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Flight Tests of a Hovering Jet-Lift Aircraft (Rolls-Royce Flying Bedstead)

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Summary.

This report describes the flight tests made at the Royal Aircraft Establishment on the Rolls-Royce Flying Bedstead to investigate the stability and control problems of a hovering jet-lift aircraft.

Tests made with varying amounts of artificial stabilisation (including a few without stabilisation) showed that some artificial stabilisation was necessary in pitch and roll for operation in other than very favourable weather conditions. Yaw stabilisation was not essential for hovering flight.

The main difficulty in flying the Flying Bedstead with artificial stabilisation was the height control, because of the slow response of the engines to throttle movements.

Tentative conclusions are also drawn about the control power required by a hovering jet-lift aircraft, the desirable amount of artificial stabilisation, and suitable forms for the autostabiliser control equation.

LIST OF CONTENTS

* Replaces R.A.E. Report No. Aero. 2651—A.R.C. 23,219.

LIST OF ILLUSTRATIONS

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1. *Introduction.*

The Rolls-Royce Thrust Measuring Rig (T.M.R.), Fig. 1, better known as the 'Flying Bedstead', was, as far as is known, the first jet-lift aircraft to fly anywhere in the world. Its construction was originally suggested by Dr. A. A. Griffith of Rolls-Royce as a means of demonstrating the practicability of controlling a jet-lift vertical-take-off aircraft in hovering and low-speed flight, and for research into the control powers and the degree of artificial stabilisation which such an aircraft would need.

The Flying Bedstead was built by Rolls-Royce at Hucknall, its autostabiliser being designed and built by the Instrument and Air Photography Department at the Royal Aircraft Establishment, Farnborough. A 'gantry', Fig. 2, was built at Hucknall for its initial trials, in a form designed to offer no restraint to the aircraft movement within a restricted space while preventing it from going outside that space and also preventing its rate of descent from ever exceeding 10 feet per second: thus a pilot in difficulty could close the throttles without fear of destroying the aircraft in a crash landing. The aircraft first flew in the gantry on 19th August, 1953, and made its first free flight (i.e. outside the gantry) on 3rd August, 1954.

At the end of 1954 the aircraft was transferred to R.A.E. Farnborough where, after modification, it began the programme of tests described in this report in March, 1955. The aircraft was transferred to R.A.E. Bedford in June, 1956 where the tests continued until it was severely damaged in an accident in September, 1957. The actual practicability of controlling the aircraft having been demonstrated at Hucknall, the flight test programme at the R.A.E. was designed to investigate whether artificial stabilisation was essential for jet-lift aircraft while hovering and in low-speed flight, and, if so, what stability characteristics were most desirable.

2. *Description of Aircraft and Control System.*

2.1. *Description of aircraft.*

The construction of the Flying Bedstead is made clear in Figs. 1 and 3. It consisted essentially of a tubular framework in which two Rolls-Royce Nene jet engines were mounted. Fuel tanks were fitted below the engines and a platform above the engines carried the pilot, the batteries and the autostabiliser. The crash pylon was intended to protect the pilot in the event of the aircraft overturning. In order to eliminate gyroscopic effects, the engines were mounted back to back, and the jet-pipes therefore contained right-angle bends with cascades to reduce the thrust losses in turning. The jet-pipe from the forward engine was bifurcated, terminating in two nozzles on either side of the single nozzle from the rear engine. The thrust line from each engine thus passed through the centre of gravity of the aircraft so that the failure of an engine would not have resulted in any moment being applied.

A four-leg, long-stroke undercarriage was used, with small castoring wheels. The maximum designed vertical velocity of the undercarriage was 34 ft/sec and it was intended to withstand a landing after a failure of one engine at any height up to 50 feet.

The all-up-weight of the aircraft as flown at R.A.E. was about 7,600 lb. The maximum thrust from the engines, including the jet-control thrust, was about 8,100 lb giving a nominal maximum thrust-weight ratio in I.S.A. sea-level conditions of 1·07, which was in practice somewhat reduced at take-off by the recirculation of hot gas into the engine intakes. The fuel capacity was 190 gallons, giving a flight endurance of about 11 minutes. With 50 gallons left, fuel warning lights came on, indicating to the pilot that about 3 minutes flying time remained, and the flight was then terminated. The weight at the end of the flight, with 50 gallons of fuel, was about 6,500 lb and the maximum thrust-weight ratio was then 1·25.

