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Development and Flight Tests of an Instrument Flight Director for Helicopters

By

P. Brotherhood, D.L.C.

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Development and Flight Tests of an Instrument Flight Director for Helicopters

by

P. Brotherhood, D.L.C.

SUMMARY

This note describes the development and flight testing of an instrument system which enables the pilot to fly a helicopter in instrument flight conditions with considerably less concentration or fatigue compared with that required using previous instruments. This instrument, which is intended to replace the present inadequate artificial horizon, gives longitudinal and lateral indications derived from the appropriate mixing of signals from angular displacement of the helicopter, rate of change of angular displacement and control position. The presentation is in the form of a zero-reader. No interpretation by the pilot of the helicopter's behaviour is necessary, his only actions being to keep the instrument indications zero.

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1 Introduction

At the present time, the utility of the helicopter is limited by the high degree of concentration and skill required to fly on instruments, particularly at the lower airspeeds. An account of flight tests made some time ago (1948) on a Sikorsky R4B helicopter using a standard blind flying panel is given in ref. 1. Much of the difficulty experienced then was due to the unsatisfactory longitudinal flying characteristics, i.e. dynamic instability, both stick-fixed and stick-free. It was thought at that time that the difficulties would be considerably reduced as improvements in helicopter stability were effected. However with minor exceptions no basic improvements in stability have been forthcoming and in consequence the problem of instrument flight largely remains.

In this note satisfactory instrument flight is taken to mean blind flying at any condition within the flight envelope without undue concentration or fatigue. It is considered that once this is achieved the problems of indicating to the pilot approach paths and navigational aids are no greater than with fixed-wing aircraft.

Some work on providing more suitable instrumentation has been done elsewhere[2] with a flight director system in which information usually obtained from several different instruments is displayed on a single indicator in a manner more easily interpreted by the pilot. With this system the degree of concentration required was less than that using standard instrumentation.

Instrument flight trials have also been made on helicopters having various degrees of stability imparted artificially by auto-stabilization[3,4]. As may be expected less effort is required as the degree of auto-stabilization is increased. With a complete auto-pilot having stabilization about all axes the problem of instrument flying as discussed here does not really exist. Also, there may be many helicopter applications when the fitting of a complete auto-pilot is not justified, but the performance of instrument flight to a standard comparable with that possible in fixed wing aircraft would be an asset.

This note describes the development and preliminary flight testing of an instrument system in which the onus of interpreting and anticipating the motion of the helicopter from an instrument display is removed from the pilot, and performed by the instrumentation. The correct stick movements to apply during a disturbance are those necessary to zero horizontal and vertical bars in a zero reader type of display. Since the pilot has a direct control over the bars with his stick, control of the helicopter is reduced to mechanical movements in response to visual error signals. In other words the human pilot is required to play exactly the same part as the servomotors in an auto-stabilizer system. The Westland S-51 Dragonfly helicopter was used for this work.

2 Description of preliminary tests

These were confined to the pitching plane only, aimed at exploring the feasibility of the system in general. No provision was made for restricting the pilot's external view.

The form of control law thought to be required was:-

$$\Delta B_1 = a(\theta + b\dot{\theta} + c\ddot{\theta})$$

where ΔB_1 is the longitudinal cyclic pitch application relative to the trim

θ is the increment in fuselage attitude in the pitching plane

a, b and c are arbitrary constants.

The basic circuit used was similar to that used frequently in auto-pilot work. The basic unit was an angular rate gyro, and angular acceleration and attitude were obtained by differentiation and integration respectively. In order to eliminate the effect of progressive errors of integration, a "leaky integrator" was used. This had the effect of modifying the above equation as follows:-

$$\frac{1}{K}\int \Delta B_1 dt + \Delta B_1 = a(\theta + b\dot{\theta} + c\ddot{\theta})$$

The time constant K of the "leaky integrator" was about 15 seconds, which was sufficiently long to have a negligible effect on the transient response of the helicopter and pilot, thus giving a good approximation to the required control law. The cyclic pitch term was obtained from a potentiometer in the control circuit. The control law constants could be varied over wide limits.

The form of display is shown in Fig. 1a, and the sense is such that the needle rises when the attitude, angular rate and angular acceleration are in a nose up direction. A forward stick movement depresses the needle, and the control law is satisfied when the needle is at zero. The datum of the stick signal could be varied by means of a knob on the instrument panel.

Flights were made at or near hovering where control of the helicopter is generally more difficult. The nose of the helicopter was brought up sharply to an angle of about 20°, and recovery effected by zeroing the instrument. A wide range of constants was first tried with the angular acceleration term deleted. The response of the aircraft was varied from a neutrally stable oscillation to a heavily damped subsidence, and the pilots impressions of the degree of difficulty in zeroing the needle were obtained. The angular acceleration term was then added and variations of the constants assessed as previously.

Flights were then made throughout the speed range with the more satisfactory settings found previously, with the pilot referring to the zero reader only as far as longitudinal control was concerned.

3 Discussion of preliminary tests

The factors governing the choice of control constants conflict and a compromise has to be made. In order to minimise the response of the helicopter to gusts and turbulence, the ideal response would be a very rapidly damped motion in response to a sudden disturbance. This would require large and rapid stick movements in response to the visual display in order to satisfy the control law, and there is a limit to the pilot's ability to do this for physiological reasons. The problem of providing stability at the expense of manoeuvrability sometimes encountered with auto-stabilizers does not occur here, since the pilot is not obliged to zero the display when making a manoeuvre.

The control law found most satisfactory by the pilot in the hovering tests (without an angular acceleration term) resulted in the aircraft motion taking the form of a well damped pure subsidence in response to the initial disturbance. These tests were made in calm conditions, and when the aircraft was flown on the instrument display in fairly turbulent conditions the pilot complained that the needle movements were too erratic. The degree of damping (c in the control law) was accordingly reduced to the pilot's satisfaction. The motion of the helicopter was subsequently found to have a time of oscillation of from 4 to 5 seconds and to be about 0.5 of critically damped.

The tests in hovering with the angular acceleration term added were less satisfactory from the pilot's point of view. The needle appeared too sensitive, and was difficult to zero for an overall response similar to that obtained without the extra term. It had been thought previously that the addition of such a term would be helpful in reducing the effect of lags in the system, due to the pilot's reaction time, and the relatively low natural frequency of the display instrument (2 cycles per sec.).

Two features unconnected with the general principle of the instrument but nevertheless important for future development came to light. The first was that the time constant of the "leaky integrator" (15 seconds) was sufficiently large to cause large errors during quite low rates of turn. In effect the rate of pitch occurring in a steady turn was integrated, and the needle tended to rise off the scale. Secondly trimming the zero reader for each new speed with the knob provided was not easily accomplished, and occupied too much of the pilot's attention.

The results of the preliminary tests may be summarised as follows. The principle of indicating to the pilot the stick movement necessary to stabilize the helicopter visually on a zero reader type of display was shown to be sound, and enabled the pilot to fly at any speed without undue concentration. A control law containing fuselage angle and rate appeared adequate to stabilize the helicopter. It was therefore decided to incorporate a similar system using information obtained about the roll axis in addition to that of pitch on an orthodox zero reader indicator. It was further proposed to incorporate improvements in the trimming arrangements, and to record the stick movements and response of the helicopter.

4 Later development

In order to keep the system flexible for experimental purposes, and to avoid the turning error, it was decided to obtain the parameters in the control laws independently. Attitude and angle of bank were obtained from an artificial horizon with potentiometer outputs for pitch and roll. Rate of pitch and roll were obtained separately from two angular rate gyros. Lateral and longitudinal stick positions were obtained from potentiometers in the control circuits. The signals, variable over a wide range, were mixed in magnetic amplifiers, and the output from the pitch axis fed to the horizontal bar of the standard zero reader type of display, and that from the roll axis was fed to the vertical bar. The sense of the bar movement is shown in Fig. 1b, and a block diagram of the system in Fig. 1c.

