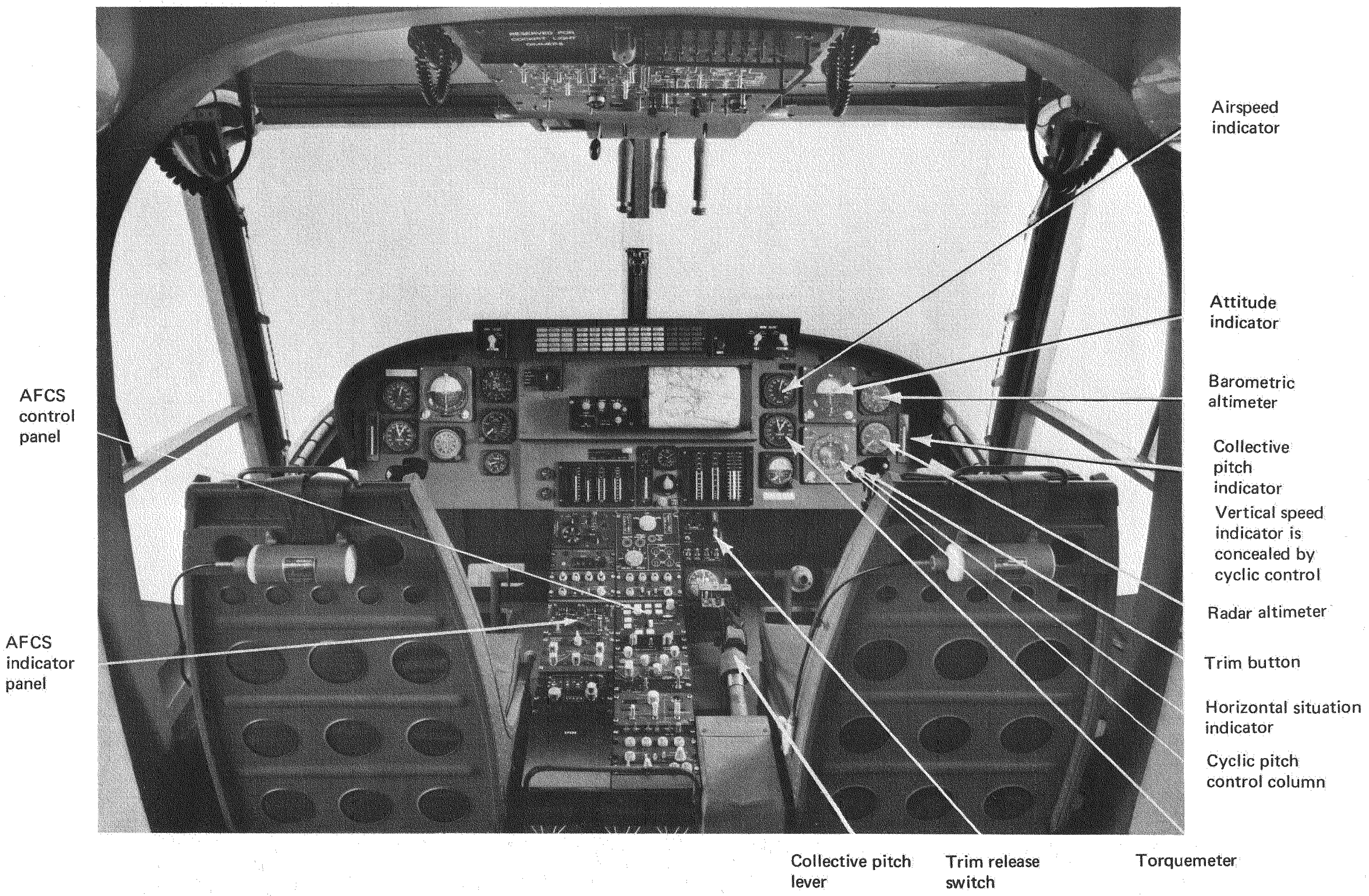
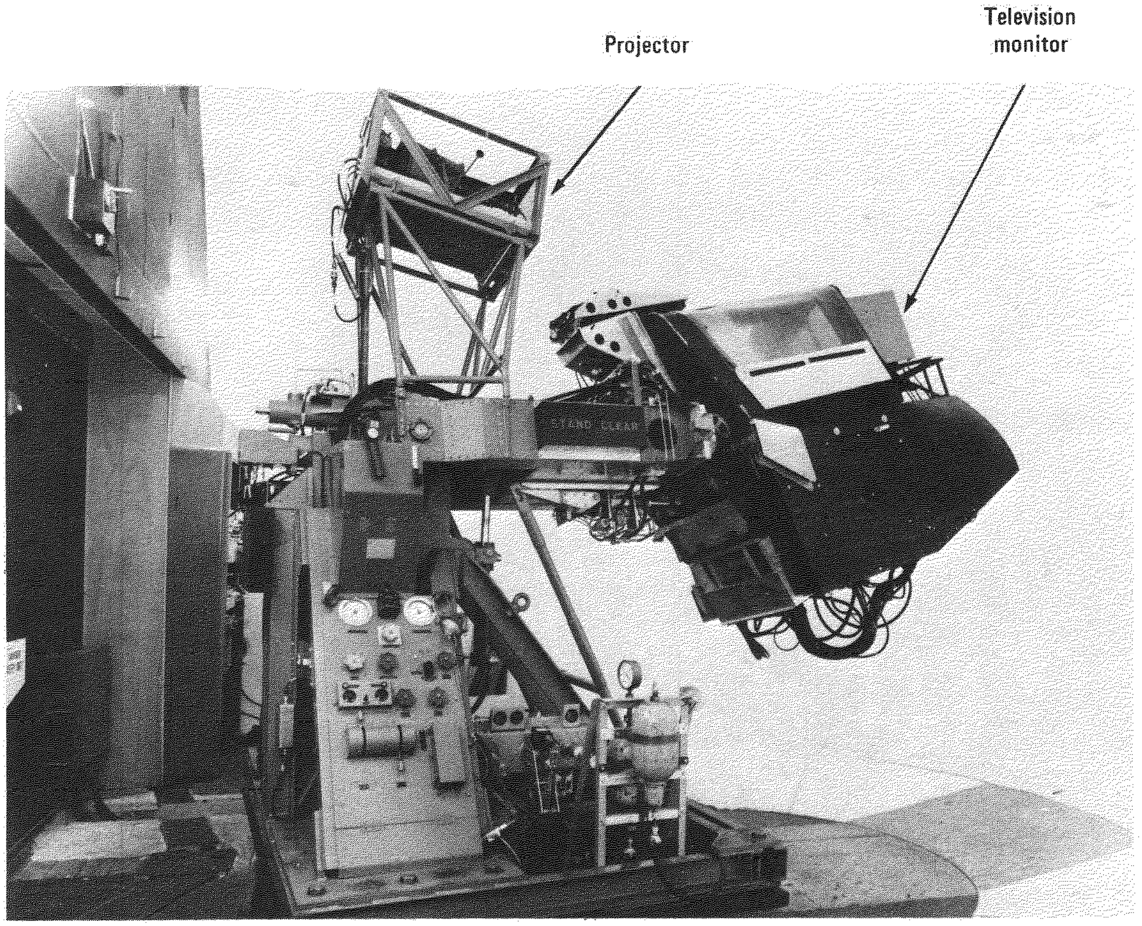


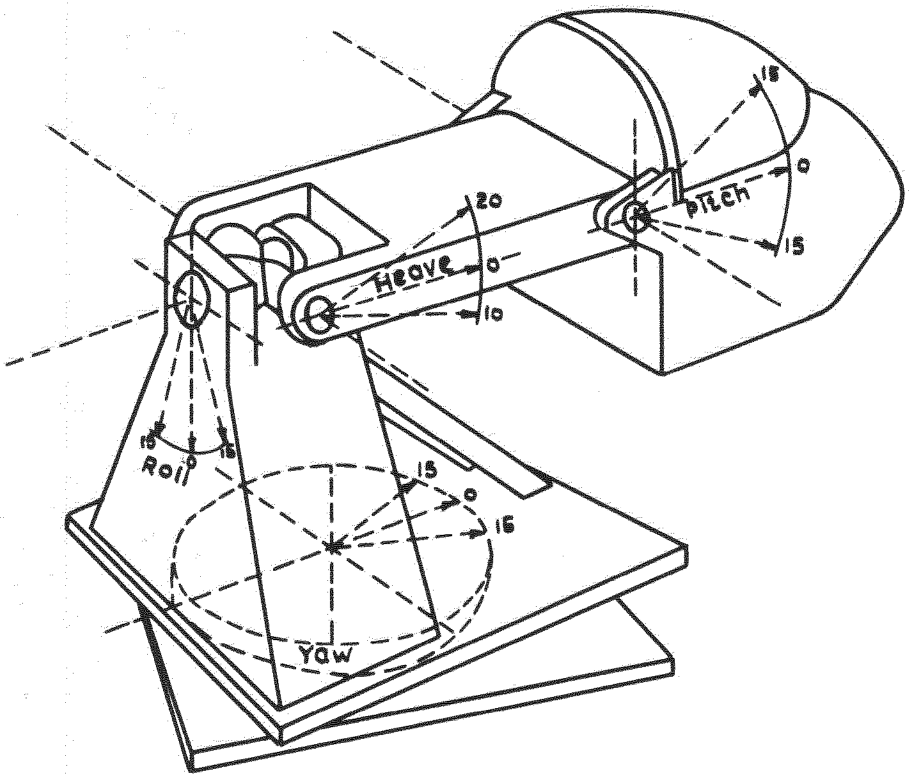
**Fig.4b Cockpit interior – Lynx (utility version)**