2.2. *Control System.*

The aircraft was controlled by air jets at its extremities. Fig. 4 shows, diagrammatically, the layout of the ducting system. 9% of the mass flow of each engine was bled from the compressor and ducted through non-return valves to a toroidal collector box in the centre of the aircraft. Thence it was ducted through further pipes containing butterfly valves to control nozzles at the aircraft extremities. With the controls neutral the pitch-control nozzles produced equal thrusts of 290 lb each and the roll-control nozzles produced 38 lb each; a control movement in pitch or roll then moved the corresponding pair of butterfly valves, increasing the thrust from one nozzle and decreasing that from the other so that a control moment was produced without altering the total lift appreciably. The pitch-control nozzles were pivoted about fore-and-aft axes and movement of the rudder bar rotated them differentially, through a maximum of 30 degrees each, to produce a yawing moment. Application of the yaw control produced no pitching moment but caused a slight loss in lift which was noticeable when large control movements were made.

Translational movements of the aircraft were made by pitching or rolling it to produce a horizontal thrust component and therefore a horizontal acceleration. Height control was purely by means of the engine throttles which were arranged so as to resemble the collective pitch lever of a helicopter. They were pivoted at their rear ends a little above the platform level, on the port side of the seat, and were arranged to lie horizontally when closed, moving upwards and slightly backwards when opened. They thus moved in their quadrants in the opposite sense to the throttles of a conventional aircraft.

The application of full control in pitch was capable of producing an angular acceleration of approximately 43 degrees (0·75 radians)/sec^2. The corresponding figures in roll and yaw were 32 degrees (0·55 radians)/sec^2 and 21·5 degrees (0·375 radians)/sec^2. The original intention was to provide 60 degrees (1 radian)/sec^2 in pitch and roll and 30 degrees (0·5 radians)/sec^2 in yaw, these figures being based on model tests[1] at R.A.E., but this aim could not be realised in practice.

2.3. *Autostabiliser.*

2.3.1. *General.*—While the yaw and height controls were purely mechanical, the pitch and roll controls were electrically signalled throughout with no provision for mechanical reversion. A block diagram for one channel of the autostabiliser is given in Fig. 5.

Movement of the pilot's control column in pitch or roll moved the brushes on potentiometers and the signals generated were added in the autostabiliser to gyro signals. The maximum gyro signal and the maximum stick signal were equal, each being just sufficient to apply full control so that the autostabiliser had 100% authority. The amplified output signals switched the current to electric servo-motors which moved the butterfly valves to the demanded position. In normal operation 0·3 sec was required to achieve full deflection from the neutral position. A 'fault circuit' was included to detect any failures in the equipment, to switch out faulty units and to warn the pilot.

Initially the stick potentiometers, the gyros, and the servo-motors were duplicated* but it was then impossible for the fault circuit to detect failures infallibly. It would always prevent a control 'runaway' and was considered adequate for flight in the confines of the gantry at Hucknall, but was not thought to be safe enough for the extended tests in free flight at R.A.E. The autostabiliser was therefore made partially triplex by the addition of a third reference stick potentiometer and gyro in each channel. It was not practicable to add a third servo-motor, and servo faults were therefore detected by comparing the differences between the demanded and the actual positions of each pair of servo-motors. Since rapid stick movements always produced appreciable servo-motor lags extreme care was required in matching components so that real faults could be detected quickly without spurious faults being easily produced by sharp stick movements.

If the fault circuit detected a fault in any line, that line was automatically switched out and warning lights showed on the instrument panel. If a servo-motor was switched off, it was effectively locked by the irreversible gearing through which it normally drove and the remaining servo-motor drove the valve alone, at half-speed, through a differential gear. The servo-motor movement needed to produce a given valve movement was therefore doubled and in order that the total valve movement should be unchanged the valve position feedback was automatically switched from the normal potentiometers on the servo-motor outputs to a potentiometer on the valve shaft. The doubling of

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* Strictly speaking, since both lines of each channel were working simultaneously in normal operation, the system was duplex.

the servo-motor movement required for a given valve movement after an autostabiliser fault increased the effective lag in the system by an amount which could be important under certain circumstances.