Adjustment of the longitudinal and lateral zeros to suit any flight condition was effected by motor driven potentiometers controlled by a four position switch on the control column. Holding the button forward raised the horizontal bar progressively thus requiring a forward stick movement to zero. Similarly holding the button back, left and right required back, left and right stick movements respectively to maintain zero. The setting of the potentiometer brushes was indicated on two voltmeters placed near to the zero reader on the pilot's instrument panel. The lateral trimming arrangement was later modified as discussed in section 8.2.

Lateral and longitudinal stick position, rate of pitch and roll obtained from independent angular rate gyros were recorded using an A22 type recorder.

The "two-stage amber" system was used to restrict the pilot's external vision when instrument flying.

5 Description of flight tests

Tests to evaluate the response of the helicopter were made in two ways. The first method was that described in section 2 where recovery was made from a nose up disturbance by zeroing the instrument. Recoveries from lateral disturbances were effected in a similar manner. The second method used was to fly at about 30 kts, adjust the longitudinal trimmer for an increase of about 30 kts, and then to re-zero the instrument using the control column. During all the recordings made an event marker was operated by an observer when the instrument was considered to be zeroed. A wide range of control constants was assessed.

General instrument flying was done with various control law constants in varying weather conditions. Extracts from pilots' reports are given in the appendix.

6 Results and discussion of response tests

6.1 Longitudinal tests

Before discussing the results of the response tests, the following points should be emphasised. Firstly, the control laws quoted are those which would exist if the instrument had no lag and was exactly zeroed by the pilot. In practice these conditions cannot be completely realised, and the event marker mentioned in the previous section was in fact operated when in the observer's opinion the instrument was reasonably well zeroed. Secondly, for practical reasons the values of the control constants quoted were obtained from static ground calibrations, but the error involved is thought to be small at the frequencies concerned.

Typical records with identical stick gearing and various values of damping are given in Fig. 2(a, b and c). Records 2(a) and (b) are of the type in which a speed change of 30 to 60 kts was made. It will be seen from record (a) that with stick application proportional to attitude only, the motion is oscillatory, and only slightly damped with a period of oscillation of about 4 secs. The addition of the rate of pitch term ($\dot{\theta}$) increases the damping of the oscillation to about 0.4 of critical, and slightly increases the period of oscillation. Although not apparent from the record, it was about one minute before the new trim speed was reached. Record (c) shows a recovery from a pitch up near hovering with a further increased $\dot{\theta}$ term, and the motion appears to be about critically damped.

In Fig. 3(a, b) are shown two records in which the stick gearing has been reduced i.e. a smaller stick movement being required for a given movement of the display pointer. They show recoveries from pitch ups near hovering. It will be seen (Fig. 3a) that without the $\dot{\theta}$ the motion is oscillatory and only slightly damped, with the period of oscillation about 7 secs. The addition of the large $\dot{\theta}$ term (Fig. 3b) makes the motion more than critically damped.

In Fig. 4(a, b) the stick gearing has been still further reduced, and with the large $\dot{\theta}$ terms the recoveries from pitch ups in hovering are more than critically damped.

It is interesting to compare the recoveries shown previously with those made by reference to the ground as in normal ground contact flying. Two such records are shown in Fig. 5(a, b), made in or near hovering flight, at about 500 ft above the ground. It will be seen that the motion is somewhat less than critically damped with a period of 3 to 4 secs.

6.2 Lateral tests

The lateral response tests were less extensive than the longitudinal, mainly because of the limited time available, and also because in general the lateral characteristics in forward flight are better than the longitudinal. Throughout the range of control laws tested the motion was more than critically damped, and a typical record is given in Fig. 6. The record shows a recovery from a lateral disturbance at low forward speed.

7 Choice of control laws

7.1 Longitudinal motion

It is useful to examine the stability of the helicopter with this type of control law assuming no lag of any kind. If two degrees of freedom only are assumed the characteristic equation for the longitudinal motion using the standard helicopter notation is:-

$$\lambda^3\left[\overline{\frac{W}{g}B}\right] + \lambda^2\left[-\frac{W}{g}M_q - X_u B - \overline{a\,b M_{B_1}\frac{W}{g}}\right]$$

$$+\lambda\left[X_u M_q - W M_u ab - \overline{a M_{B_1}\frac{W}{g}} + a\,b M_{B_1} X_u\right]$$

$$- W M_u a + a M_{B_1} X_u + \overline{M_u W} = 0$$

where the control law is given by:-

$$\Delta B_1 = a(\theta + b\dot{\theta}) .$$

With the values of a and b used during the tests, only the overlined portions in the brackets need be considered at low speeds. To a good approximation the factors are given by

$$\left[\lambda^2\left(\frac{W}{g}B\right) - \lambda\left(a\,b M_{B_1}\frac{W}{g}\right) - \left(a\,M_{B_1}\frac{W}{g}\right)\right]\left[\lambda - \frac{M_u g}{a M_{B_1}}\right] = 0$$

or $\lambda_1 = \dfrac{M_u g}{a M_{B_1}}$ and if $\lambda_{2,3} = r \pm is$

$$r = \frac{a\,b M_{B_1}}{2B}$$

Using estimated derivatives for the Dragonfly and the control law

$$\Delta B_1 = 0.8\ (\theta + 0.8\dot{\theta})$$

we obtain:-

$$\lambda_1 = -0.035 \qquad r = -1.3$$

and the period of oscillation 5.5 secs.

If we now consider the response of the helicopter to an impulsive force $X_u U_o$ and moment $M_u U_o$ which may be said to result from a horizontal gust we have numerically:-

$$U = -0.0345\, U_o e^{-0.035t} + U_o e^{-1.3t}\,(0.00628 \sin 1.14t + 0.0058 \cos 1.14t)$$

and

$$\theta = 0.00215 U_o e^{-0.035t} + U_o e^{-1.3t}\,(0.165 \sin 1.14t - 0.00215 \cos 1.14t)$$

(degrees).

An examination of these figures shows that such a gust mainly excites the heavily damped oscillatory motion in pitch, but not the poorly damped subsidence. However in translation the reverse occurs, but the coefficient in the subsidence term is small and calculations show that a gust which causes a maximum change in attitude of 5° causes a maximum change in speed of only 3.5 ft/sec. During the tests changes in attitude of 5° due to gusts were not encountered even during quite severe turbulence, from which we may conclude that the poor damping of the subsidence is of little practical importance.

The choice of control law cannot be decided on the response records alone, since they do not indicate the degree of difficulty experienced by the pilot in satisfying the control law i.e. in zeroing the instrument. From general instrument flying several conclusions were reached. The pilot said that the horizontal bar was becoming "too sensitive" when flying in turbulent conditions as the rate of pitch term was increased to give a bar movement of about 0.1" per degree per second. Also the pilot did not like too small a stick movement for a given bar movement, and experience showed that at a gearing of about 0.18" per degree cyclic pitch i.e. 0.18" per 2" stick movement, the bar was becoming too sensitive. However the figures for stick sensitivity are not so definite as those for rate of pitch. No limit was found to the sensitivity of the angle of pitch term over the range tested. The maximum sensitivity available was a bar movement of 0.13" for 1° change of pitch.

Within the limits mentioned above it was found that a wide range of constants were satisfactory in providing stabilization, and it was difficult to find optimum values. The pilot tended to get used to one control law and any change tended at first to be an adverse one. Some of the initial instrument flying was done with the law $\Delta B_1 = 0.4\,(\theta + 1.7\dot{\theta})$ (see Fig. 3b) and the scale such that:-

$$\left.\begin{array}{ll} & \Delta B_1 = 11.5^\circ \\ \text{or} & \theta = 29^\circ \\ \text{or} & \dot{\theta} = 17^\circ/\text{sec} \end{array}\right\} \equiv 1.35''\ \text{bar movement.}$$

Later the contribution of the attitude term was increased giving the control law $\Delta B_1 = 0.8\,(\theta + 0.8\dot{\theta})$ and the scale such that:-

$$\left.\begin{array}{ll} & \Delta B_1 = 11.5^\circ \\ \text{or} & \theta = 14.4^\circ \\ \text{or} & \dot{\theta} = 18^\circ/\text{sec} \end{array}\right\} \equiv 1.35''\ \text{bar movement.}$$

The final and major part of the tests were made with this setting, and the discussion which follows in section 8 and the appendix refers to this setting.