Fig.5 View of television display

Fig.6 Shadow horizon display



a Cockpit with TV monitor



b Motion travel available

Fig.7 a & b Cockpit and motion system

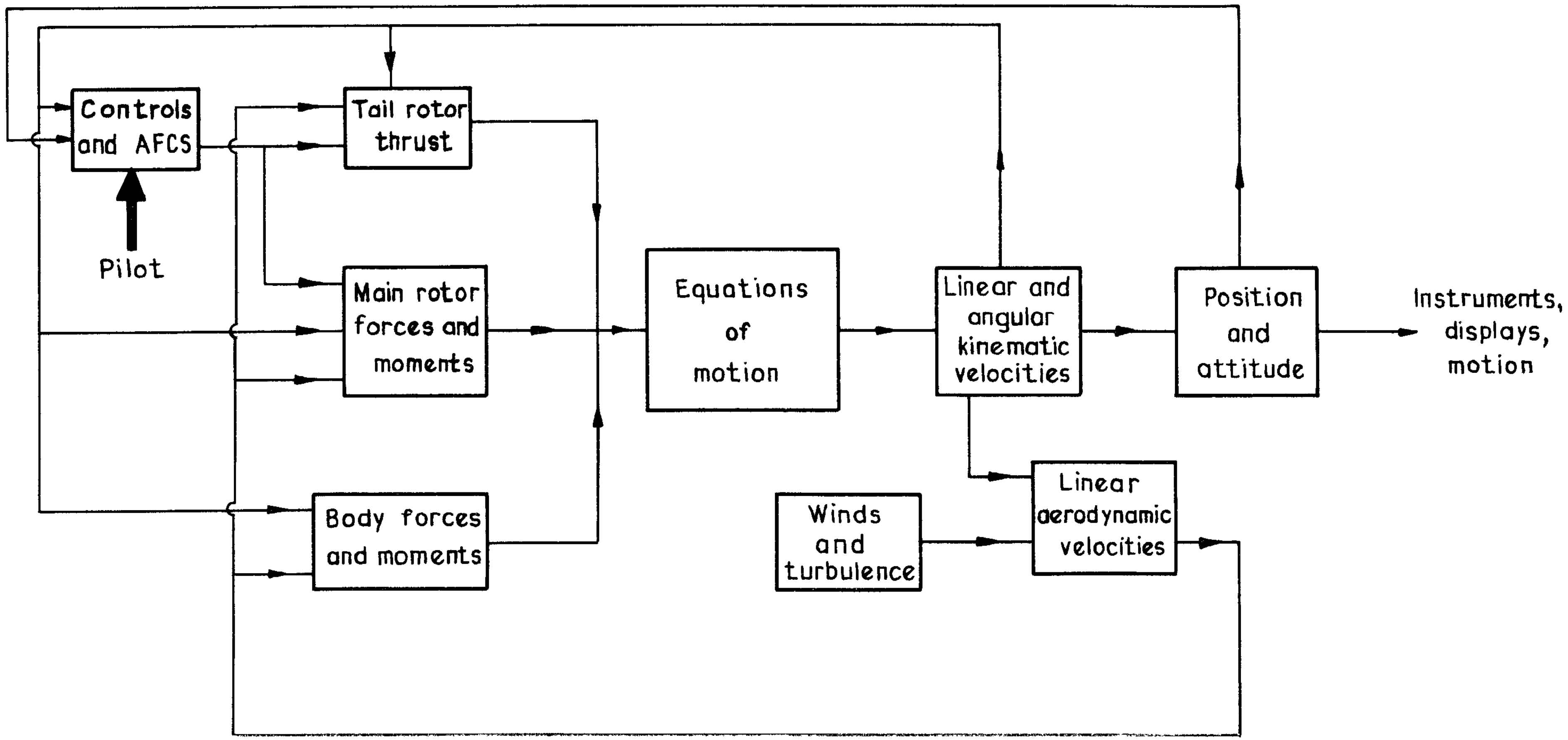


Fig. 8 Block diagram of computation

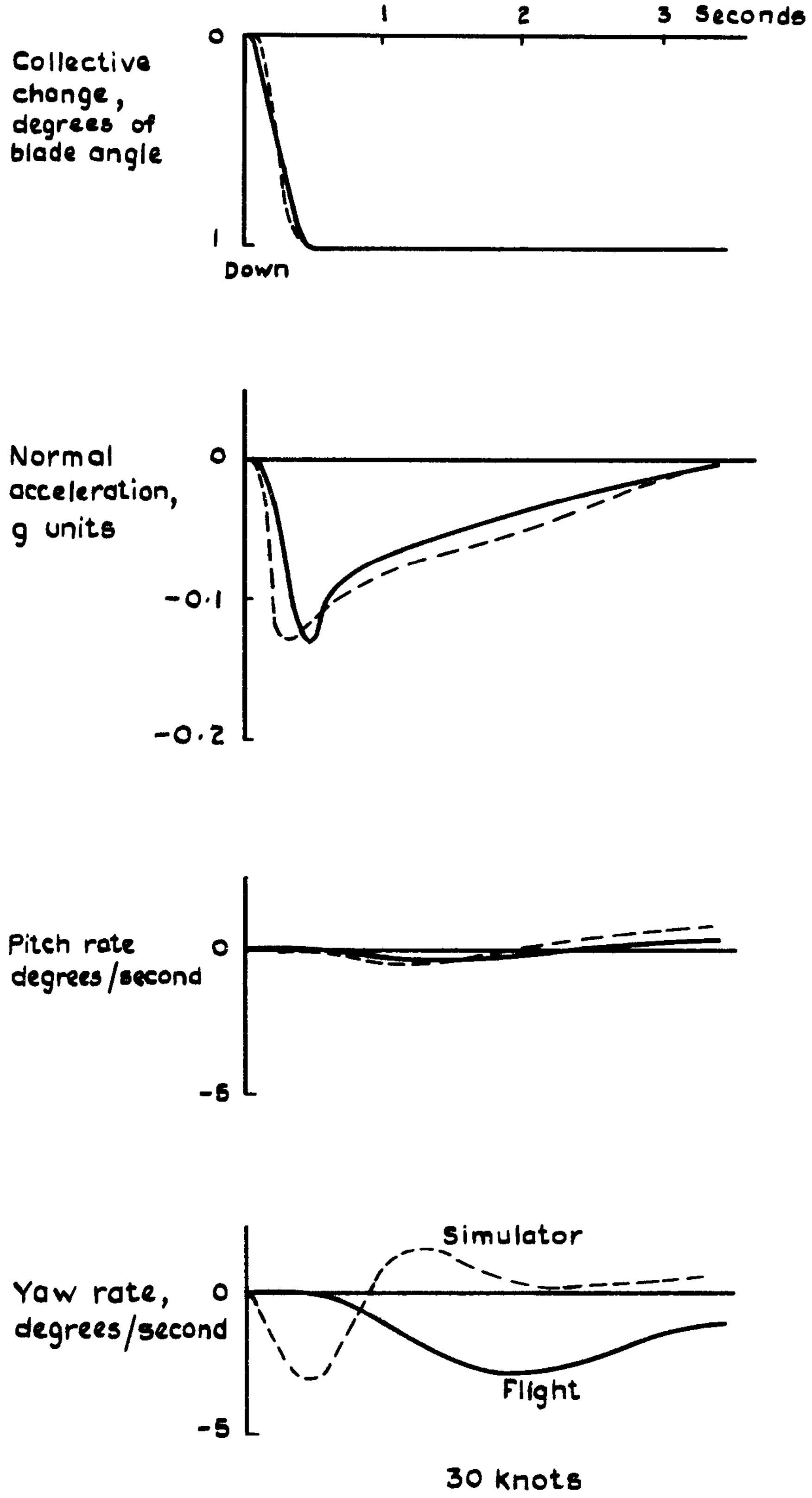


Fig.9 Wessex simulation – response to collective step in flight and simulator

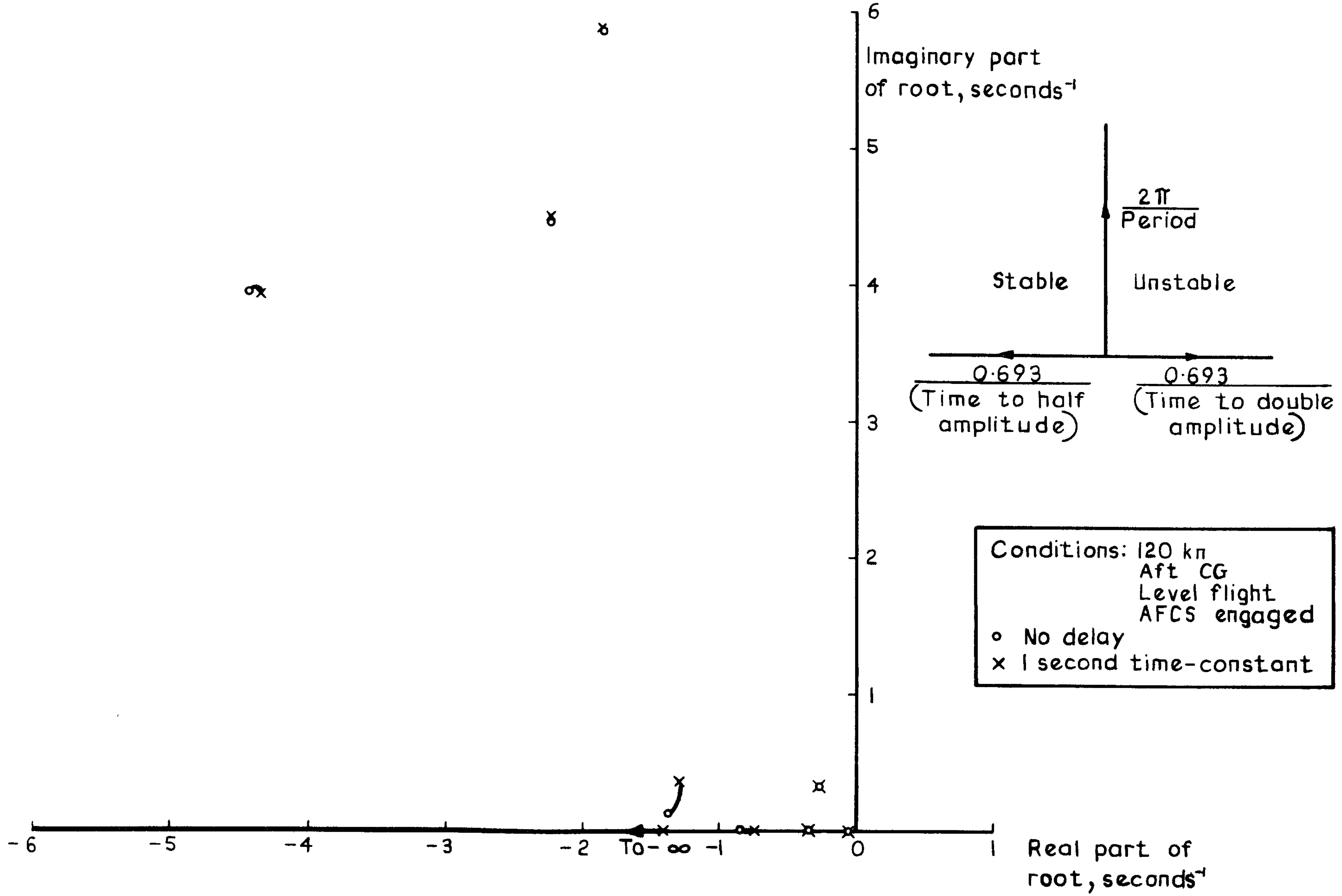


Fig.10a Effect of torque time delay on stability roots — level flight

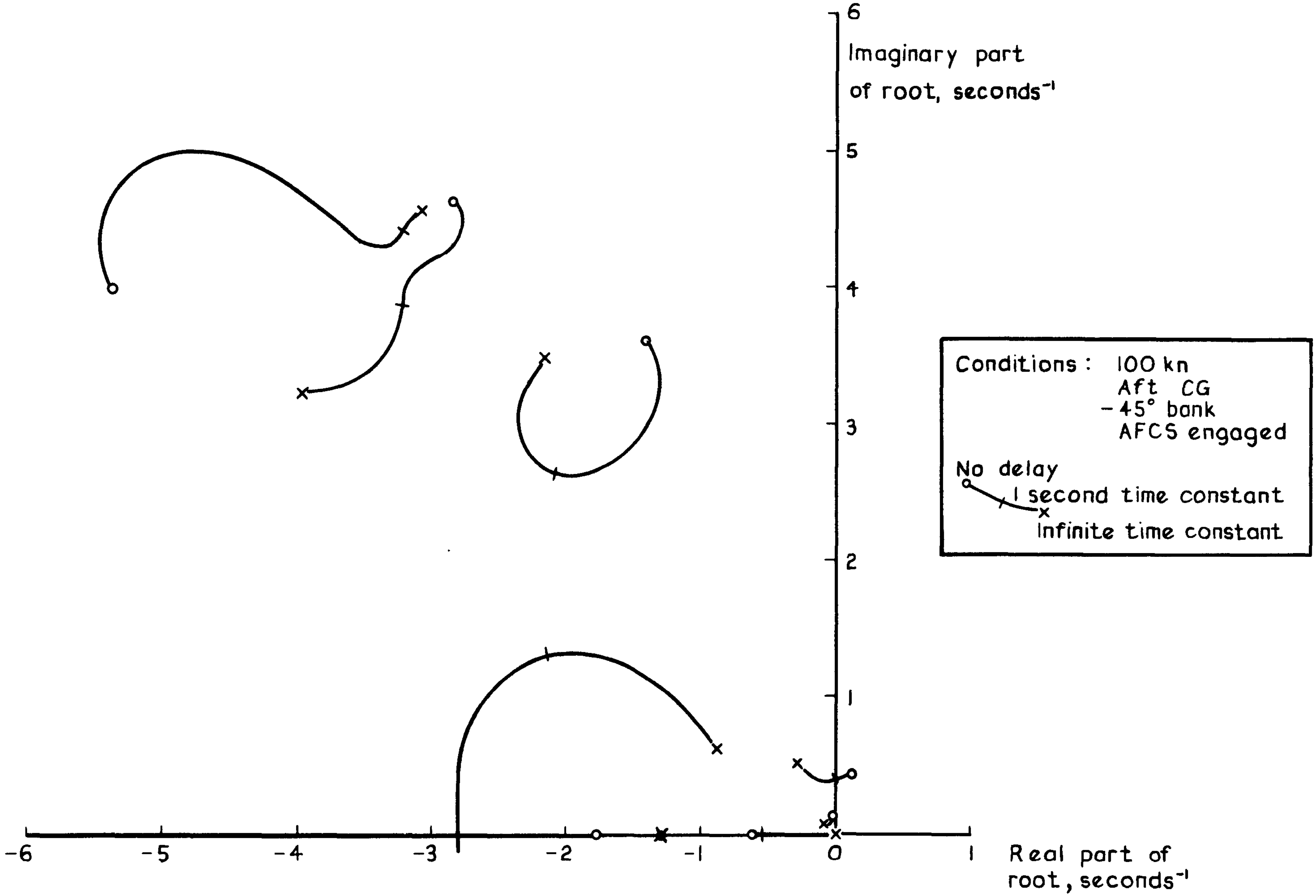


Fig. 10b Effect of torque time-delay on stability roots – left turn with 45° bank