2.3.2. *Control equation.*—The gyros used in the autostabiliser were electric-spring rate gyros, giving an output current proportional to the rate of pitch or roll of the aircraft. Condensers were used in series with the gyro coils (Fig. 6) and had the effect of integrating the rate output and so of producing an additional autostabiliser term proportional to aircraft attitude. The autostabiliser amplifier then added to the pilot's demand signal the sum of these two stabilising terms, proportional to aircraft rate and position, the output being used to switch the current to the servo-motor and being neutralised by the servo-motor position feedback signal. Since the latter was equivalent to an aircraft acceleration the overall control equation was of the form:

$$\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} + C\theta = AS \tag{1}$$

S being the stick movement, θ the angular displacement of the aircraft in pitch or roll, while A, B and C are constants. The maximum signals which could be put into the autostabiliser by the stick and by the gyro circuit were equal and were just sufficient to apply full control, so that full control movement was applied as a result of a stick movement of the maximum 15 degrees, an aircraft rate of $15A/B$ degrees per second, or an aircraft attitude of $15A/C$ degrees. The state of the autostabiliser was usually described in terms of these two quantities, the aircraft rate and attitude which demanded the application of full opposite control, since they corresponded to easily visualised physical quantities. With this control equation a stick signal produces a steady attitude and it is described as a position control.

With this arrangement, however, slight differences between the rate gyros in different control lines were rapidly integrated into large differences between the attitude signals in the lines and hence into large differences between the servo-motors which were interpreted as faults by the fault circuit. It was quickly realised that in practice it was not possible to reduce the differences between the gyros to a level at which this was not a problem, and in order to cure the trouble 'leak' resistors were wired across the integrating condensers (Fig. 6), giving the effect of a quasi-attitude term as far as short-period control was concerned.

The effect of this modification on the control equation was to replace the original attitude term, θ, by a term

$$\frac{\tau p}{1 + \tau p}\,\theta \tag{2}$$

τ being the time constant RC of the 'leak circuit' formed by the integrating condenser and its by-passing resistor, and p differentiation w.r.t. time.

The control equation with which the aircraft was normally flown was then obtained by replacing θ in equation (1) by the expression (2)

$$\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} + C\frac{\tau p}{1 + \tau p}\,\theta = AS$$

which can be rearranged as

$$\tau\frac{d^3\theta}{dt^3} + (1+\tau B)\frac{d^2\theta}{dt^2} + (B+\tau C)\frac{d\theta}{dt} = AS + \tau A\frac{dS}{dt}. \tag{3}$$

This equation is derived directly by consideration of the circuit in the Appendix.

The condition of the aircraft with the complete autostabiliser control equation in use was known as 'Full-Auto', and this term is used hereafter to denote a control which can be described by equation (3).

The effect of this modification on the response of the aircraft to a control input is shown in Figs. 7a and b. With the original position control the rate of pitch or roll resulting from a stick movement rose to a peak and then fell off again to zero, after a slight overshoot in the particular case shown. The attitude changed correspondingly to a new steady value. With the modified control equation the initial response was little changed, but after the rate had reached its peak it fell off again to a steady value which in the case illustrated ($\tau = 3$) was 38% of the peak rate. The attitude, instead of reaching a new steady value, went on increasing at a constant rate. The leak resistors, and hence the time constant, τ, could be varied, and the relation between the time constant and the ratio of steady rate to peak rate is shown in Fig. 8.

As well as the condition of 'Full-Auto', with the complete autostabiliser control equation in use, the facility was available of switching out either or both of the gyro terms. Firstly the integrating condensers could be switched out of circuit, leaving only the rate-damping term. The control equation then became simply

$$\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} = AS.$$

In this condition, which was known as 'Auto-Rate', a stick demand resulted in a steady rate of pitch or roll and the aircraft response is also shown in Fig. 7.

Finally the rate-damping term could also be switched out leaving a simple acceleration control

$$\frac{d^2\theta}{dt^2} = AS.$$

This condition was known as 'Manual', but the control was still electrically signalled.