7.2 Lateral motion

As mentioned previously the lateral tests were less extensive than the longitudinal. It was found that as with the longitudinal response the values of the control constants were not critical. One conclusion was reached however. From instrument flying in turbulent conditions, the pilot said that the vertical bar was becoming too sensitive as a sensitivity of about 0.1" bar movement per 4.5° per second was exceeded.

The control law finally adopted and with which the majority of the instrument flying was done was $\Delta A_1 = 0.27\,(\varphi + 0.47\dot{\varphi})$ and the scale such that:-

$$\left.\begin{array}{ll} & \Delta A_1 = 9^\circ \\ \text{or} & \varphi = 34^\circ \\ \text{or} & \dot{\varphi} = 70^\circ/\text{sec} \end{array}\right\} \equiv 1.35\text{" bar movement.}$$

With this control law the lateral motion was more than critically damped.

8 Instrument flight technique

8.1 Longitudinal control

As mentioned in section 4, the adjustment of the datum of the horizontal bar was effected by a motor-driven potentiometer controlled by a switch on the control column. The setting of the potentiometer brush was indicated on a voltmeter on the pilot's instrument panel. A plot of this longitudinal trim reading against airspeed measured in level flight is given in Fig. 7a. This curve is made up of a combination of stick position and attitude to trim, and was found to be very useful in indicating to the pilot the setting required for any particular speed. Eventually this voltmeter was graduated directly in knots. In no sense did this reading replace the airspeed indicator as a measure of speed, but merely indicated the correct zero to obtain that speed. The calibration is a function of C.G. position rotor speed, and flight path. However the effect of change in stick position and change in attitude that result from a change in C.G. position tend to cancel one another. Also the attitude of the fuselage is largely independent of flight path, and the result is that at constant rotor speed the calibration is substantially correct over the range 500 ft/min rate of descent to 500 ft/min rate of climb.

In order to change speed on the zero reader alone, the trimmer was first adjusted to the new speed, and the bar then zeroed. The helicopter took about a minute to change speed from 20-40 kts and half a minute from 60-80 kts. These times may be too long for some applications, and it should be remembered that in manoeuvres made under visual contact conditions the amount of stick used is several times that required to trim at the new speed. Quicker changes in speed were therefore effected by adjusting the trimmer as before but using stick movements greater than that demanded by the instrument, and zeroing as the desired speed indicated on the A.S.I. was approached.

This additional facility, discussed above, of indicating the trim required for any forward speed, is not a necessity of the system, but it did appear to take away much of the anxiety and uncertainty normally experienced in helicopter instrument flight, in that having selected a particular speed, the pilot knew he would eventually stabilize at or near it. This facility was particularly useful in turbulent conditions when there was some difficulty in obtaining trim with reference to the A.S.I. alone.

The problem of flight at low airspeed is much reduced using the zero reader, since intrinsically stabilization is with respect to fuselage attitude, and the ability to achieve it is largely independent of forward speed. Thus hovering and low airspeeds present no greater difficulty than any other flight condition, apart from the greater concentration on collective pitch and throttle needed under these conditions. Steep descents at airspeeds at and below 20 kts were accomplished quite easily. It should be emphasised here that during flight at low airspeeds as for example on an approach to land, it seems more advantageous to maintain a constant attitude in turbulent conditions than to try and follow the fluctuations of the A.S.I.

8.2 Lateral control

Basically the lateral control i.e. the ability to maintain the desired lateral level, was satisfactory but some difficulty was experienced in obtaining the correct datum with the lateral trimming device at first available. This was described in section 4 and was similar to that used for longitudinal trimming. The lateral stick position to trim measured during straight and level flight is given in Fig. 7b. The change in stick position with forward speed cannot be used to advantage as in the longitudinal case. The pilot considered that too much of his attention was occupied in obtaining a correct lateral trim after speed changes particularly in turbulent conditions.

The lateral trimming system was therefore changed to one in which by pressing a button on the control column, a small follow up motor zeroed the output signal from the lateral stick potentiometer. The motor used was one whose speed was proportional to the applied voltage, and with button pressed the stick signal was nulled exponentially with a time constant of about 4 seconds. In order to obtain a correct datum the pilot pressed the button and flew the helicopter with the vertical bar zeroed ("wings level") for several seconds. The button was then released and the lateral datum was established from that instant.

This latter system greatly reduced the concentration required to obtain lateral trim, and was used for the remainder of the tests.

Although not tried specifically during the tests, it has since been thought that a transient stick signal of time constant about four seconds would be adequate to provide lateral stability thus obviating the need for any manually operated trimming device. This would be equivalent to flying with the button permanently pressed in the present system.

Left and right turns were accomplished by keeping the vertical bar permanently displaced to left or right of zero. In this way a turn was regarded as an error from straight flight. If the horizontal bar was kept zeroed during the turn, there was an increase in speed (from the trimmed speed) during a turn to the right, and a decrease during a turn to the left. The decrease in speed when turning left is not fully understood as theoretically an increase in speed during both left and right turns was expected when made with the horizontal bar zeroed. Possible reasons for the discrepancy are turning errors in the artificial horizon unit used, and misalignment of the roll and pitch control column potentiometers with the true rolling and pitching axes of the rotor. This tendency to change speed was not disconcerting to the pilot, who made allowance i.e. he flew with the horizontal bar raised slightly during turns to the right, and lowered during turns to the left.

8.3 Directional control

Maintaining a constant heading by zero reader alone was not entirely satisfactory. This is because no direct heading term was incorporated in the display, and at the comparatively low speeds of the helicopter rate of turn is very sensitive to angle of bank, and large changes in heading may pass unnoticed.

The problem was reduced when reference was also made to the direction indicator although this was some distance away from the zero reader on the instrument panel. However directional control was less satisfactory than control about the other two axes.

9 Conclusions and future development

Flight tests made on a Dragonfly helicopter show that the principle of indicating visually the stick movements required to stabilize the helicopter on a zero reader type of display is sound, and one that is generally liked by the pilot.

The law used for longitudinal control for the majority of the tests was:-

$$\Delta B_1 = 0.8 (\theta + 0.8\dot{\theta})$$

and this was satisfied when the horizontal bar of the zero reader was zeroed. Control was satisfactory over a wide range of constants, but it is thought that the values quoted above are somewhere near the optimum for this helicopter.

The law used for lateral control was:-

$$\Delta A_1 = 0.27 (\varphi + 0.47\dot{\varphi})$$

and this was satisfied when the vertical bar was zeroed. Again control was satisfactory over a wide range of constants, and the values given are thought to be near the optimum for this helicopter.

Using this system instrument flying required less concentration than when using the standard blind flying panel. Much of the uncertainty normally experienced is removed because the pilot always knows the precise stick movement to make. Speed holding at low airspeeds and steep approaches was no more difficult than at any other speed, although greater concentration on collective pitch and throttle was required.

Direction holding on the zero reader alone was not entirely satisfactory mainly because of the high rates of turn associated with small angles of bank particularly at the lower airspeeds.

It is considered that this system is capable of being developed to show a distinct improvement over existing blind flying instrumentation based largely on the orthodox artificial horizon. Described below are several features which it is thought would improve the instrument.

The lateral control column signal could be a transient one with a time constant of say four or five seconds which would be sufficiently long to confer stability and thus obviate the need for a lateral trimming device.

A direct indication of heading (or heading error) should be available in or near the zero reader display. One solution would be to have a course selector the error signal from which could be fed to the vertical bar in addition to existing signals as in existing flight director systems. One possible disadvantage of this would be that the vertical needle would then cease to indicate a true angle of bank, and a cross reference with the artificial horizon would be required to obtain a knowledge of this quantity.

Also as mentioned previously, rate of turn is very sensitive to angle of bank particularly at low speeds, and this feature might introduce additional difficulties. Alternatively an indication of course error might be given on a separate needle immediately below the zero reader (Fig. 8a).