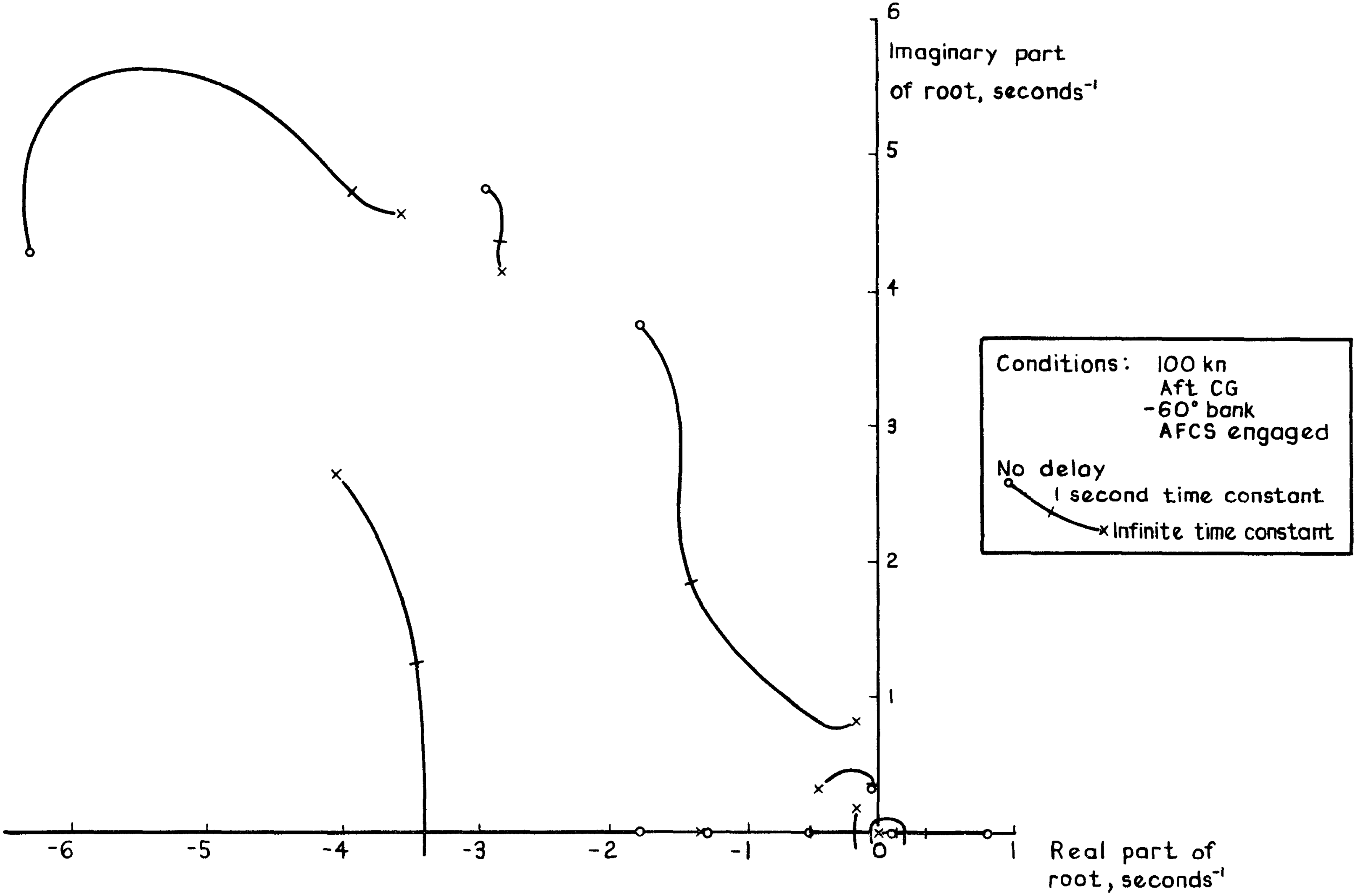
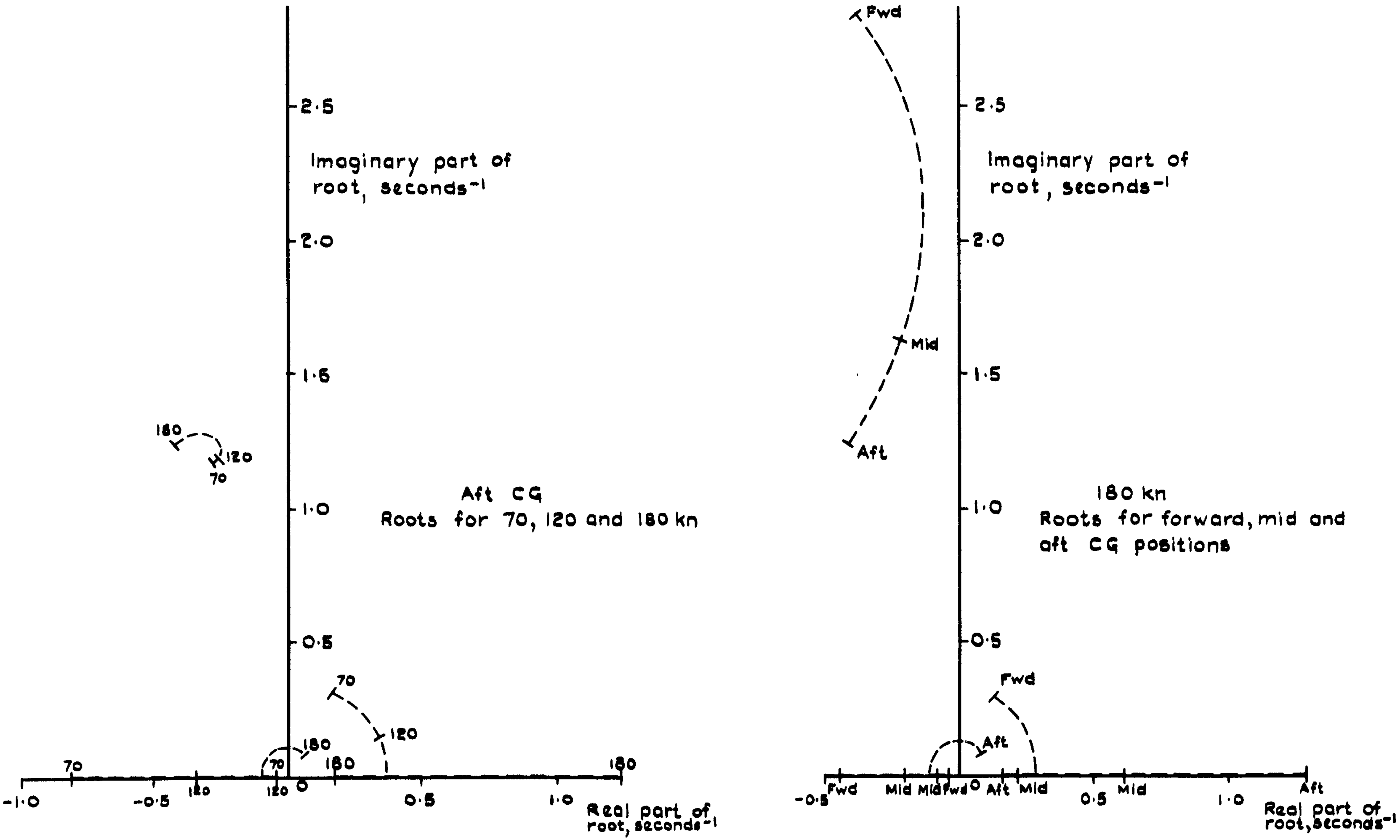