3. *Tests Made.*

Much of the information desired from the flight tests of the Flying Bedstead had to be based on pilots' opinions and was obtained in handling flights without any specific manoeuvres being required. However, when tests were being carried out on the effects of varying the overall stability level, an attempt was made to quantify these effects. In these tests the pilots were asked to carry out as rapidly as possible a standard manoeuvre, which was intended to represent the kind of manoeuvre which the pilot of a V.T.O.L. aircraft would have to perform at the end of a transition with the aircraft hovering. Under such circumstances the pilot would, in general, have to turn towards the desired touch-down point, fly to it and land, and the manoeuvre therefore consisted of a 90° rotation, an 80 yard translation and a descent of 40 feet.

In order to achieve results which were as objective as possible, independent observers timed the tests. The pilots were given a period of familiarisation after any change in stability so that no reduction of manoeuvre time with learning affected the results.

3.1. *Operating Restrictions.*

The aircraft was not normally flown unless the wind speed was 10 knots or less, basically for safety reasons. As stated previously, if the fault circuit detected a fault in one of the control lines, that line was switched out, the maximum rate of control-valve movement being thereby halved. This effectively increased the lag in the control system and made the pilot's task more difficult.

Since the safety of the aircraft depended on the pilot's ability to control it after a fault had occurred, it was necessary to restrict flying to weather conditions in which the aircraft could be controlled after a fault.

Further the lag in single-line operation of the autostabiliser could be sufficient for an almost undamped aircraft oscillation of about 1 c/s to occur; when the lag became as large as this the overall stability and control in the single-line flight condition became still poorer. This oscillation could occur in either 'Full-Auto' or 'Auto-Rate', being effectively caused by the lag in the complete loop, including the aircraft, being too high for the system to be stable. The lower the damping and stiffness of the aircraft were, the less was the liability of the oscillation to occur, but it caused trouble occasionally in all conditions. A great deal of ground testing was done in attempts to pin-point the cause of this lag increase without any satisfactory solution being discovered. There appeared to be some correlation with servo temperature, but tests at Rolls-Royce showed no deterioration of servo output torque up to considerably higher temperatures than those measured on the aircraft.

Since this deterioration could occur imperceptibly in a series of flights it was necessary for the pre-flight checks to be completed by lifting the aircraft off with each line operating alone in turn and hovering it momentarily at a height of a few feet. The accident which terminated the flight programme was caused by a relay failure with the consequent application of full control in pitch, under these conditions.

4. *Results and Discussions.*

4.1. *Height Control.*

One of the first lessons learned from the tests of the Flying Bedstead, which became apparent while it was still flying in the gantry at Hucknall, was that the main difficulty in hovering flight was the height control. Once a pilot had mastered the problems involved in the reasonably accurate control of height he had no real difficulty in flying the aircraft.

The main reason for the difficulty experienced by pilots in controlling height was the lag between the throttle movement and the engine response, illustrated in Fig. 9, taken from Ref. 2. The Nene engines which provided the lift of the Flying Bedstead were modified production propulsion engines and their response to throttle movements was slow compared with that of more recent specialised lifting engines, or compared with the response of a helicopter rotor to movements of the collective pitch lever. Thus during the flight recorded in Fig. 9 the lag between the curves showing r.p.m. demanded by the throttle and actual r.p.m. was around 1 second, and on occasions the pilot had to start reversing the direction of a large throttle movement while the engine response to this movement was still building up.

It should be observed that Fig. 9 refers to a flight in the gantry at Hucknall in which the pilot was trying to make accurately controlled changes in the aircraft height. During free hovering the height was not normally controlled so accurately and the number of throttle movements was smaller. Fig. 9 also tends to exaggerate the lag, in that a change in thrust would occur before the r.p.m. changed, due to the much more rapid change in fuel flow rate following a throttle movement.