It was not the purpose of the present tests to produce actual equipment for blind flying, and the method of obtaining the required signals although producing flexibility for experimental purposes was clumsy. An alternative method using the artificial horizon was a basis, is shown in Figs. 8b and c. The rate signals are obtained by differentiating the pitch and roll signals. All signals are mixed in a hypothetical zero reader having twin coils per axis, each movement having the sensitivity of the present instrument. It will be seen that such a scheme requires a relatively small amount of equipment extra to that already used in the standard panel.

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3	James B. Whitten, John P. Reeder and Almer D. Crim	Helicopter instrument flight and precision manoeuvres as affected by changes in damping in roll and pitch. NACA T.N. 3537.
4	Seymour Salmins and Robert J. Tapscott	Instrument flight with a helicopter stabilized in attitude about each axis individually. NACA T.N. 3947.

APPENDIX

Pilots' assessment of system

Approximately 22 hours development flying were done on the zero reader installation by Lt. Cdr. R.A. Thurstan, R.N., and a further 4 hours were flown in assessment by five other pilots from the Royal Navy, Royal Air Force and British European Airways. The total instrument flying with the two-stage amber equipment was about 5 hours.

Extracts from pilots' reports

Lt. Cdr. Thurstan, R.N., who did the development flying was naturally able to give a more detailed report than other pilots and his comments are given first in each section below.

General comments

"Helicopter instrument flying with the zero reader has been readily accomplished in all flight conditions from 20-80 kts (N.B. 20 kts was the lowest airspeed reliably indicated on the A.S.I.) and with further development the instrument appears to go far towards solving many instrument flight problems".

"After only 40 minutes I was quite at home with the system, and quite happy to go into cloud and fly the aircraft on the zero reader. Considering that the instruments used are existing instruments adapted for this prototype system one cannot but feel enthusiastic as to what could be achieved with instruments specially made for the finalised version of the system".

"In flight some difficulty was at first experienced with the presentation which is of opposite sense to the normal Flight Director, I.L.S. and artificial horizon indicators. In the system as flown the stick is used to "fly" the pointers to the centre of the instrument. Difficulty was experienced in maintaining a heading on zero reader alone. In spite of the above mentioned shortcomings, the system, in the short time it was flown eased the problem of instrument flight over the flight region examined".

"We were particularly impressed by the ease with which recovery could be made from disturbed states using the instrument, and with the steadiness of approaches at low airspeeds. I consider that instrument flight was more accurate and less strenuous than with normal instruments. We think however that the presentation should conform with the presentation on artificial horizon and existing flight directions where the fixed datum is flown back to the moveable bar".

"At slow speeds and level flight at 20 kts the information was good, and I thought the helicopter was easier to control in this condition by reference to the zero reader than by visual reference.

The most noticeable weakness in flight is the long time taken to change pitch attitude on zero reader alone after selecting a new airspeed. For practical use in instrument approaches a modification is needed which will allow a newly selected speed to be achieved more rapidly than at present".

Longitudinal control

"Straight and level flight was easy to maintain in calm and turbulent conditions. The damping of the bar (rate of pitch contribution) was considered satisfactory for use in turbulent conditions, and sensitive enough in calm conditions.

The speed selected was maintained at about ±5 kts indicated on the A.S.I. in fairly turbulent conditions.

When a new speed is selected by the trimmer, and the discrepancy between the horizontal bar and the datum is zeroed, the speed takes some time to stabilize e.g. reducing speed from 40 to 25 kts takes up to 45 secs. This feature is not necessarily a disadvantage, since in the low speed range considerable changes in power occur, and a steady transition can only be achieved if the new flight condition is approached slowly. The penalty of rapid transition to low speed flight may well be a rate of descent, which induces a vortex ring state with its consequent loss of control. Quicker changes of speed may be made by using larger stick movements than zero the bar and effecting zero as the desired speed is approached. With regard to flight at low airspeeds an accurate means of indicating airspeed and rate of descent is highly desirable. The present A.S.I. was useless below 20 kts and the rate of descent meter needle seemed unreliable and fluctuated badly.

During turns there is an error in the pitch zero datum. The result of the error is to cause a slight dive when turning to starboard, and a climb when turning to port if the horizontal bar is maintained at zero. By positioning the bar slightly above or below the zero position to suit the direction of turn, the pitching error can be anticipated, and the speed maintained constant. It is thought however that this error should be eliminated or compensated so that zero can be maintained on the horizontal bar during a turn".

Lateral control

"A lateral level in straight flight can be easily maintained with reference to the zero reader alone. The lateral zero button has proved to be an effective method of obtaining a valid lateral zero with speed change but a fully automatic method of maintaining the correct zero datum is highly desirable".

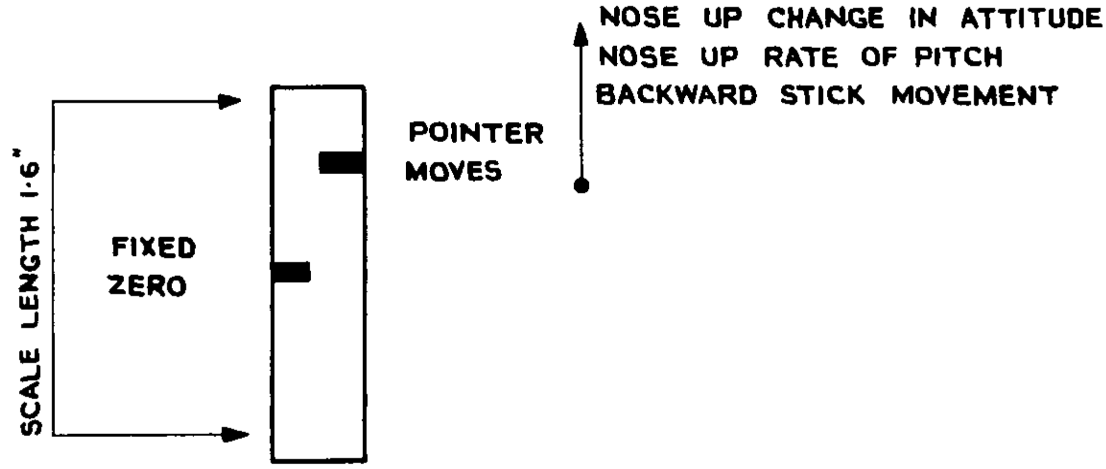
"The present requirement for zeroing the lateral indicator bar is a nuisance, and if this could be achieved automatically it would be a great help to the pilot (this is not difficult with the existing system but it is one more thing to worry about).

The lateral bar should be damped sufficiently so that in turbulent weather a pilot is not making unnecessary lateral stick movements".

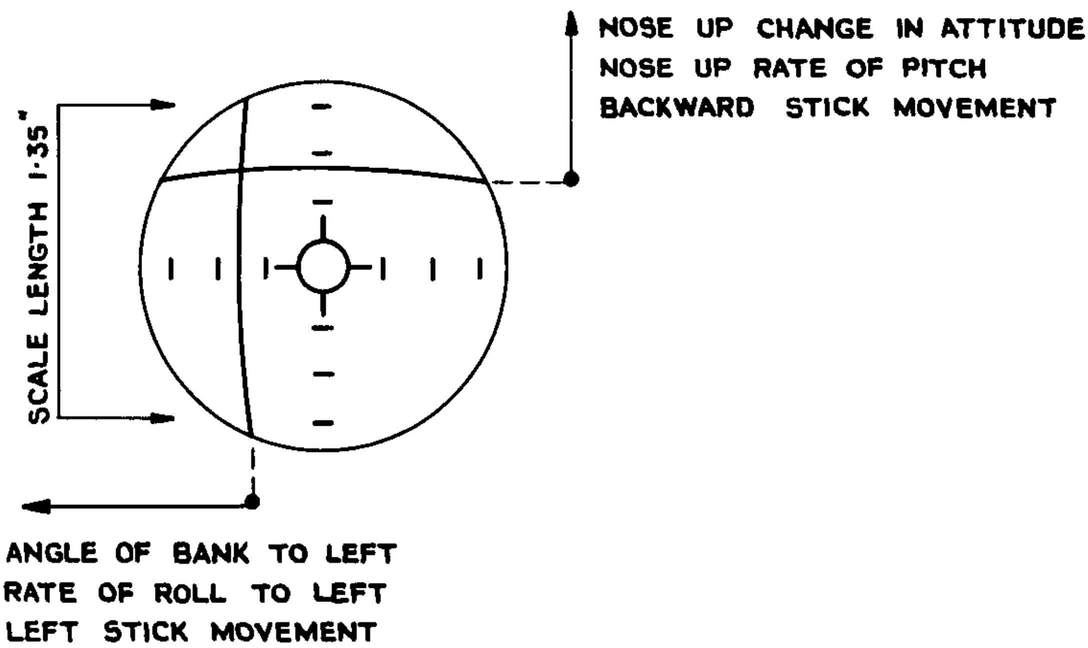
Directional control

"Maintaining course on zero reader alone is not satisfactory, particularly at the lower speeds, where large rates of turn may result from small errors in zeroing the lateral bar ".