Fig.10c Effect of torque time-delay on stability roots–left turn with 60° bank



a Effect of forward speed on roots

b Effect of CG on roots

Fig. 11a&b Stability roots of the unstabilised helicopter

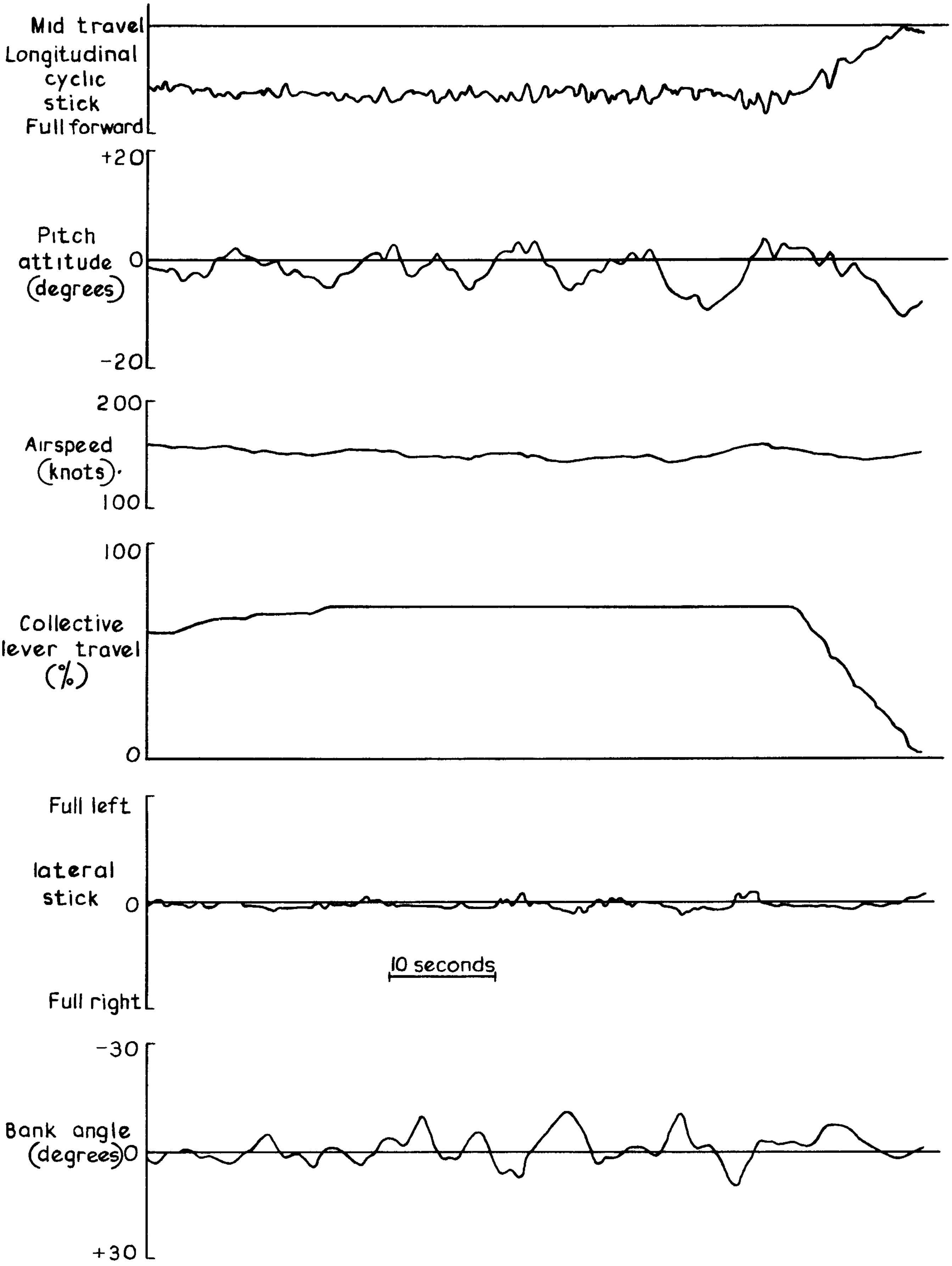


Fig.12a Pitch control in unstabilised fight – calm, aft CG

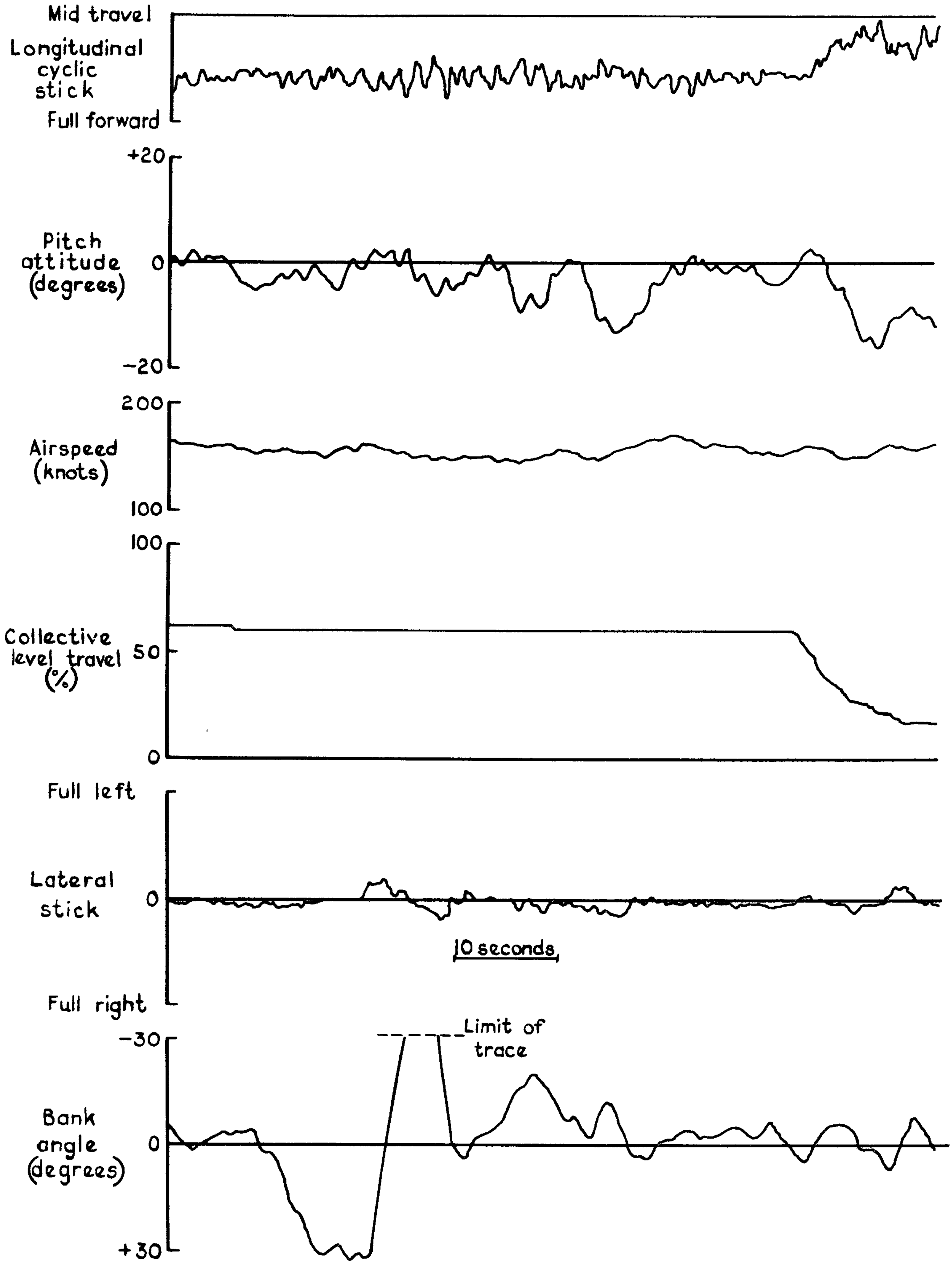


Fig. 12b Pitch control in unstabilised flight – turbulence, aft CG

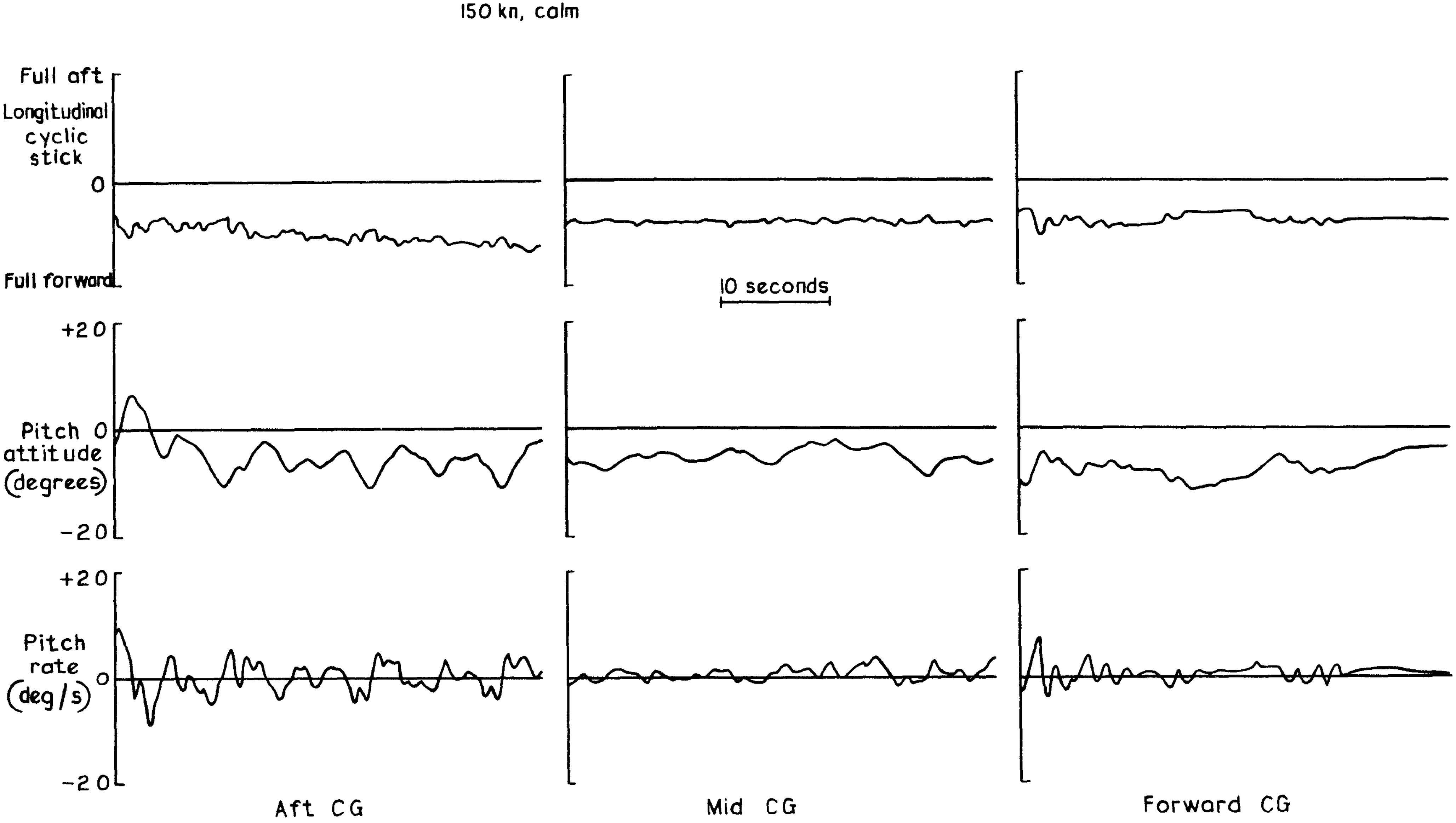


Fig.12c Pitch control in unstabilised flight – effect of CG position

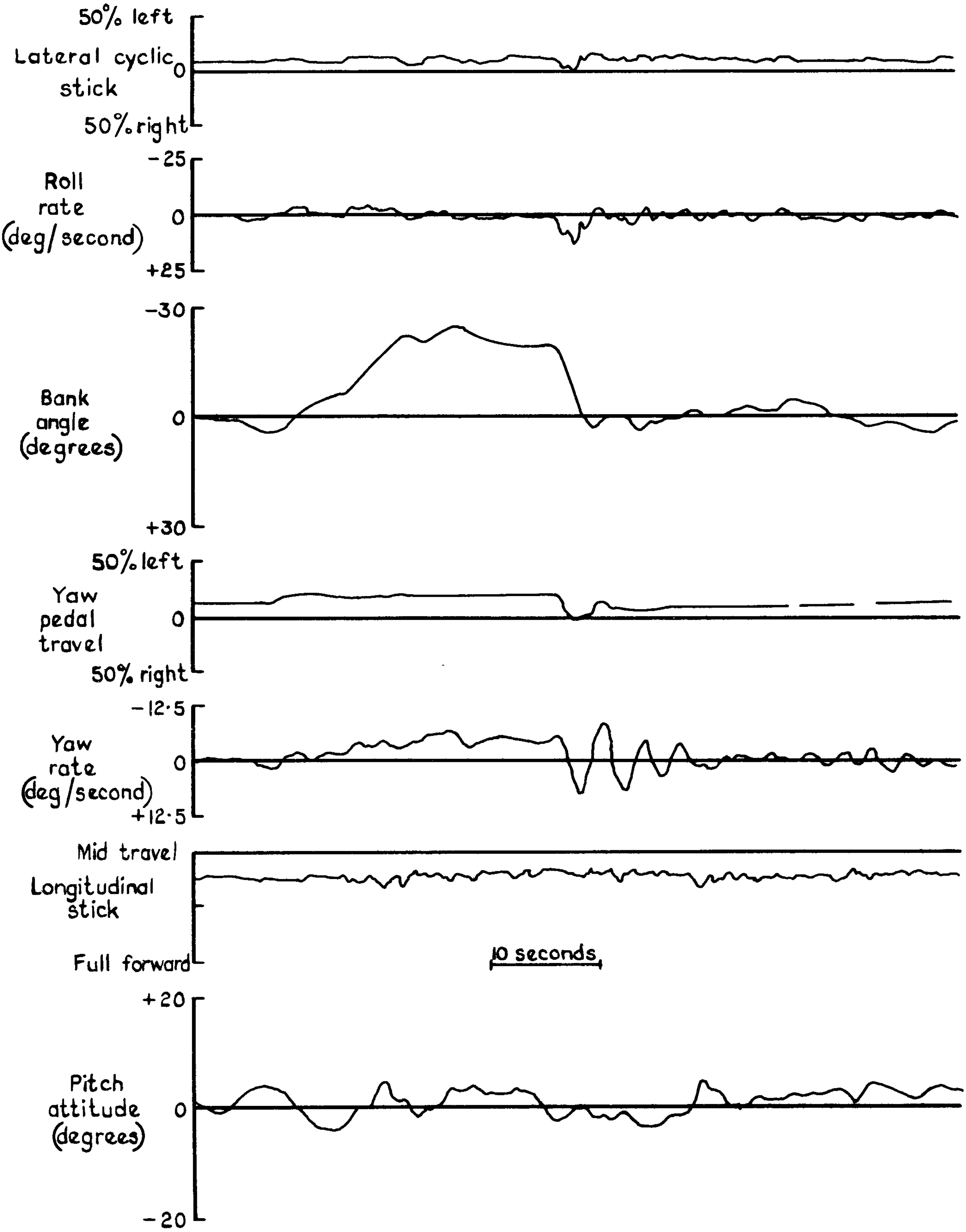


Fig. 13a Roll control of the unstabilised helicopter-80kn