Fig. 10 shows the response to throttle movement in terms of r.p.m. for the Nene engines used, and illustrates more exactly the actual lag in the thrust variation on this aircraft. Measurement of the difference between the throttle movement and the r.p.m. response at the point where 90% of the r.p.m. change demanded has been achieved shows a lag which increases with the speed of the throttle movement. This lag is about 2·1 seconds for the fastest movement shown and would be between $2 \cdot 1$ and $2 \cdot 2$ seconds for an instantaneous throttle movement. For comparison, for a specialised light-weight lift engine such as the RB 108, 90% of an r.p.m. change demanded instantaneously would be achieved in about $0 \cdot 45$ seconds. 90% of the corresponding thrust change would be reached more rapidly, in about $0 \cdot 3$ seconds.

Pilots were thus required to introduce a phase advance in their operation of the throttle and one of them aptly described the problem by writing: 'Control of the height can best be imagined by considering a long coil spring with a weight hanging on the end of it. The pilot holds the other end of the spring and must move his hand in order to control the height of the weight. Moreover the spring changes its rate'.

However with regular practice pilots became extremely proficient, being capable of controlling the height of the aircraft with astonishing accuracy, and an experienced pilot could arrest the descent of the aircraft a few inches above the ground before a touch down. It is nevertheless clear that lag in the height control can be a major difficulty in the control of a VTOL aircraft*.

Two unsuccessful modifications were made to the height control in attempts to improve it. The first of these was a simple trimmer which reduced the throttle opening at a constant rate during flight with the intention of eliminating the necessity for constant adjustments of the throttle setting as the aircraft weight varied. This device did not in practice make the pilot's task any easier while it had undesirable side-effects in reducing the aircraft's effective thrust-weight ratio. It was therefore abandoned.

The second modification, which was known as a 'throttle anticipator', used a spring and dash pot in the throttle-control run to arrange that a throttle movement by the pilot caused initially a larger throttle movement at the engine. The throttle movement at the engine returned to that demanded by the pilot exponentially with a time constant which could be varied between $0 \cdot 5$ and 5 seconds. The throttle opening at the engine was allowed to exceed its normal maximum opening momentarily, so that there was no discontinuity in the response to the pilot's throttle movement near full throttle.

Two of these throttle anticipators were installed on the aircraft, one on each engine, but severe problems were encountered in the mechanical design and they were never made to work satisfactorily. Since increased experience of the height control showed that pilots could get used to it, the idea was not developed further.

In spite of the difficulty of the height control there appeared to be no well-defined lower limit to the thrust-weight ratio at which a controlled landing was possible. In hot weather it was sometimes necessary for the pilot to wait until enough fuel had been burnt to make take-off possible. He would then hover at a height of a few feet for a period of the order of half a minute to check the controls before re-landing. While the reduction in the recirculation of exhaust gas into the engine intakes as height was gained increased the effective thrust-weight ratio after take-off, it was proved clearly possible for an experienced pilot under calm conditions to perform take-offs and controlled landings with thrust-weight ratios very little in excess of unity. Pilots found however that take-off at marginal thrust-weight ratios was more difficult if there was any wind. A reduction in lift was experienced if the aircraft was tilted to counteract the effects of the wind, this reduction being usually increased because the angle of tilt was not constant. While normally this had no appreciable effect it could prevent the aircraft from taking-off successfully under marginal conditions.

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* While the flying of the second prototype does not strictly come within the scope of this report it is relevant to say that the shortcomings of the height control were almost certainly partially responsible for the accident to this aircraft at Hucknall.

4.2. *Control Power and Lag.*

When the Flying Bedstead was designed it was intended to vary the control power in order to establish minimum values, if possible. In practice, it was never considered safe to reduce the control powers below those achieved, nor was it possible to increase them significantly, but nevertheless some useful conclusions can be drawn from the flight experience.

The maximum acceleration produced by full control application in pitch was $0 \cdot 75$ radians/sec^2, and this control power was generally considered to be acceptable under the conditions in which the aircraft was flown.

Extracts from flight records, given in Fig. 11, show stick and control-valve movements and the aircraft response in normal hovering flight and in deliberate manoeuvres. It is apparent that in the fairly calm conditions of the tests, the pilot's normal control movements were small and except in deliberate manoeuvres the stick and valve movements rarely exceeded 25% of those available. Because the pilot, as well as the autostabiliser, reacted to external disturbances, and because of the form of the control equation, it is not practicable to determine just how much control would have been applied by the autostabiliser in the absence of pilots' inputs: the amount of control used by the pilot and the autostabiliser together to keep the aircraft level in hovering flight cannot however be much different from that which would have been applied by the autostabiliser alone for the same task.