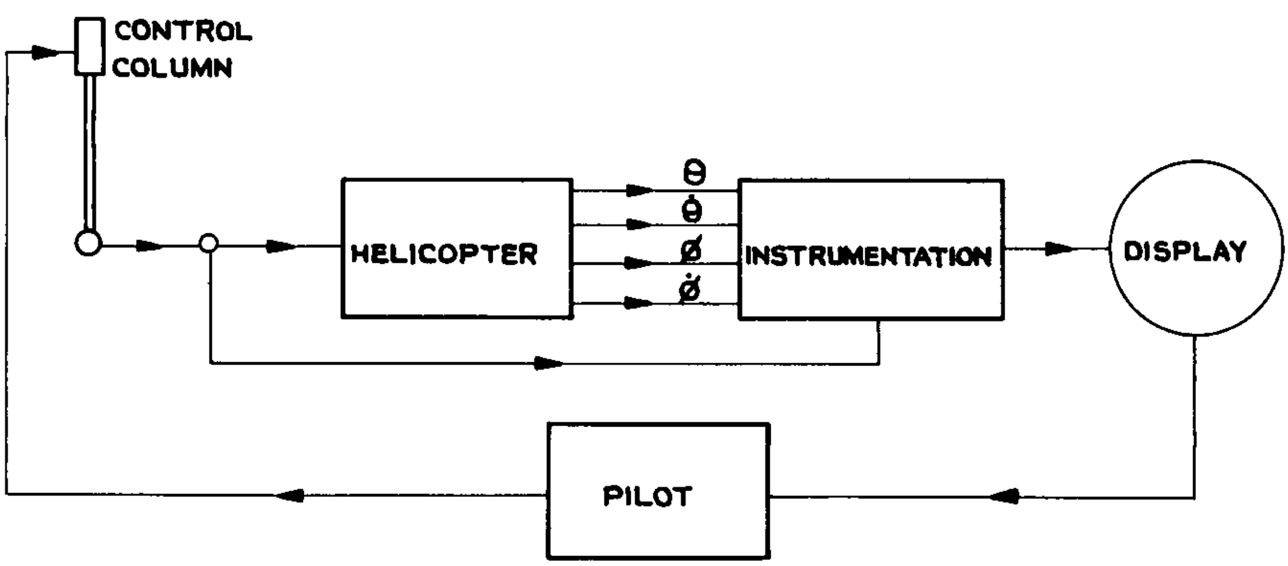
"A yaw indicator, or direction indicator should be positioned close to the zero reader, preferably immediately below. This would obviate the tendency to wander off course as happens with the existing layout because the direction indicator is so remote from the zero reader."



(a) ORIGINAL ZERO READER DISPLAY.



(b) FINAL ZERO READER DISPLAY.



(c) BLOCK DIAGRAM OF SYSTEM

FIG. 1 (a–c).

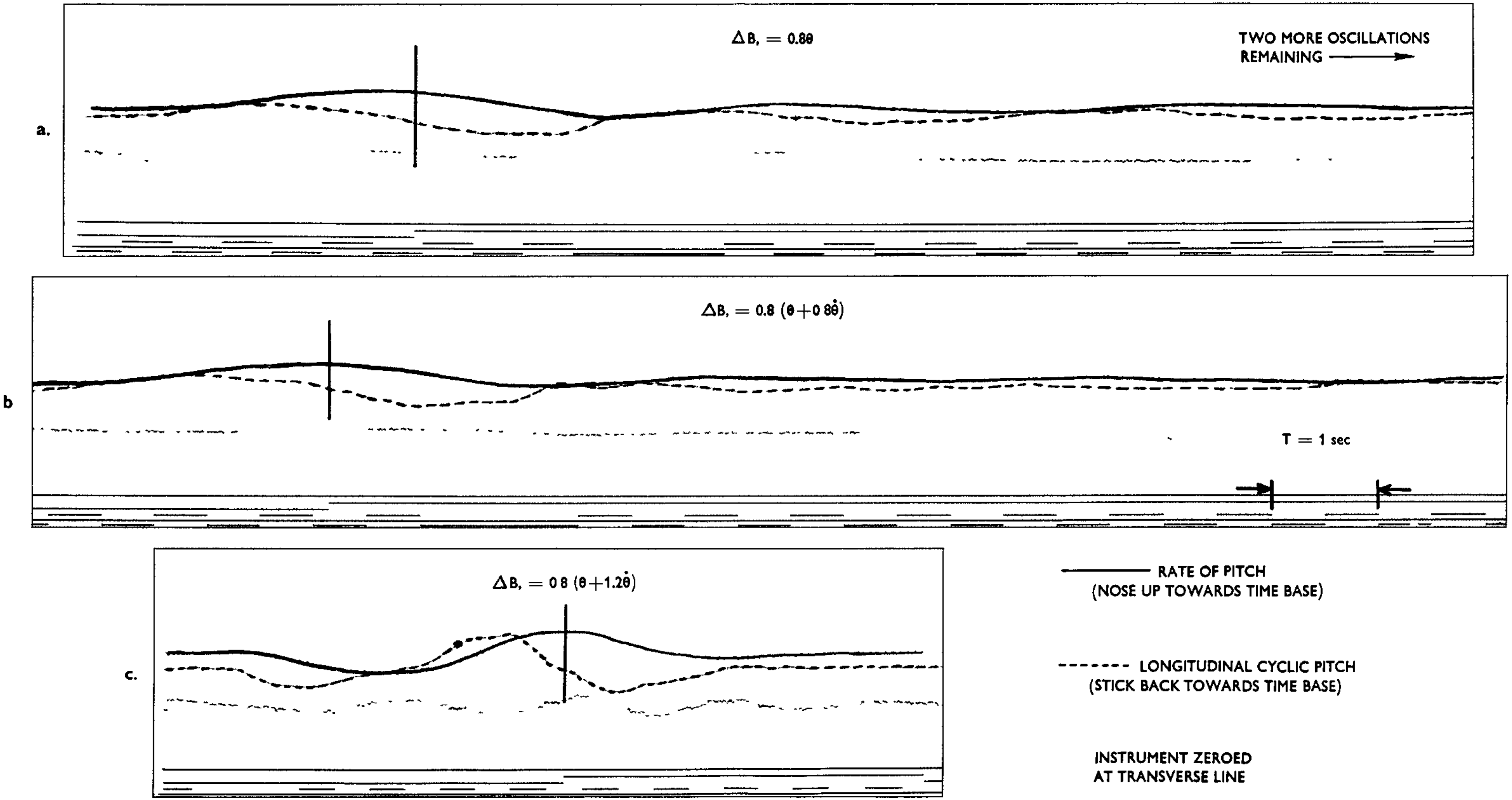
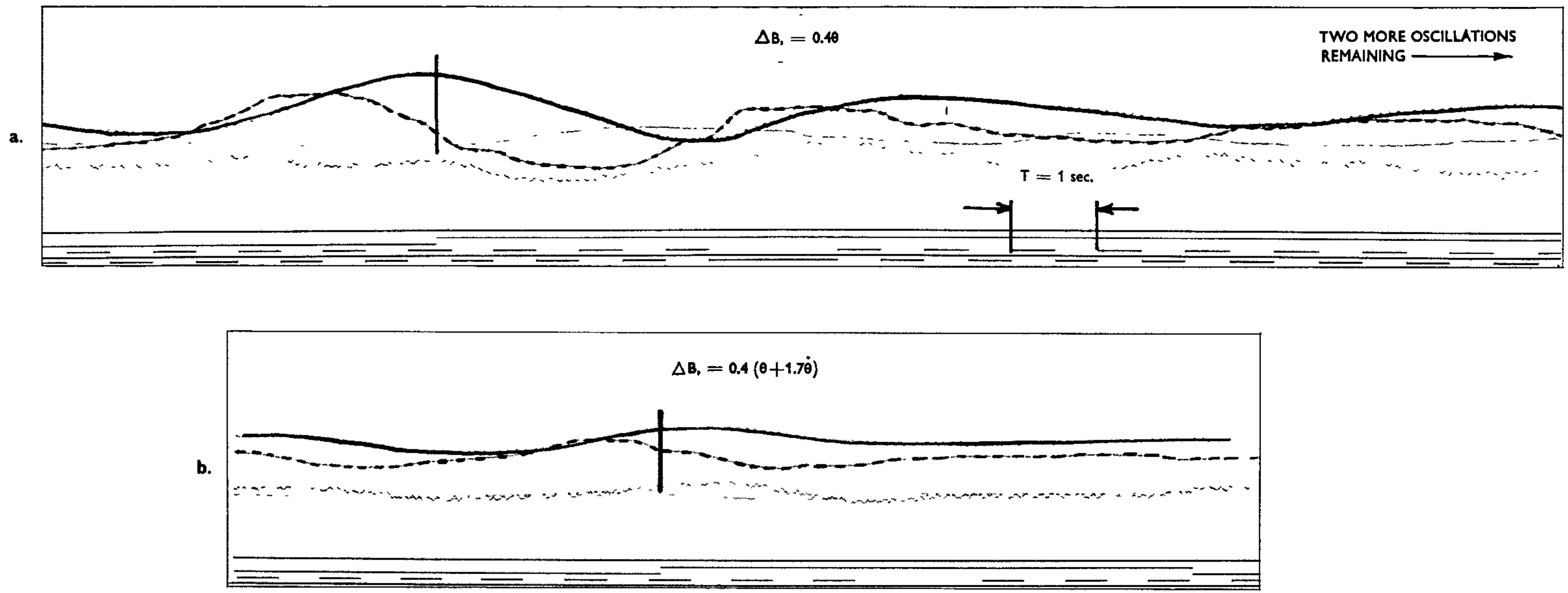