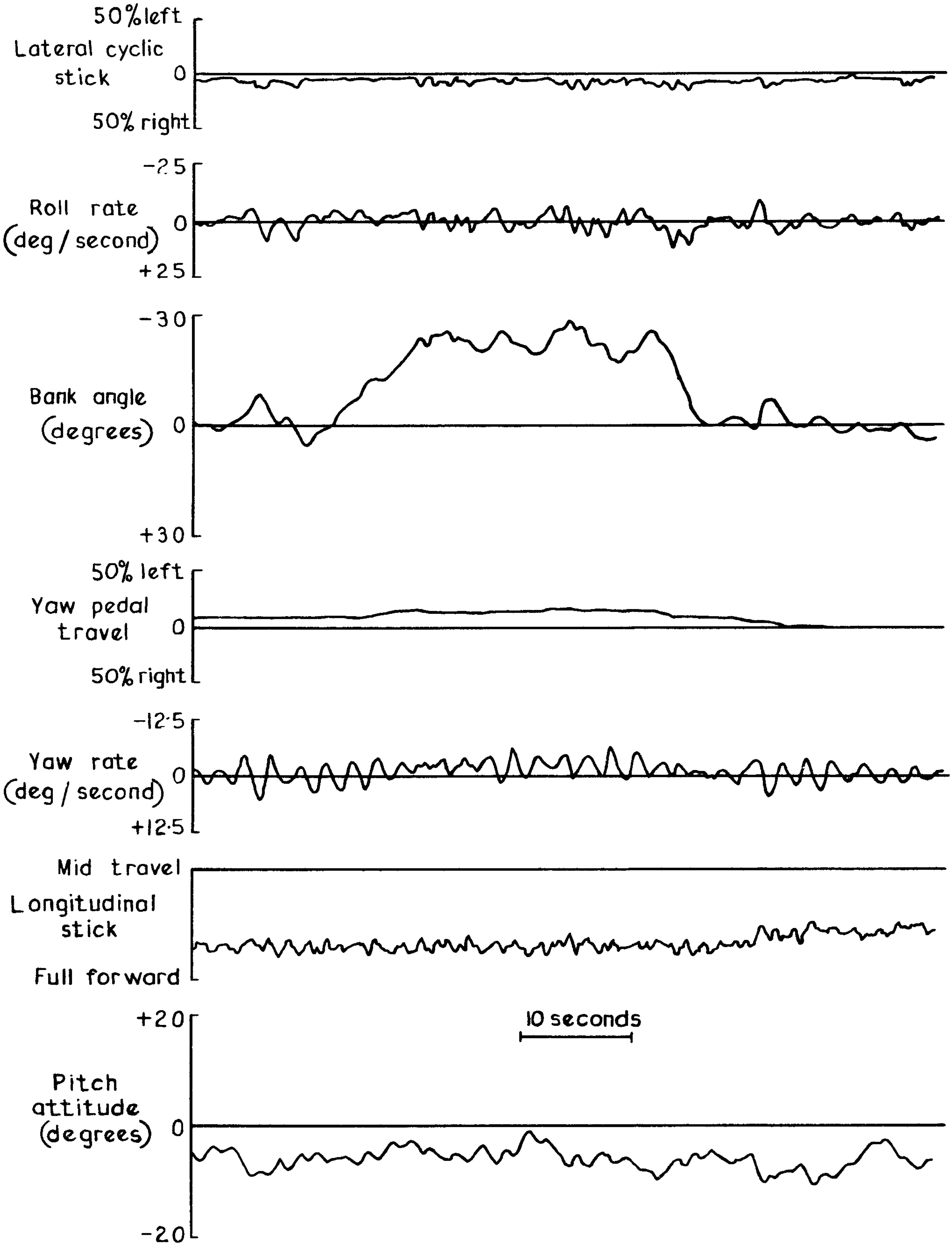


Fig. 13b Roll control of the unstabilised helicopter −180 kn

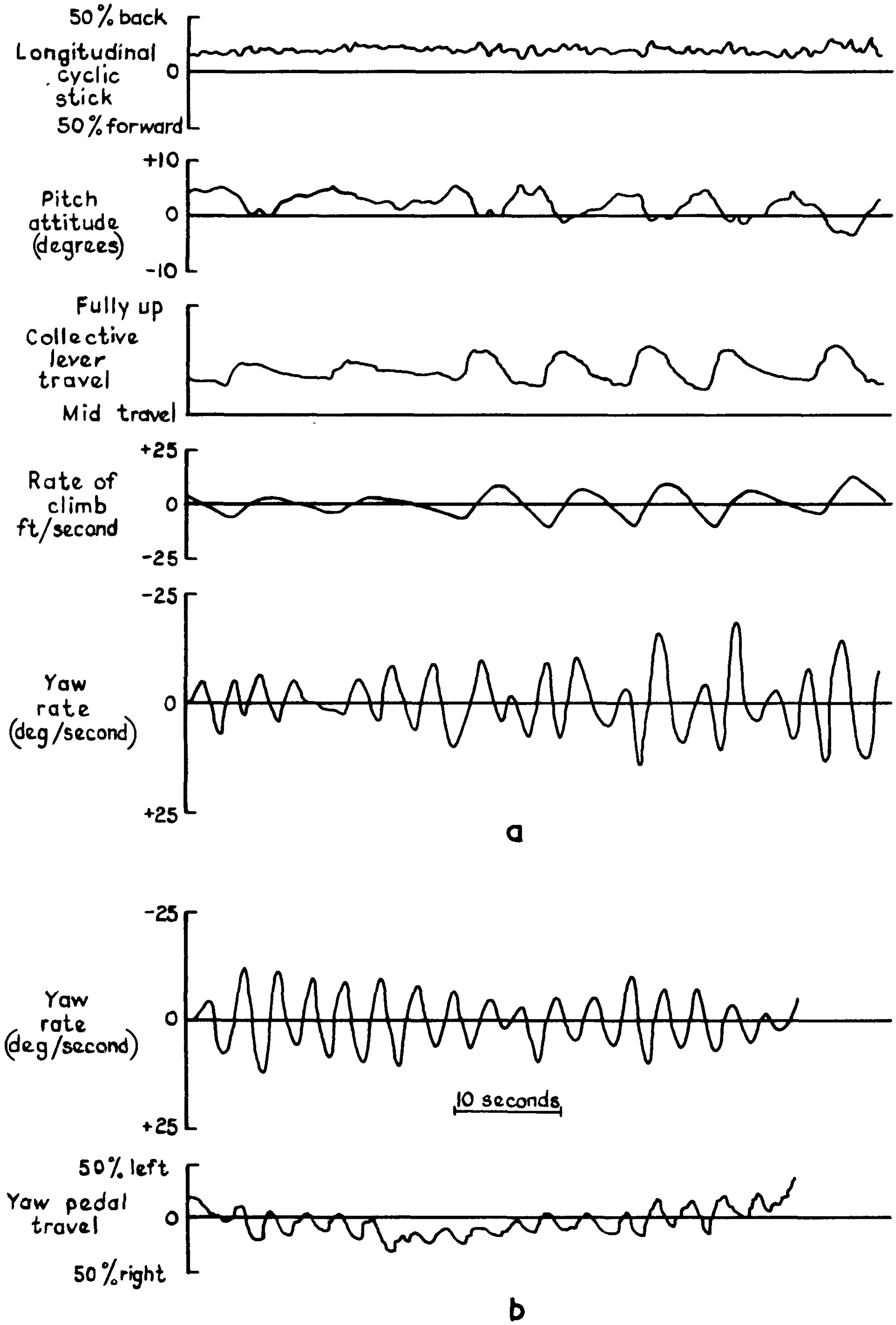


Fig. 14 a & b Height and yaw control at the hover-aft CG unstabilised

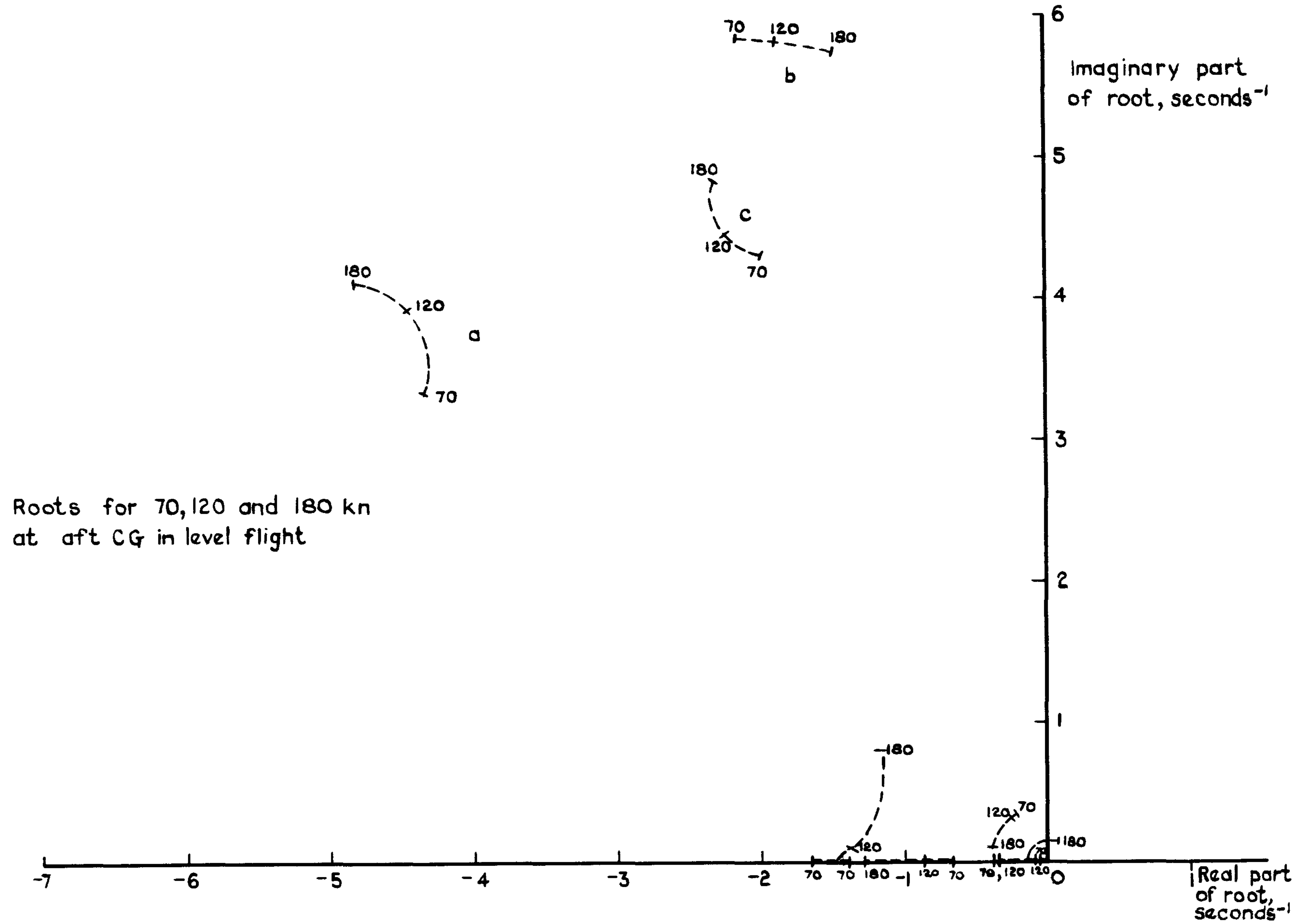
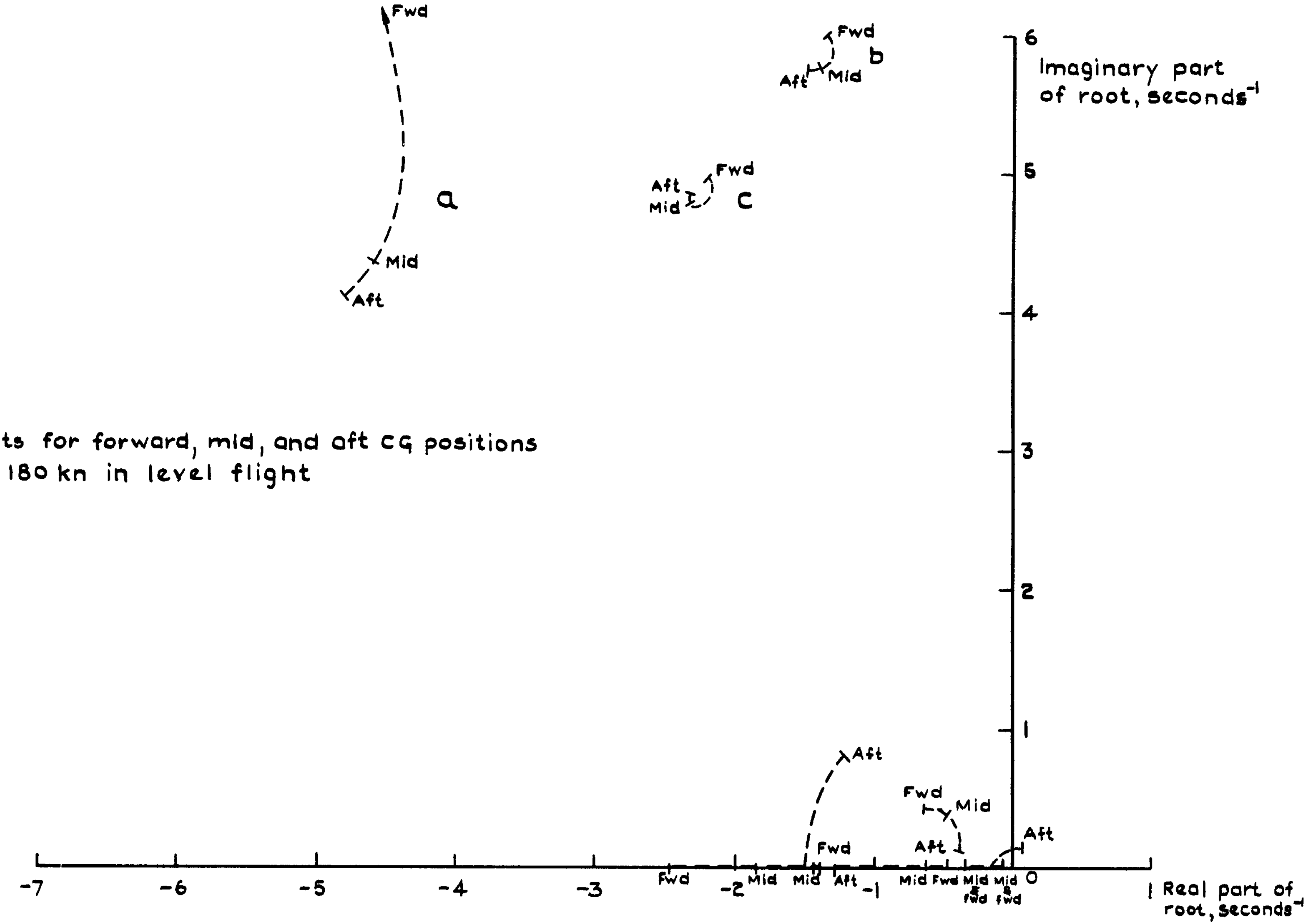


Fig. 15a Stability roots of the stabilised helicopter - effect of forward speed



Roots for forward, mid, and aft CG positions at 180 kn in level flight

Fig. 15b Stabitility roots of the stabilised helicopter-effect of CG position

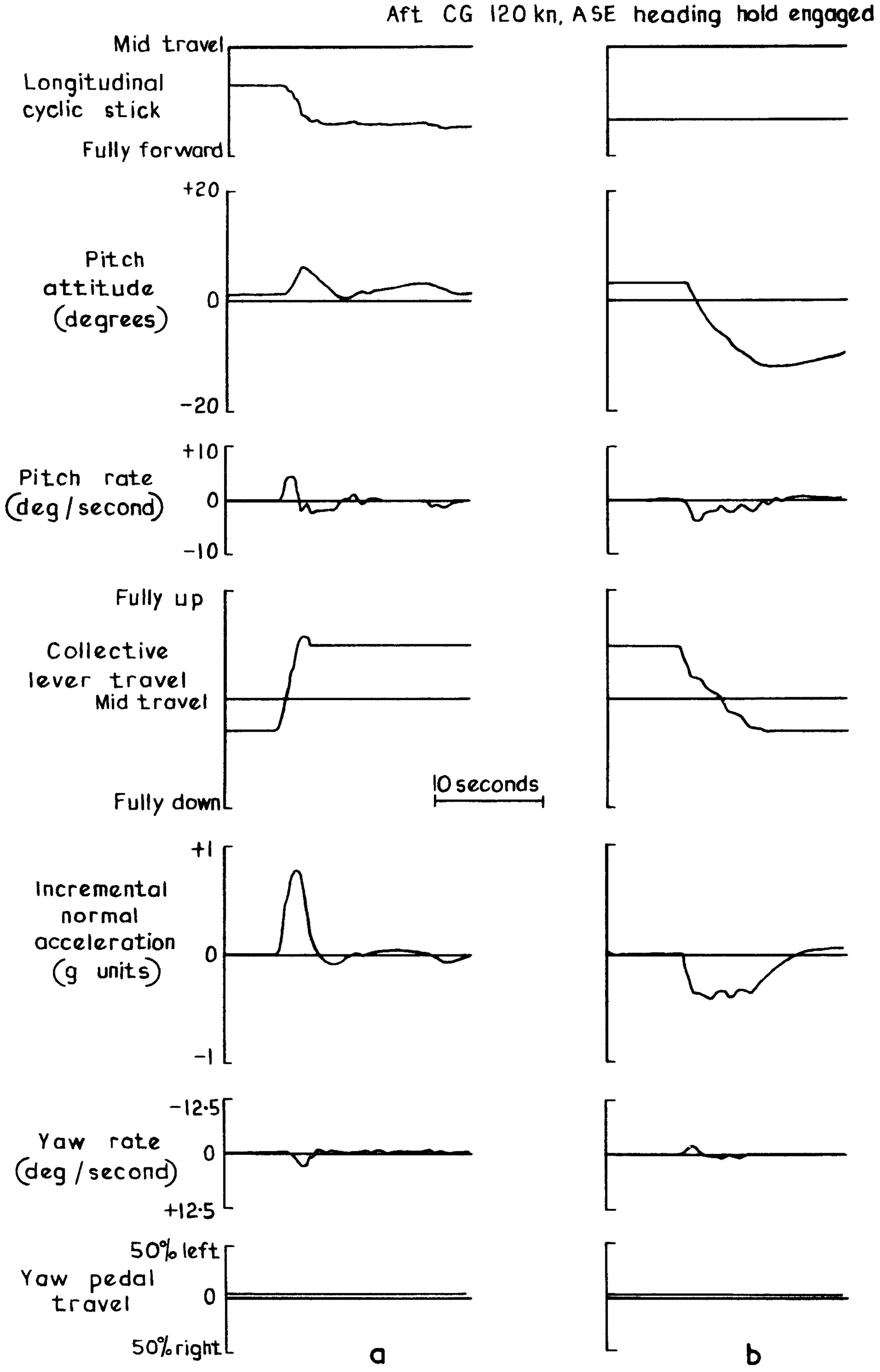
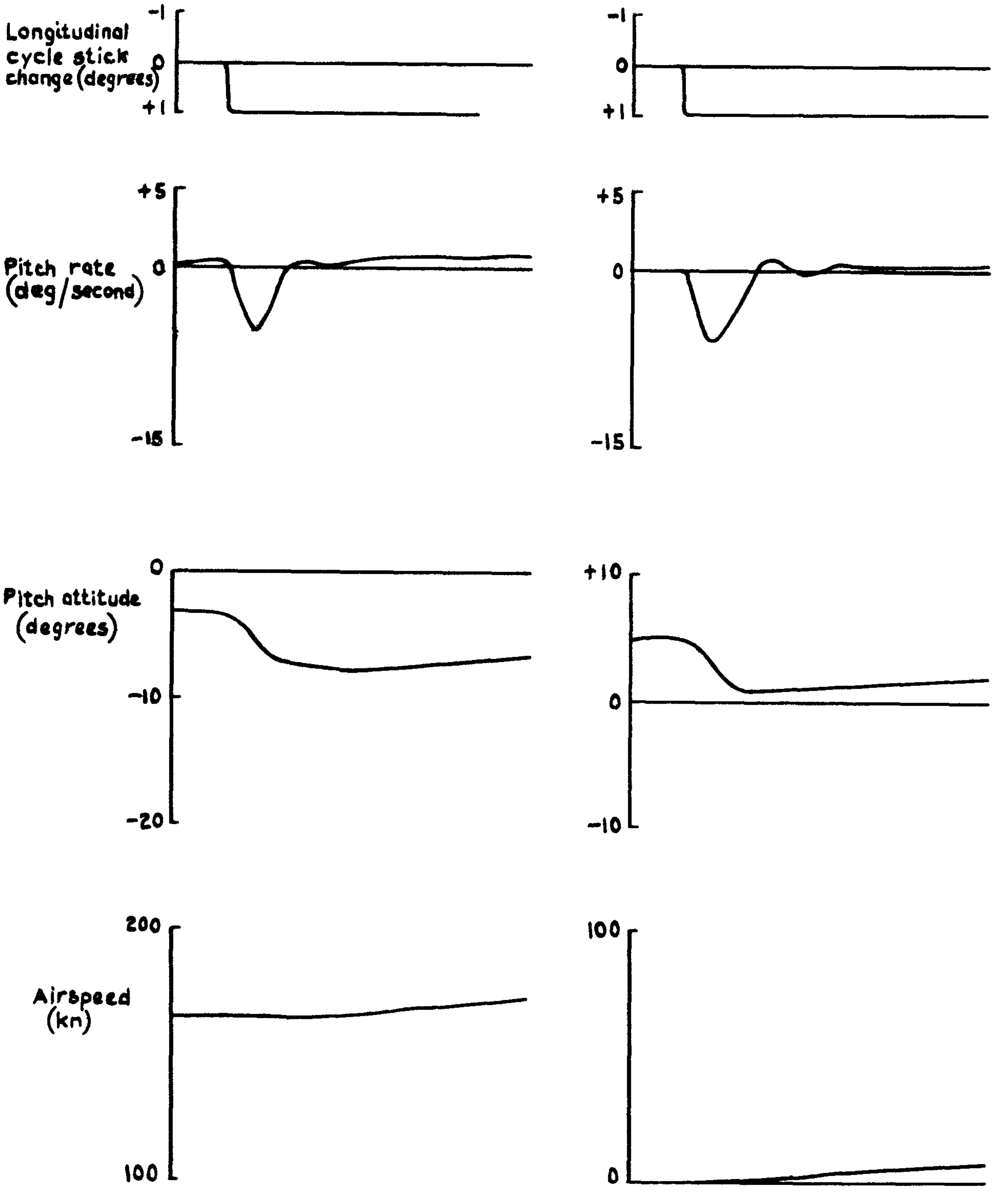