During manoeuvres, however, such as that shown in Fig. 11a in which the pilot was starting to move the aircraft from a hovering position, full control was frequently used and it was generally felt that rather more control power could have been employed and that it would have been essential in more turbulent conditions.

The maximum acceleration available in roll was less than that in pitch, being only $0 \cdot 55$ radians/sec^2, and the roll-control power was criticised much more than the pitch-control power. It was generally agreed that the roll control had insufficient power and that the power would have been dangerously inadequate in turbulent conditions. Typical pilot's comments were: 'The Bedstead suffers from poor response and power in roll. For instance in a wind of 20 knots it is likely that it can be flown without difficulty provided it is kept head or tail into wind. On the other hand it is almost certain that it cannot be flown safely with such a wind from one side', and 'The response in roll was poor in all conditions. This might well be a critical factor when gusty conditions prevail'. The second of these pilots abandoned as unsafe an attempted flight in gusty conditions with a wind of 15 to 20 knots, stating that he was frequently using full control in roll to counteract the effects of gusts.

Full control in yaw produced an acceleration of $0 \cdot 375$ radians/sec^2, and did not give rise to much comment. Full control was normally used in rotating the aircraft and a more-powerful control might have been an advantage. As however the aircraft had no stability in yaw and did not respond to turbulence it is not possible to draw any conclusions from these tests about the yaw-control requirements of future aircraft.

These views on the adequacy of the control powers, particularly in roll, cannot be entirely divorced from the large lags present in the control systems, some indication of which can be seen in Fig. 11a. The measured lag from the initiation of a control movement by the pilot to the start of the change of pressure at the control nozzle was about $0 \cdot 2$ seconds. Three-quarters of this lag occurred before there was a perceptible response of the butterfly valves and was due to lags in the autostabiliser, in particular because the high air loads on the control valves required the servo-motor to reach a high proportion of its peak torque before any movement started. The remaining lag, which was difficult to measure accurately and apparently varied[2] with the magnitude and rate of the control movement, was due to the time taken for the flow to change in the control pipes.

These large lags definitely had a deleterious effect on the controllability of the aircraft in turbulent conditions, but since it was not practicable to reduce them no estimate could be made of their effect on control-power requirements. In any case a jet-lift aircraft would have a greater response to gusts than the Flying Bedstead, which had no aerodynamic surfaces, and this might well cancel out any improvement due to reduced control lags.

It therefore seems reasonable to conclude that for an aircraft of the size of the Flying Bedstead the controls should be capable of producing maximum accelerations of at least 1 radian/sec^2 in either pitch or roll and that if the controls are much less powerful than this, operation of the aircraft in turbulent conditions is likely to be difficult or hazardous. Yaw control should be capable of producing at least 0·4 radians/sec^2, but it is not possible to say whether this will be sufficient for turbulent conditions.

It can also be said that the maximum allowable lag in the control system is about 0·2 seconds, and that less is desirable, but it is not possible to say whether reductions in lag have an appreciable effect on control-power requirements.

4.3. *Desirable Stability Level.*

4.3.1. *Form of control equation.*—Tests were carried out with the Flying Bedstead with all the forms of the control equation available from the autostabiliser, from no damping at all, through rate damping and the 'Full-Auto' control, to what was virtually a position control.