FIG.2a, b & c. LONGITUDINAL RESPONSE TIME HISTORIES

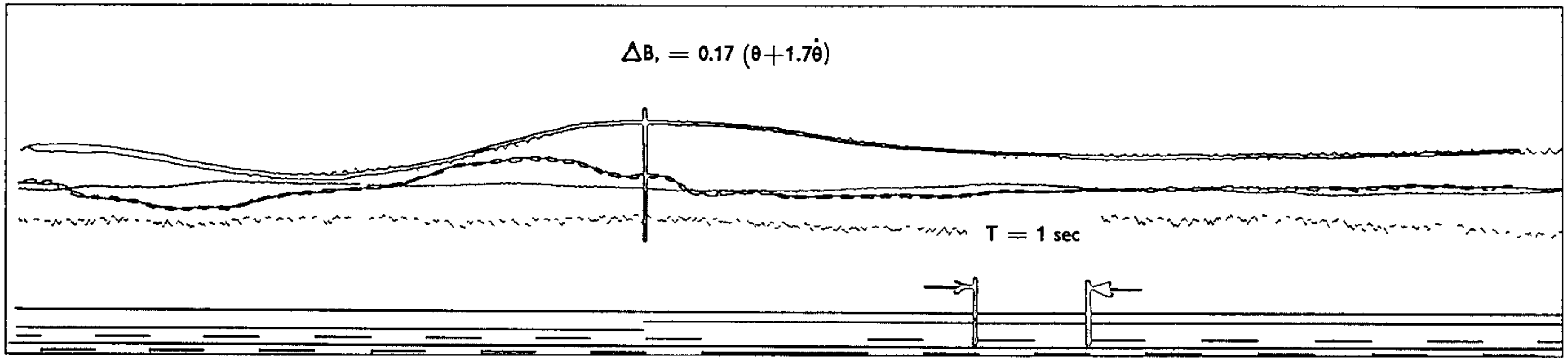


RATE OF PITCH (NOSE UP TOWARDS TIME BASE)

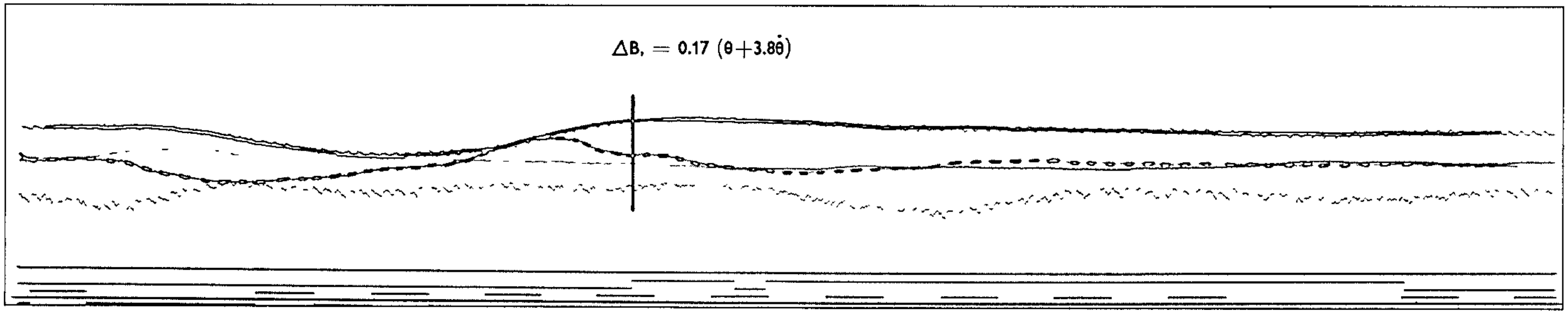
LONGITUDINAL CYCLIC PITCH (STICK BACK TOWARDS TIME BASE)

INSTRUMENT ZEROED AT TRANSVERSE LINE

FIG.3a & b. LONGITUDINAL RESPONSE TIME HISTORIES a.