Fig. 16a&b Collective lever inputs – stabilised helicopter



Aft CG

Fig. 17a & b Stabilised pitch response

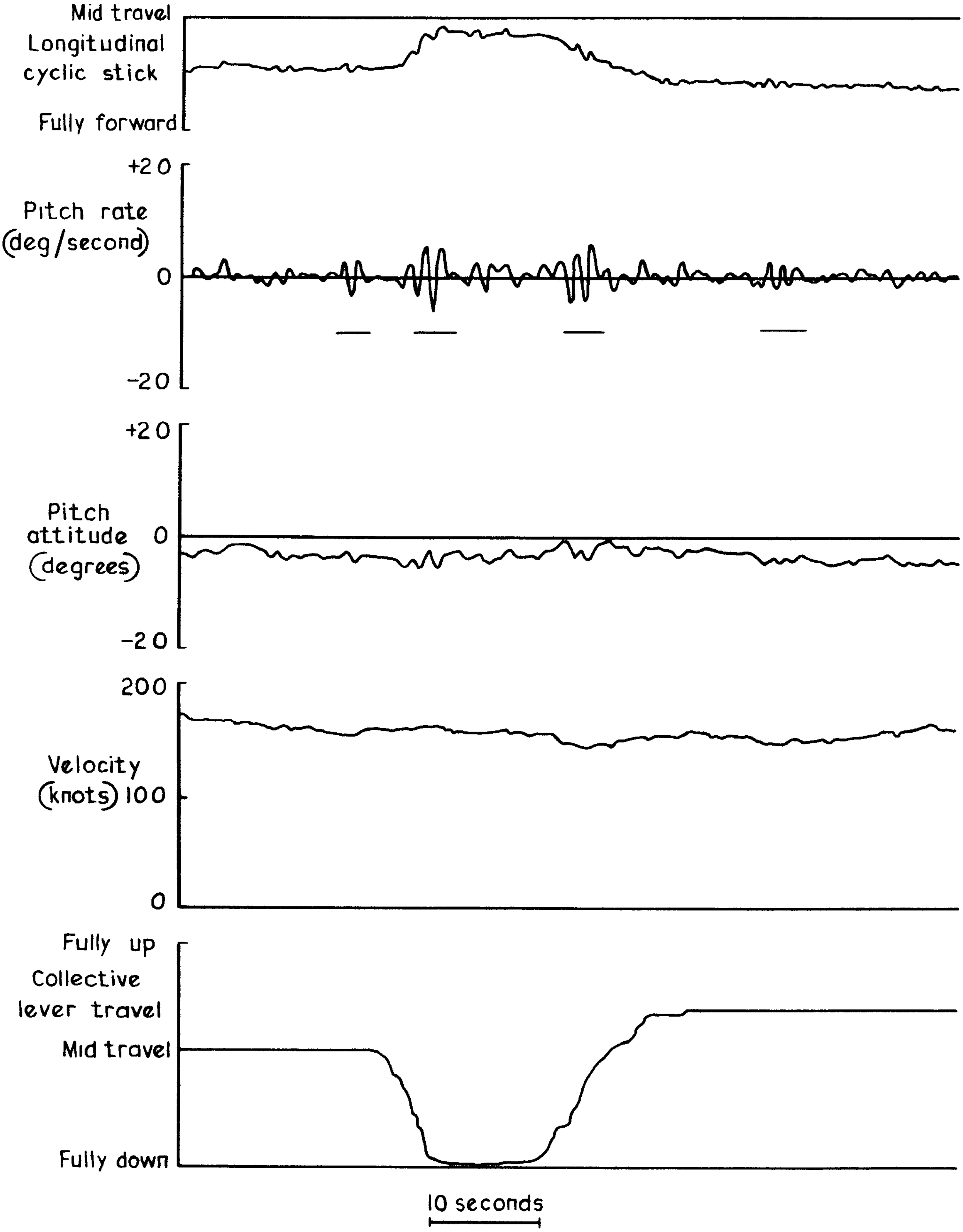
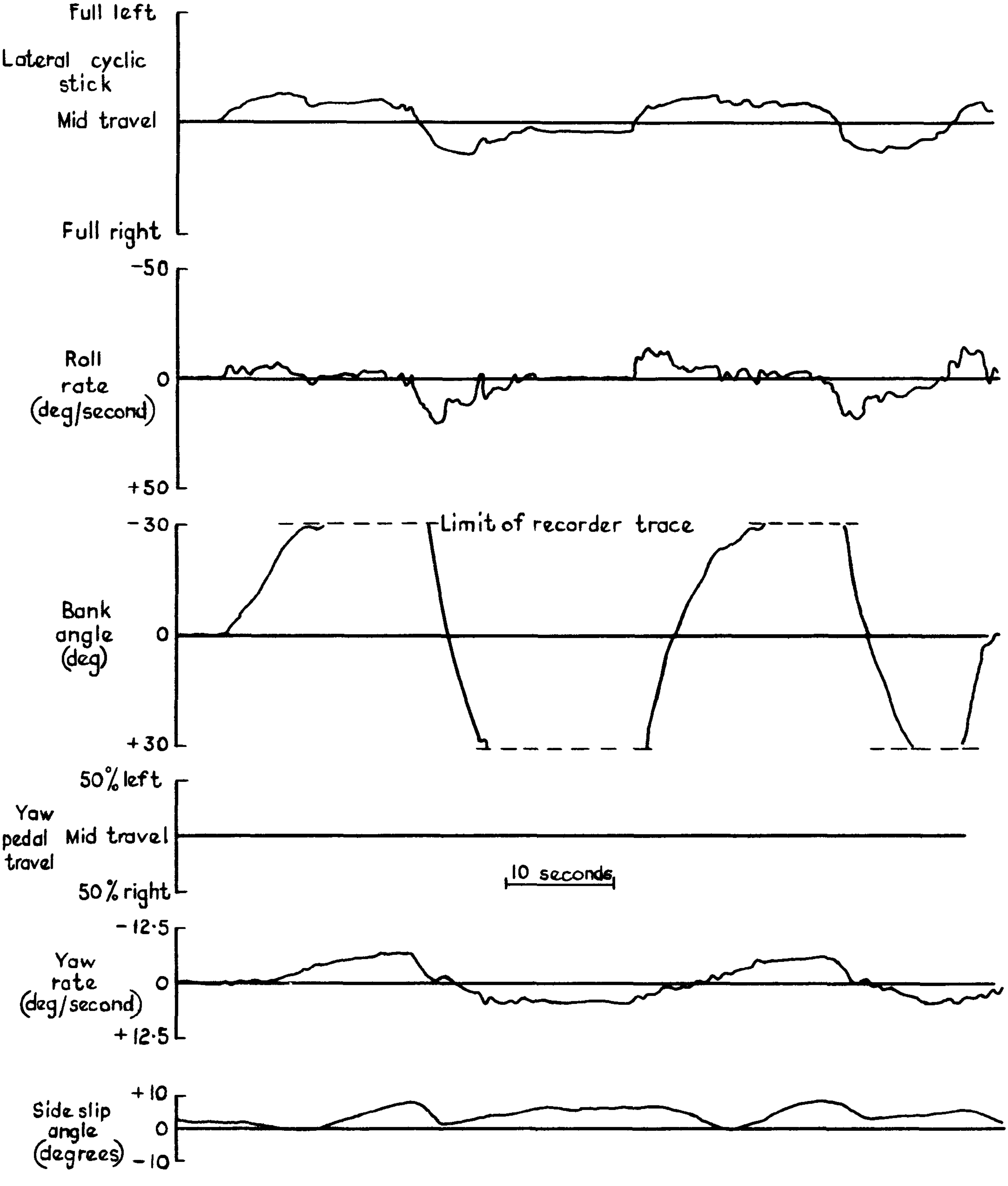
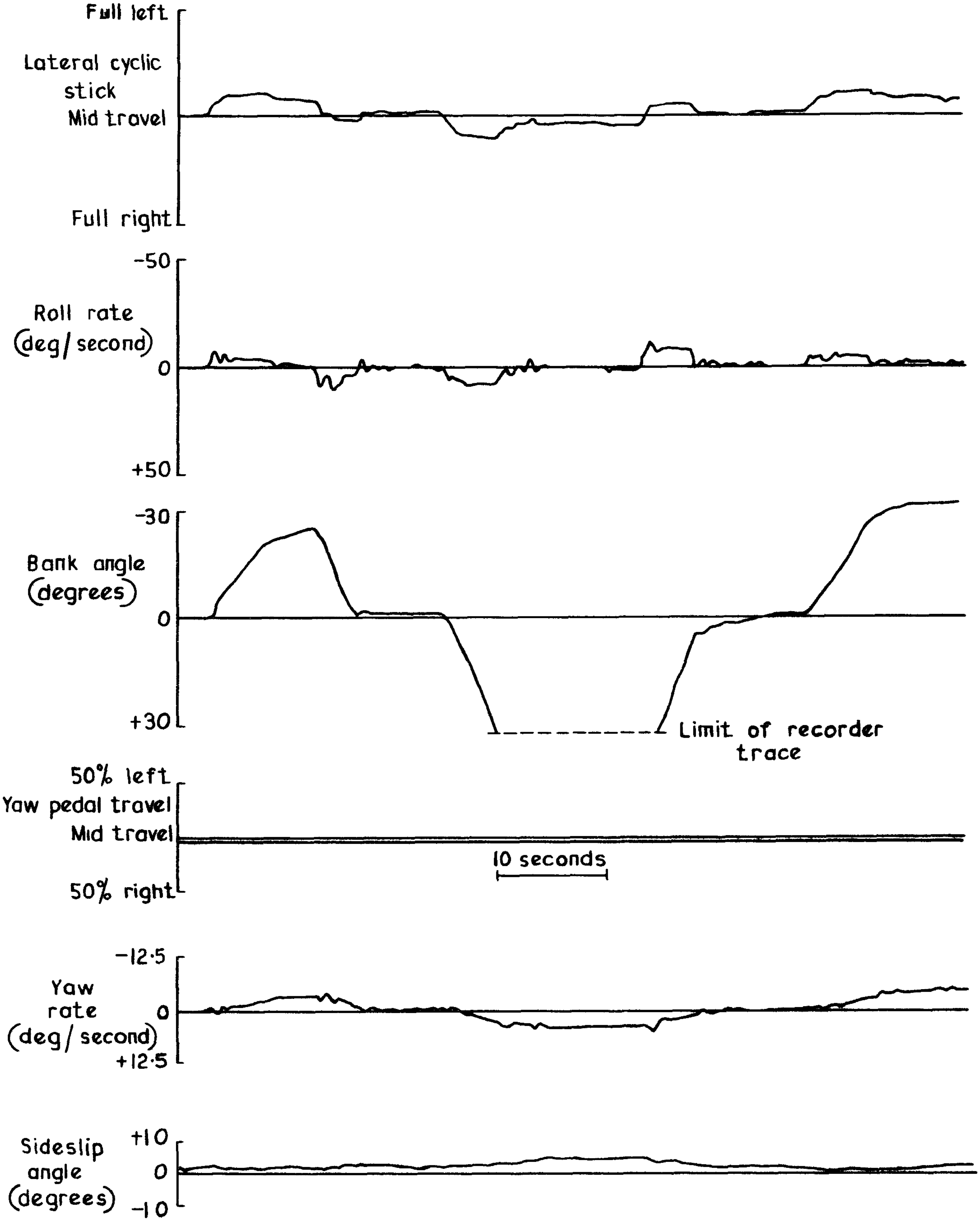