Of these the pilots' preference was for the 'Full-Auto' control with a short attitude memory, at least in pitch. As a result of a series of qualitative handling tests in which the time constant of the attitude 'leak' circuit was varied from 22 seconds down to 2 seconds, the pilots expressed a preference for a value of 3 to 4·5 seconds, giving a ratio of steady rate to peak rate of about 25% to 35%, as shown in Fig. 8. It was stated that with the shortest time constant the control was inferior to simple rate damping, while with longer time constants noticeable variations occurred in the available control power after steady attitudes had been held for some time. Thus if a negative attitude was held for several seconds as the aircraft was flown from one point to another, this attitude became the autostabiliser zero and the positive attitude available for deceleration was reduced until the autostabiliser zero had time to correct itself. This situation is illustrated in Fig. 12. With the time constant chosen this effect was not noticeable and the pilots liked the resulting control. Thus one pilot commented: 'The original leak time constant was far too long. In this condition the pilot did not have full control of the machine. At times he had to wait for the "leak" to take effect. This was an extremely uncomfortable sensation and gave the impression that the machine was misbehaving. When the time constant was reduced to 4·5, 3 or 2 seconds the above mentioned effect apparently disappeared, because the rate of zeroing of the stabiliser approached the rate of pitch selected'. He also wrote: 'The time constant of 4·5 seconds appeared to satisfy most requirements. The stability of the machine appeared quite good and controllability was all that could be asked for'.

Very little flying was done in 'Manual'. Two R.A.E. pilots tried it in the gantry but only one pilot tried free flight in this condition. He found that it was possible with concentration not only to hover the aircraft but to make a deliberate change in attitude and to bring the aircraft back to the horizontal again. Comments made by the two pilots who tried 'Manual' flight were: 'Manual control is feasible, although continuous attention must be paid to lateral control and no excessive roll be allowed to develop (limit about 5° to 10° estimated) otherwise control becomes marginal', and 'Flight in Manual is ill-advised during gusty conditions with the present response in roll'.

The general conclusion is that, while 'Manual' control was possible in good conditions, it required a great deal of concentration, particularly in roll. It would not have been a practical proposition in turbulent conditions and even in good conditions the pilot would have had little attention to spare for other problems. Reduced control lag and higher control powers, particularly in roll, on future aircraft may make Manual control less difficult but the general conclusion that it demands an impracticably large proportion of the pilot's attention is unlikely to be altered.

'Auto-Rate' control with rate damping only was on the other hand quite practical, and some pilots preferred to have only rate damping in roll, at least in good weather. In pitch on the other hand the greater ease of control with the rate-aided control was preferred even in good weather, the preference becoming stronger in gusty conditions.

A typical comment was 'Gustiness also brought out the difference between "Full-Auto" and "Auto-Rate" to a much more marked degree. The stick was used a great deal more as the machine was displaced by gusts'. Comparison between Figs. 11b and c shows the greater control movements used in hovering flight in 'Auto-Rate'.

No stability augmentation was ever tried in yaw and pilots had no difficulty with the yaw control. The Flying Bedstead however had no response in yaw to external disturbance and it therefore does not necessarily follow that on future aircraft yaw stabilisation may not be advantageous.

4.3.2. *Desirable stiffness and damping.*—The greatest part of the flight test programme was taken up with the quantitative tests on the effect of varying the stiffness and damping terms in the autostabiliser control equation. During these tests five different aircraft conditions were examined, and in each condition the mean value of the times taken to perform the standard manoeuvre described in Section 3 was obtained together with the standard deviation of the times. In the table below the times obtained are listed, together with the autostabiliser conditions as described in Section 2.3.2.

Condition	Rate of pitch to demand full control application $\equiv \frac{15A}{B}$ (degrees/second)	Attitude in pitch to demand full control application $\equiv \frac{15A}{C}$ (degrees)	Mean time for manoeuvre	Standard deviation
I	10	10	24·6	2·1
II	15	15	22·5	1·7
III	20	20	22·4	2·5
IV	10	20	27·3	2·7
V	15	20	23·5	2·3

The leak time constant was kept constant at 3 seconds and the roll control was in condition I throughout.

Although the absolute differences between the mean times for the standard manoeuvres are not large the standard deviations are also small, so that the differences are usually statistically significant, the exceptions being those between conditions II and III and between III and V.

Two main conclusions can be drawn from these figures. The first is that any of the conditions tested represents a practicable control equation for a jet-lift aircraft when hovering. Further, taking into account the pilot opinion that condition III was the most difficult in turbulent weather, it may be concluded that condition II would be a reasonable starting point for hovering-flight trials of a new aircraft.