b

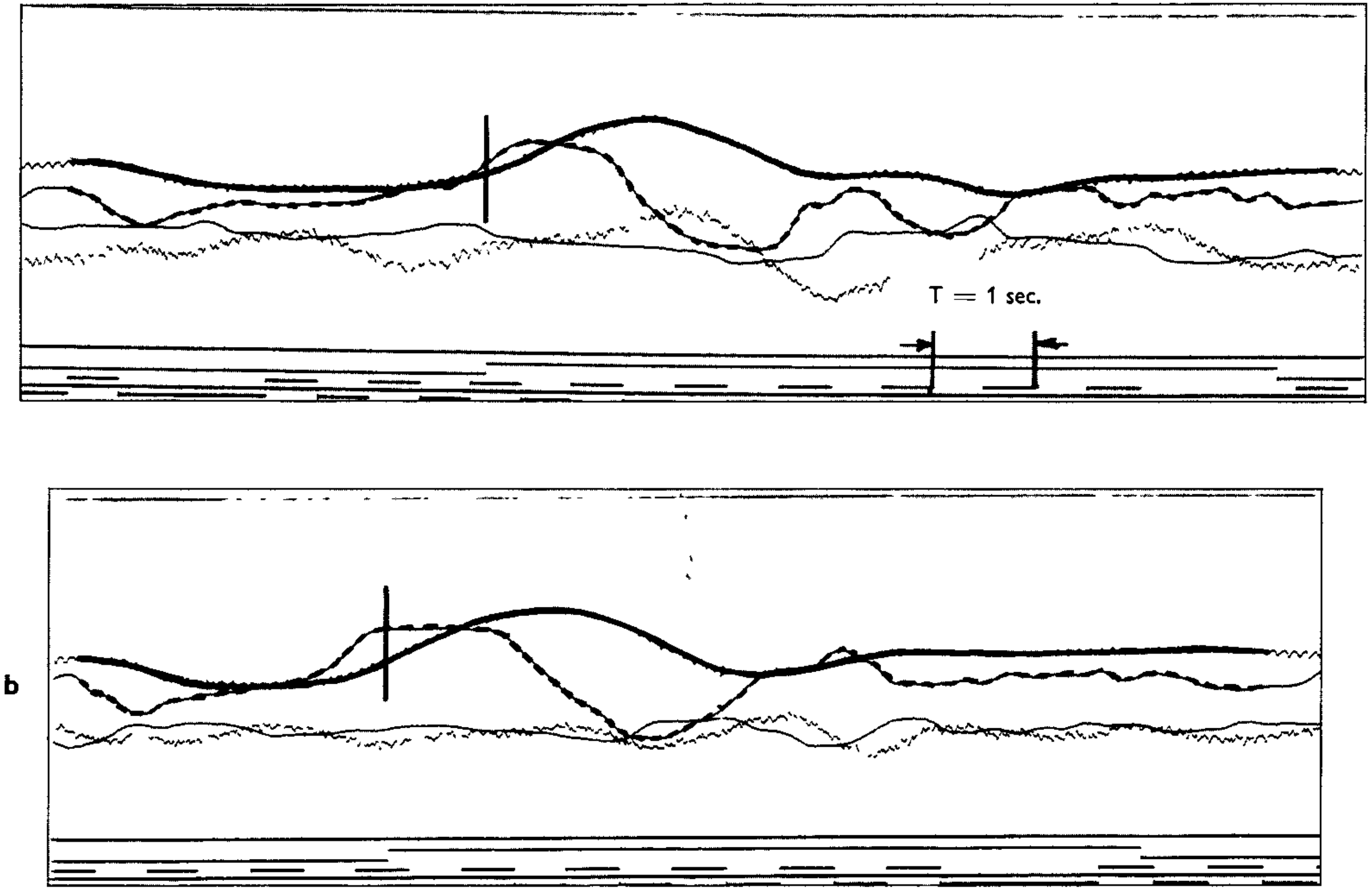


——— RATE OF PITCH (NOSE UP TOWARDS TIME BASE) - - - - - - - - - LONGITUDINAL CYCLIC PITCH (STICK BACK TOWARDS TIME BASE)

INSTRUMENT ZEROED AT TRANSVERSE LINE

FIG.4a & b. LONGITUDINAL RESPONSE TIME HISTORIES a.

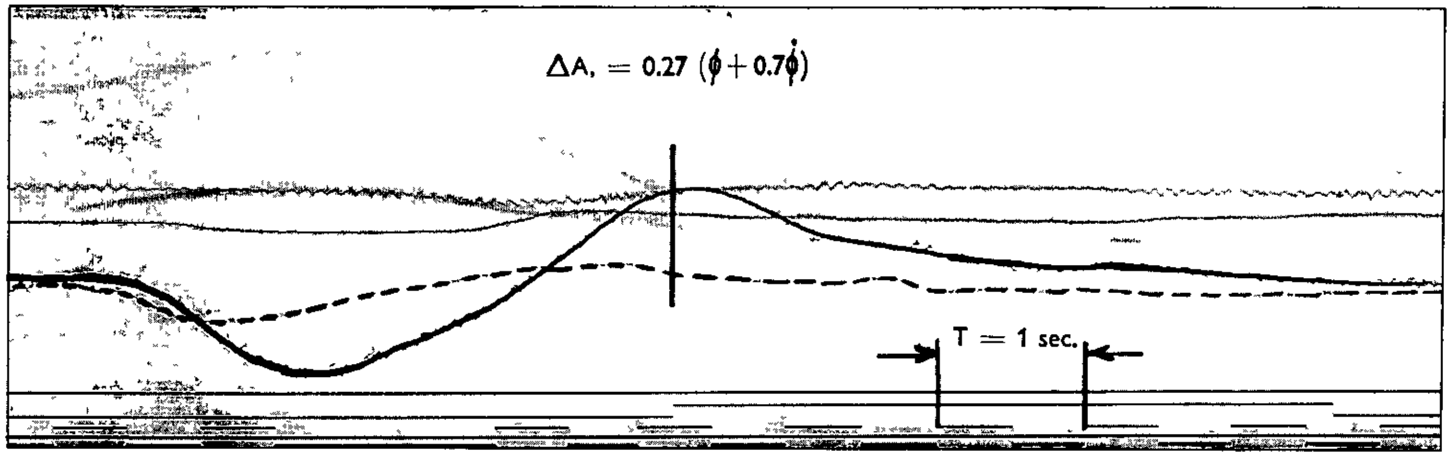
b



——— RATE OF PITCH (NOSE UP TOWARDS TIME BASE) - - - - - - - LONGITUDINAL CYCLIC PITCH (STICK BACK TOWARDS TIME BASE)

RECOVERY STARTED AT TRANSVERSE LINE

FIG.5a & b. VISUAL CONTACT LONGITUDINAL TIME HISTORIES



RATE OF ROLL (PORT TOWARDS TIME BASE)

LATERAL CYCLIC PITCH (STICK PORT TOWARDS TIME BASE)