Fig.18 PIO tendency during aiming task



Aft CG, 150 kn, body and fin terms included

Fig. 19a Turn reversals, stabilised helicopter without lateral accelerometer



Aft CG 150 kn, body and fin terms included

Fig. 19 b Turn reversals, stabilised helicopter with lateral accelerometer

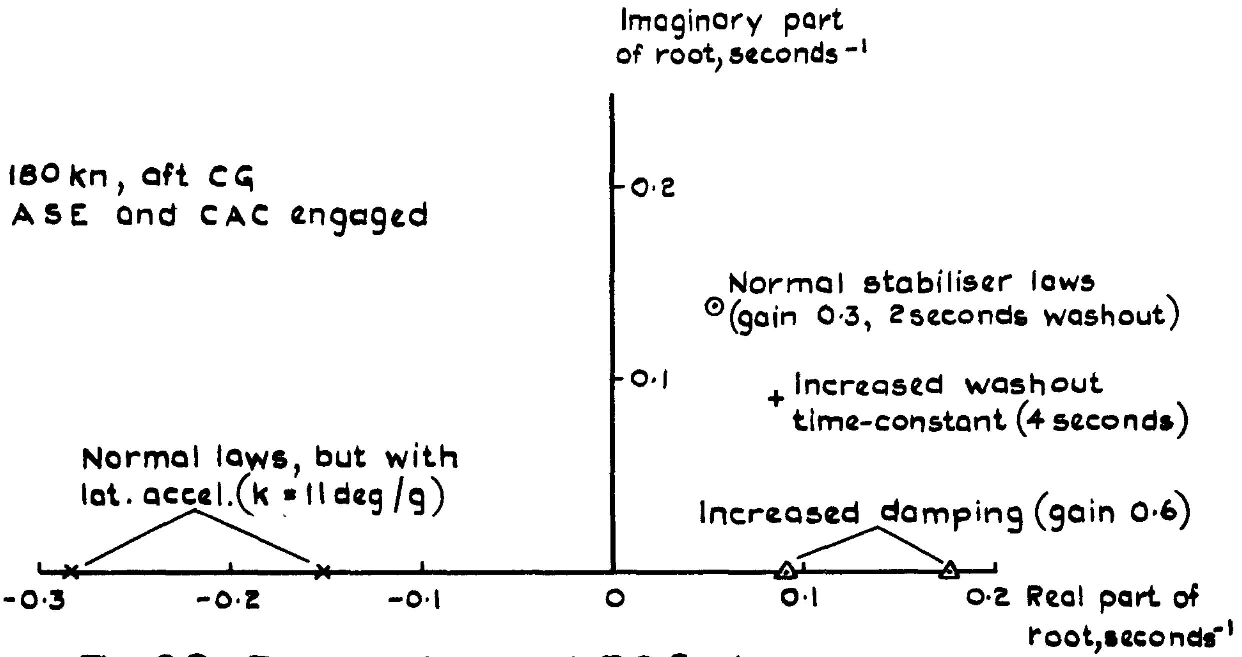


Fig. 20 Effect of yaw AFCS changes on unstable lateral root

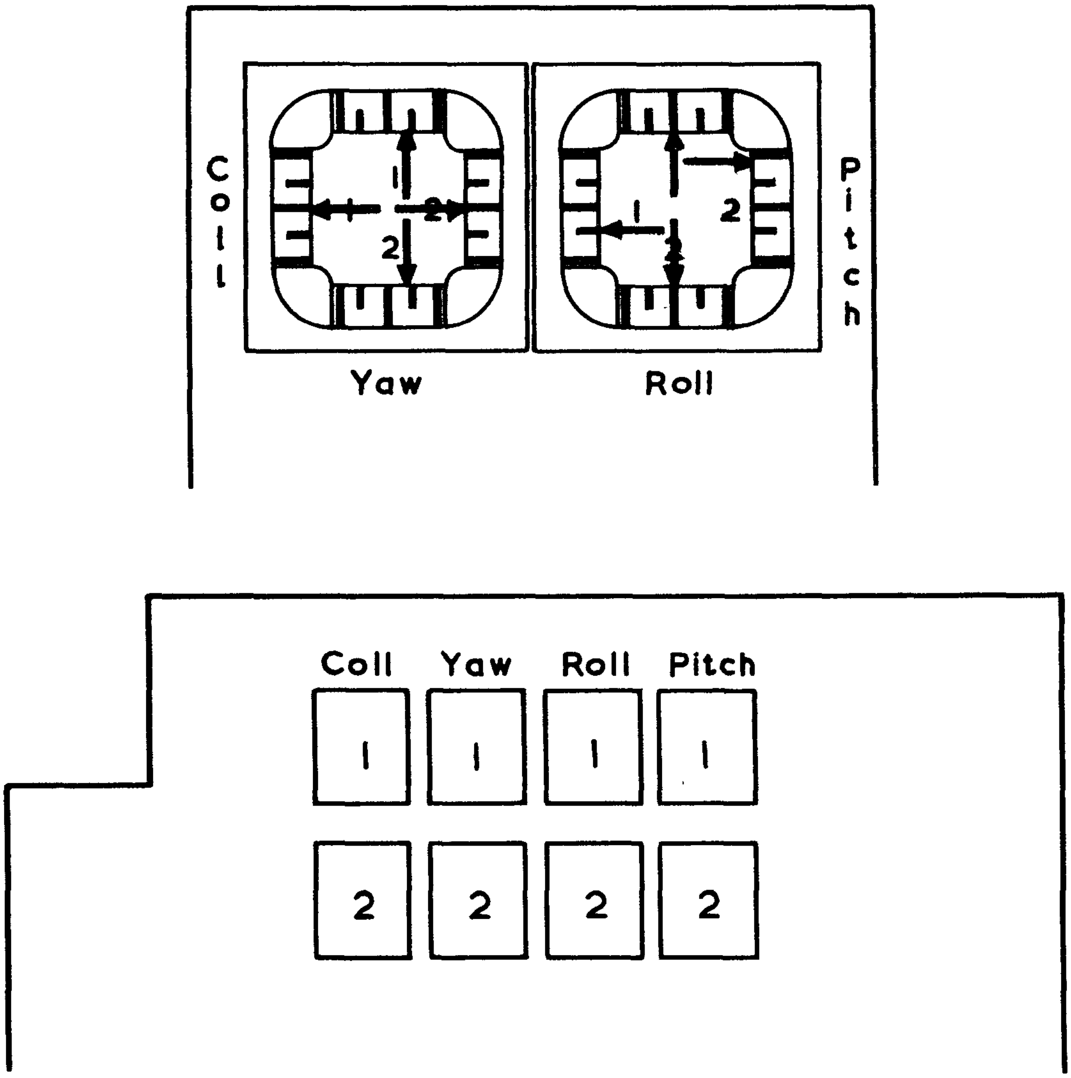
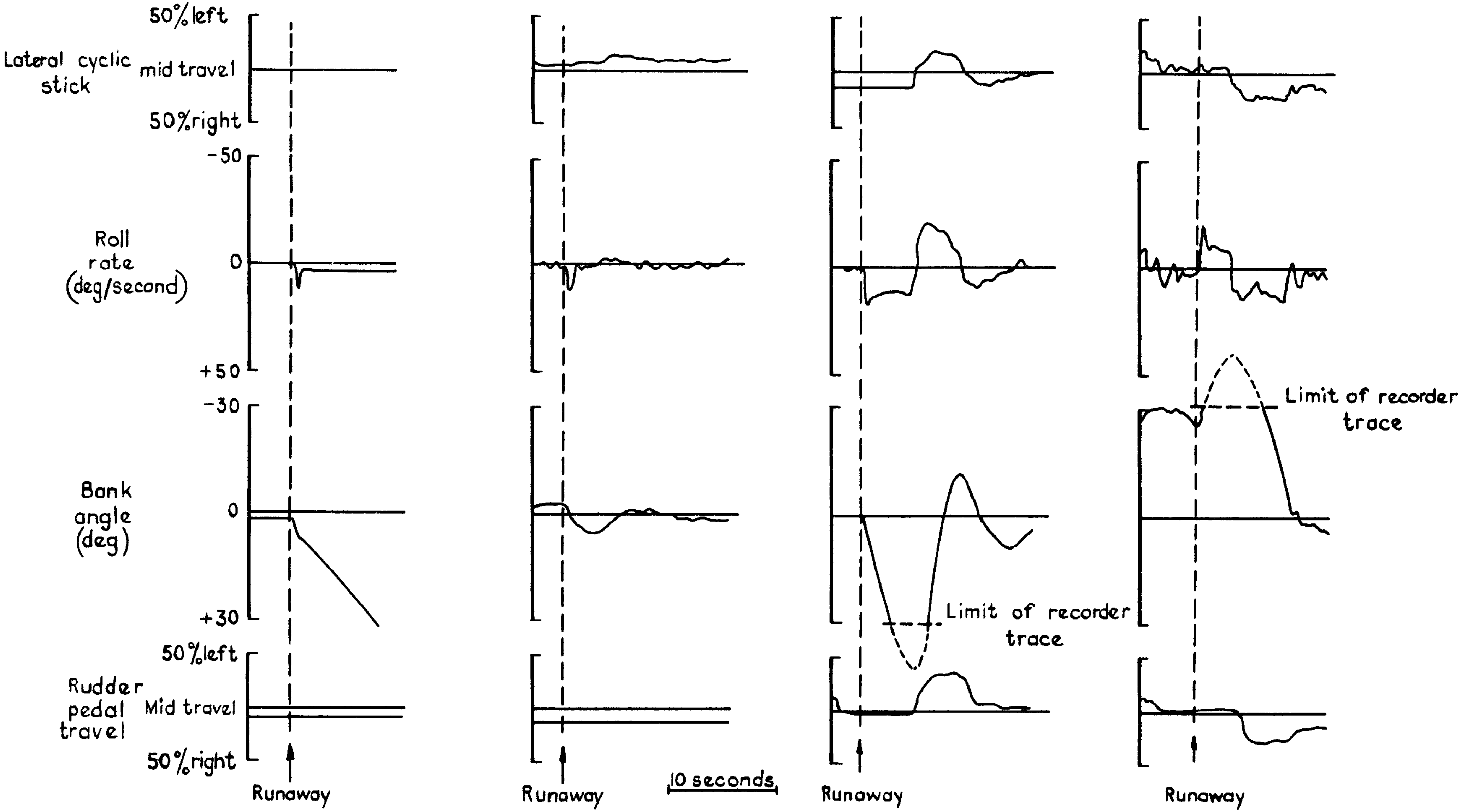


Fig. 21 ASE and CAC indicators and lane selectors



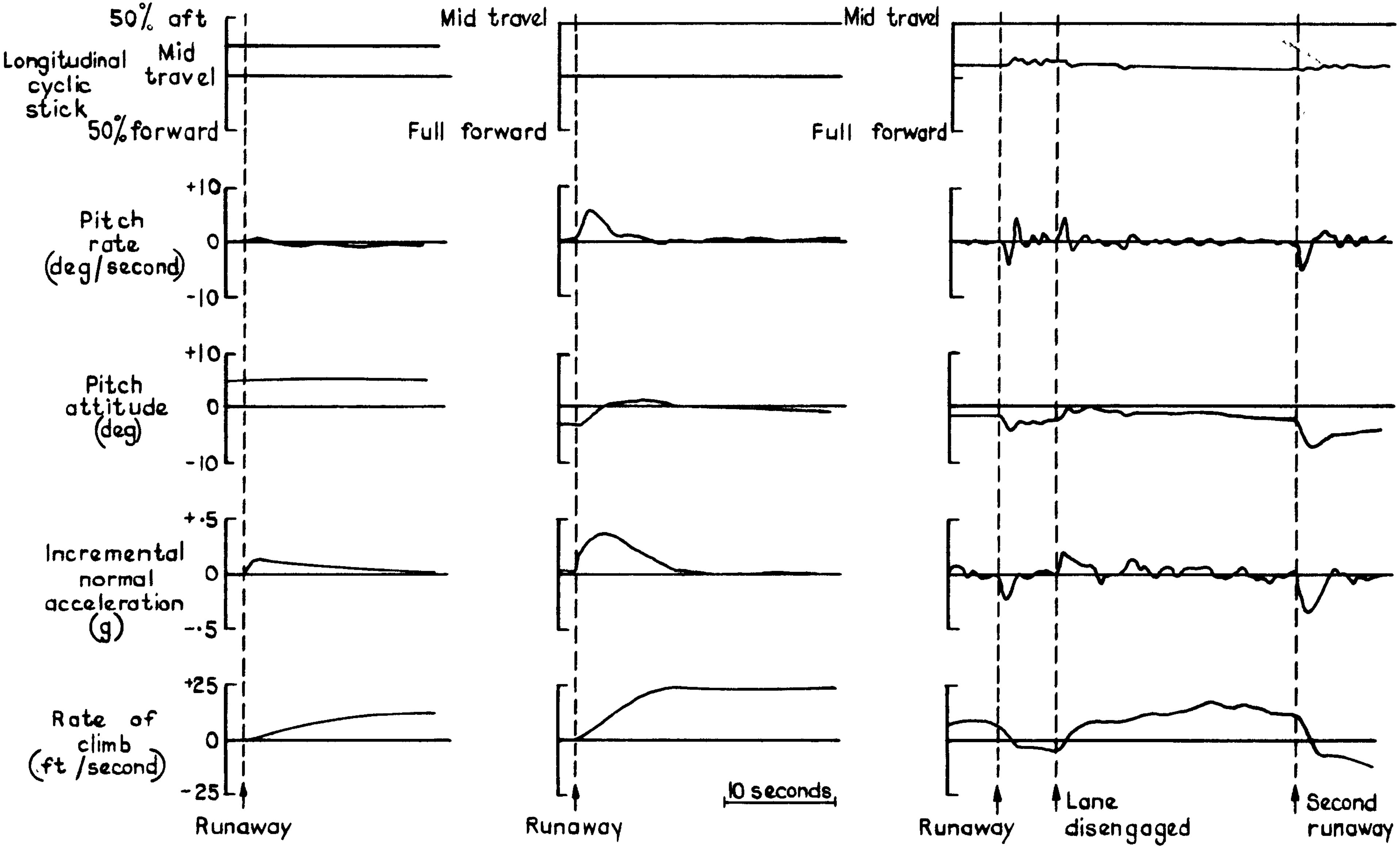
**a** Single lane runaway; no pilot intervention (160kn)