INSTRUMENT ZEROED AT TRANSVERSE LINE

FIG.6. LATERAL RESPONSE TIME HISTORY

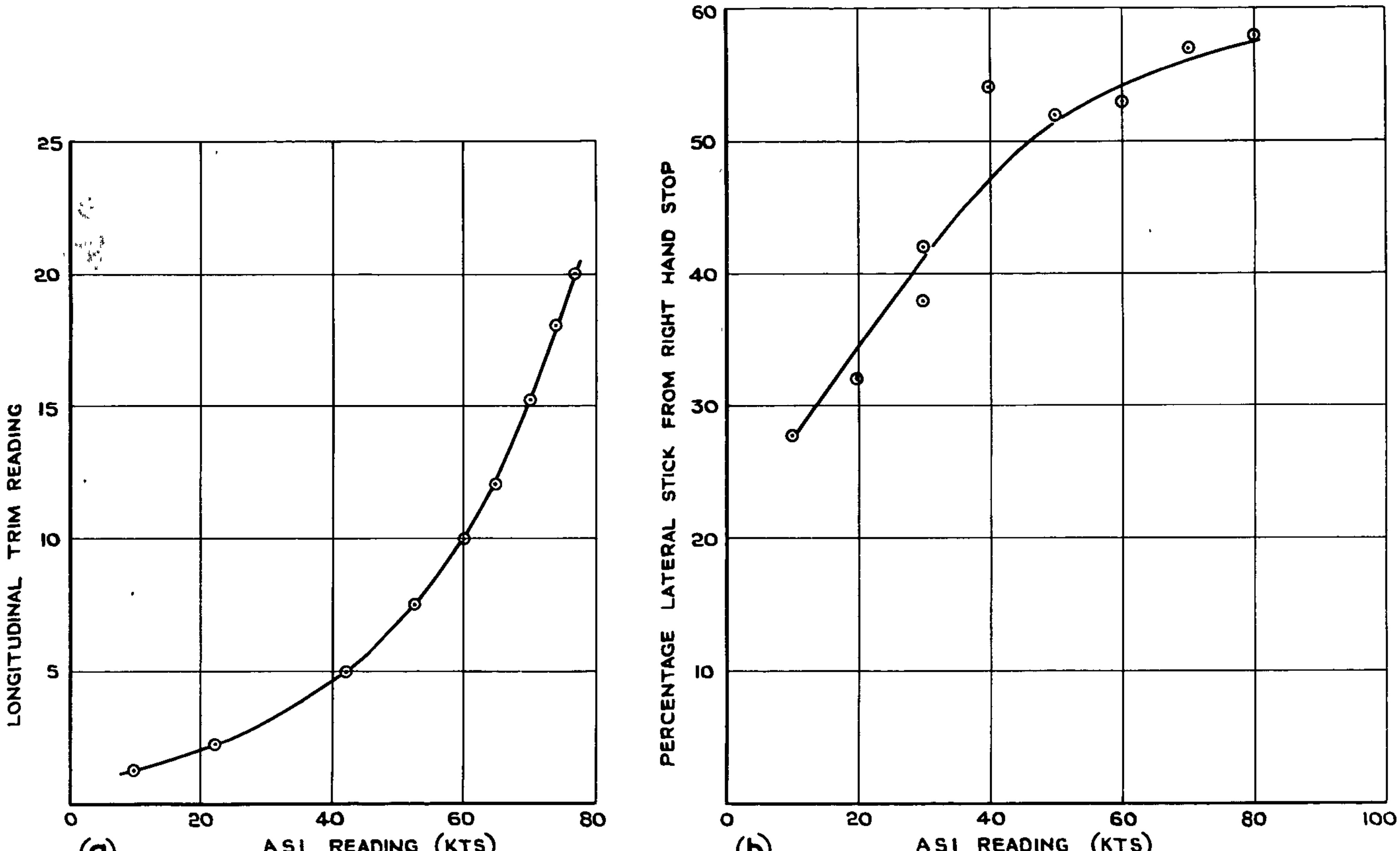
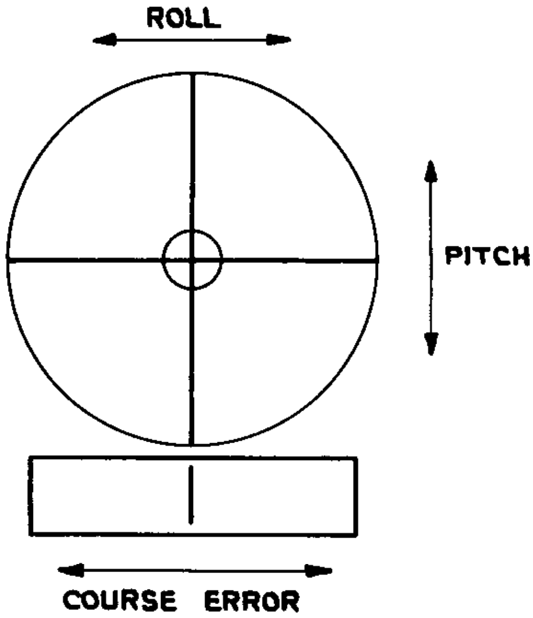
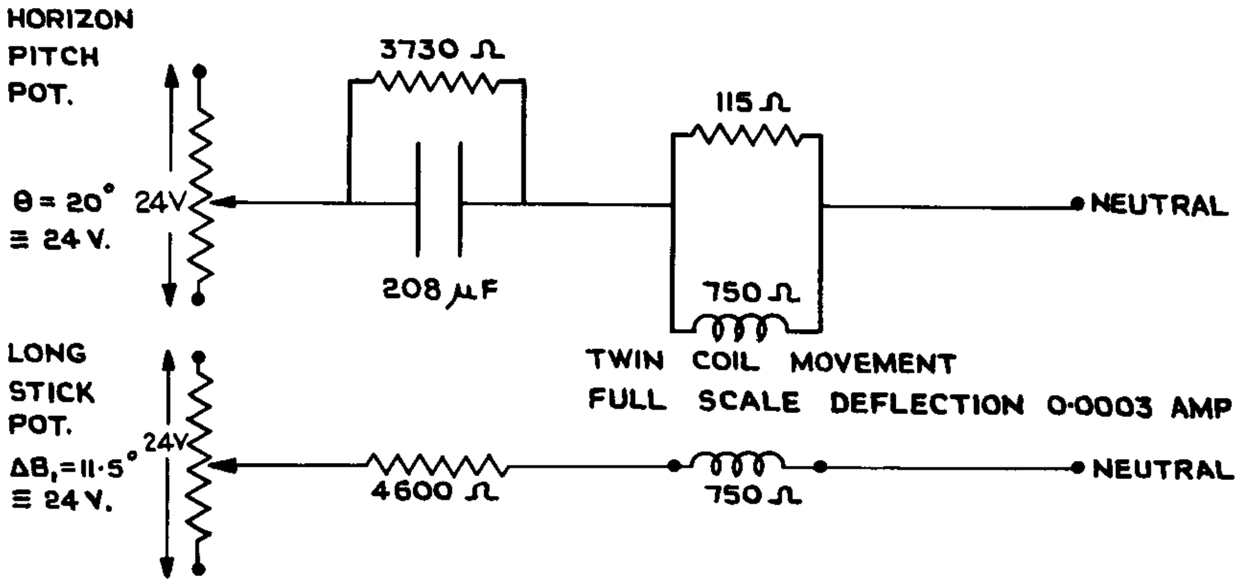


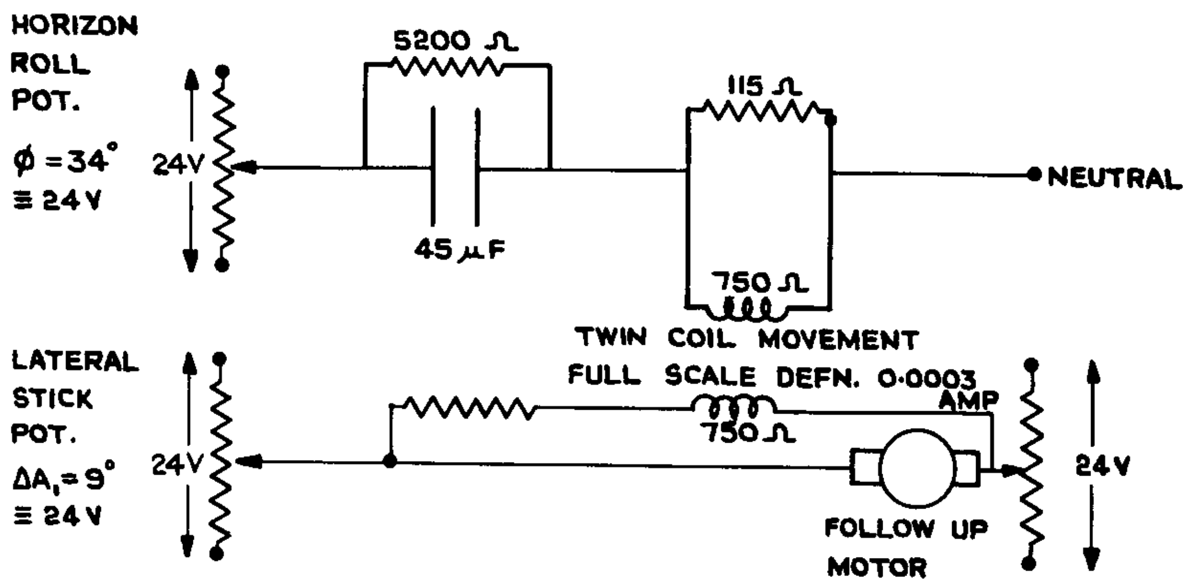
FIG. 7 (a & b). LONGITUDINAL AND LATERAL TRIM IN STRAIGHT AND LEVEL FLIGHT.



(a) SUGGESTED DISPLAY.



(b) TYPICAL VALUES TO GIVE $\Delta B_1 \simeq 0{\cdot}8\ (\theta + 0{\cdot}8\,\dot{\theta})$.



(c) TYPICAL VALUES TO GIVE $\Delta A_1 \simeq {\cdot}27\ (\phi + {\cdot}5\,\dot{\phi})$
(WITH FOLLOW UP MOTOR INOPERATIVE)

FIG. 8 (a–c)

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