**b** Single lane runaway; pilot intervenes (120kn)

**c** Single lane runaway; lanes 50% off centre (160kn)

**d** Single lane runaway in turn (160kt)

Fig.22 ASE runaways – roll channel

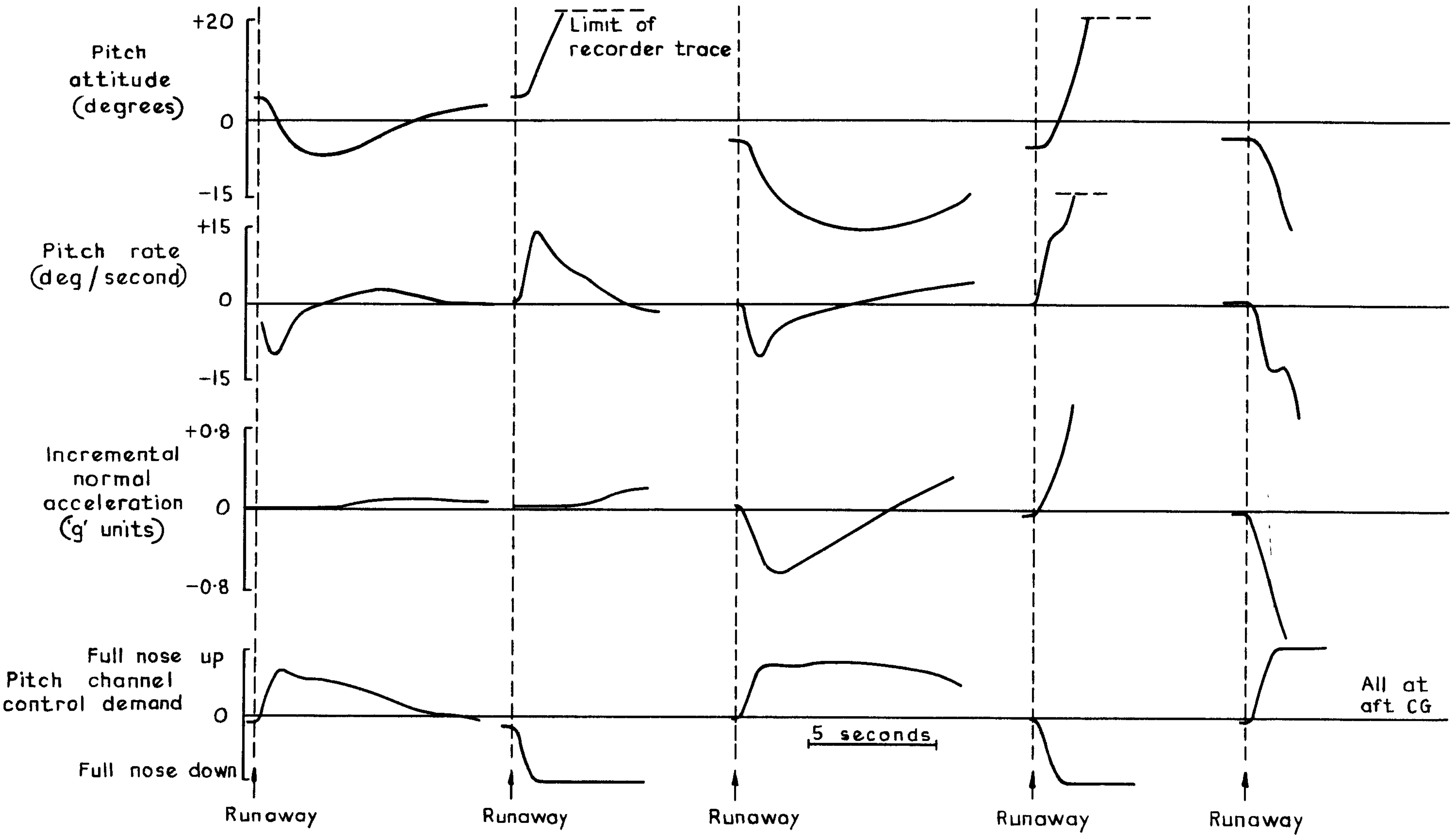


a Single lane runaway; no pilot intervention (hover)

b Single lane runaway; no pilot intervention (160kn)

c Multiple runaways with pilot intervention 140kn, turbulence

Fig. 23 CAC runaways



a Hover, nose down runaway

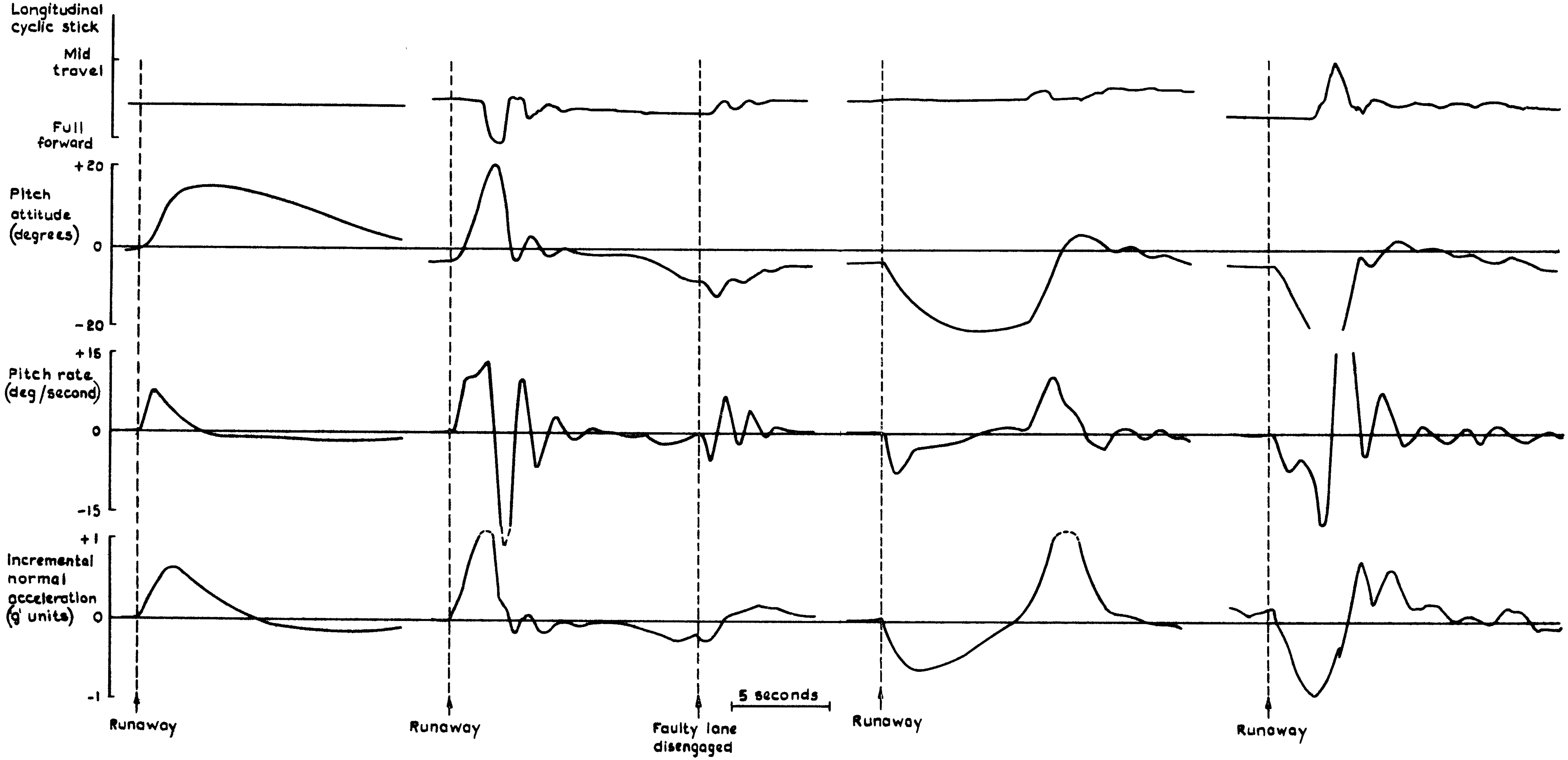
b Hover, nose up runaway

c 160 kn, nose down runaway

d 160 kn, nose up runaway

e 160 kn, nose down runaway, CAC disengaged

Fig. 24 ASE runaways—pitch channel (unpiloted)



a 140kn, nose up runaway

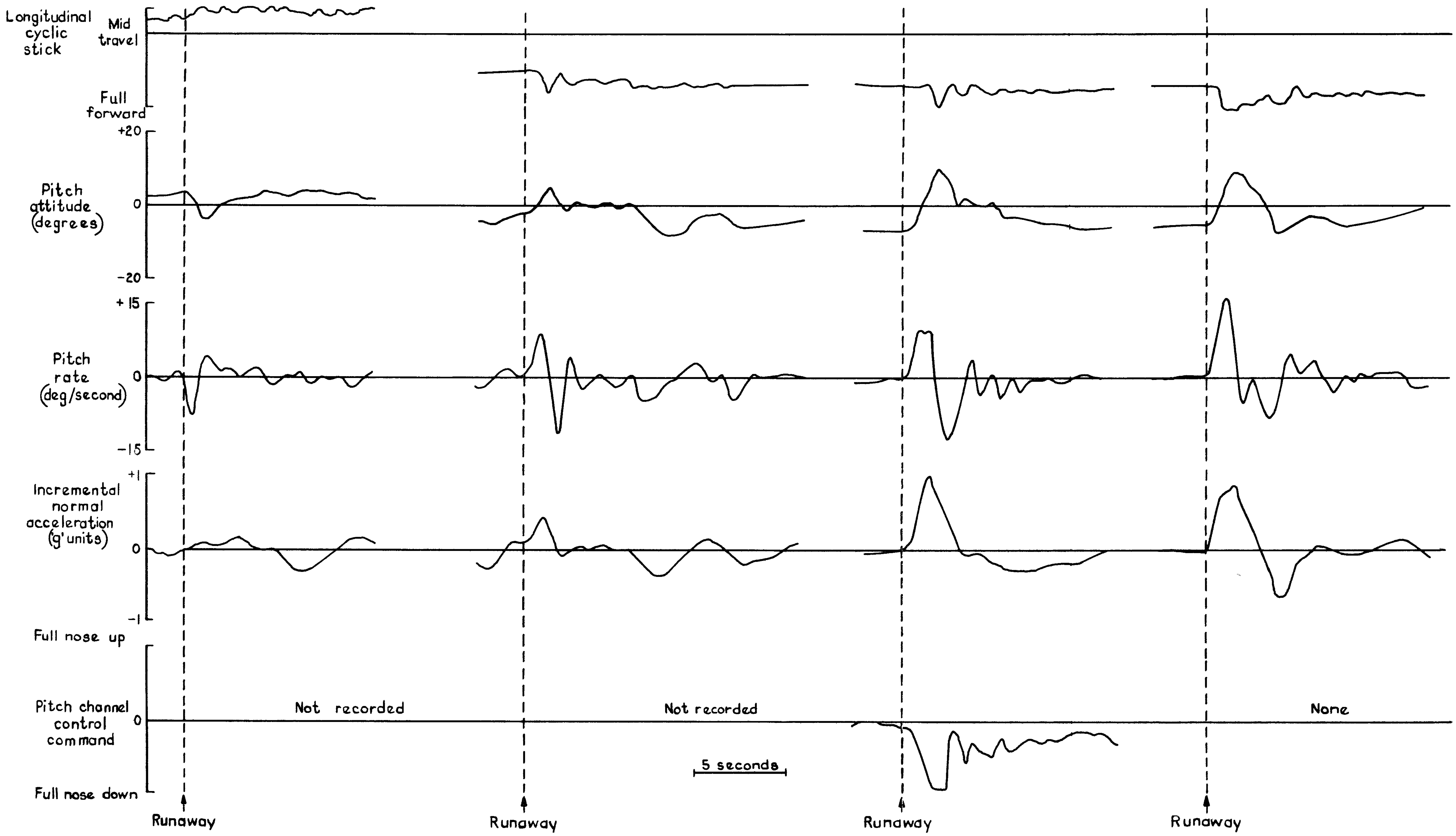
b 160kn, nose up runaway

c 160kn, nose down runaway

d 180kn, nose down runaway

All at aft CG

Fig. 25 a–d ASE Runaways — pitch channel, delayed pilot intervention



a Hover, nose down runaway

b 160 kn, nose up runaway

c 180 kn, nose up runaway

d 180 kn, nose up runaway – both lanes

All at aft CG

Fig. 26 a–d ASE runaways – pitch channel, unannounced failures

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July 1974

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629.13.074

T. Wilcock

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A brief qualitative comparison of the simulator results with results of flight tests on the actual Lynx has been made, and areas of effective simulation have been identified. The need for improved simulator motion and visual cues for certain phases of simulated helicopter flight is noted.

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