Secondly it can be concluded that even with the optimum stiffness and damping the correction of an error at the end of a transition by a hovering jet-lift aircraft will be relatively expensive in fuel. A manoeuvre such as this, taking 20 seconds to perform with the aircraft hovering, will mean the consumption of about $0 \cdot 5\%$ of the aircraft weight in fuel, which may be as much as is required in the whole of a transition from the normal aircraft approach speed down to hovering flight[3].

4.4. *Feel.*

Feel on the Flying Bedstead was purely artificial, by means of springs. The stick forces were light, being about 5 lb force for full deflection in either pitch or roll. Initially a small 'break-out' force was required to move the stick away from the neutral position, but pilots objected to this and it was reduced as nearly as possible to zero while retaining self-centring of the stick.

The general pilots' opinion was that the stick forces should be kept as small as possible consistent with self-centring. There was of course no danger of over-stressing the aircraft in flight and therefore, to quote one pilot: 'There is no virtue in making the forces heavy, and in gusty conditions a pilot would soon tire if moderately large forces were necessary'.

The rudder pedal forces on the other hand were initially heavy—50 lb for full deflection—in order to ensure self-centring despite the large friction forces in the circuit. These high forces, compared with the small stick forces, gave the impression that the yaw control was less powerful than it was and gave rise to complaints. The forces were therefore halved, but although this improved the control it was still not considered satisfactory.

The springs in the circuit were then removed entirely so that the only forces required were to overcome friction, and there was of course no self-centring. This was considered to be the best compromise and the aircraft was thereafter flown throughout in this condition.

4.5. *Electrical Signalling.*

Besides the results already discussed which were specifically concerned with the jet-lift side of the Flying Bedstead experiment, a certain amount of useful experience was accumulated on electrical signalling, and on the operation of the triplex autostabiliser.

The autostabiliser was of course purely experimental and too much emphasis should not be placed on the maintenance difficulties although they greatly reduced the amount of flying done. The principal difficulties were matching of the components in the three lines and matching of the servos to avoid the frequent occurrence of spurious 'faults' while retaining a high-enough sensitivity in the fault circuit to ensure that real faults would be rapidly detected. Difficulty was also experienced with potentiometers: too high a brush pressure caused rapid wear and shorting out of individual windings while too low a pressure allowed loss of contact and so the occurrence of a fault under acceleration. Relays, while not a constant source of trouble, caused a considerable demand for maintenance effort.

5. *Conclusions.*

(1) The conclusions from the flight experience on the Flying Bedstead are bound to be tentative in nature: its size, its lack of aerodynamic shape, and the nature of its controls are bound to have some effect on the assessment. Nevertheless it is worth while putting forward some results which can be used until further evidence from other VTOL aircraft becomes available.

(2) The main conclusion to be drawn from this experience is that any practical jet-lift aircraft must have some artificial stabilisation while hovering if it is to operate in other than very favourable weather conditions. Artificial stabilisation appears to be essential in both pitch and roll: yaw stabilisation is not essential at least when the aircraft is hovering.

(3) It is desirable for the artificial stabilisation in pitch to include both a rate-damping term and a short-memory attitude term. Suitable values for these terms are that full restoring control should be demanded by a rate of pitch of 15 degrees/second or by a pitch attitude of 15 degrees, with the attitude term decaying with a time constant of 3 to 5 seconds. Rate damping only may be sufficient in roll, with full restoring control again demanded by a rate of about 15 degrees/second (a roll time constant of 0·25 seconds).

(4) It can further be concluded that for a jet-lift aircraft of the size of the Flying Bedstead, full control should be capable of producing accelerations of at least 1 radian/second^2 in either pitch or roll. It is not possible to draw conclusions about the minimum control power in yaw but pilots are capable of using accelerations in yaw of 0·4 radian/second^2 without artificial yaw damping.

(5) The main difficulty in learning to fly the aircraft was the height control; any reduction in the time constant of the engine response would make the problem of learning to fly a jet-lift aircraft easier.

REFERENCES

No.	*Author(s)*	*Title, etc.*
1	R. R. Duddy	Experiments on the stability and control of jet-borne aircraft. Unpublished M.o.A. Report. February, 1954.
2	A. G. Smith	Further ground and flight testing of the first jet control research unit. Rolls-Royce Experimental Department Report. May, 1955.
3	J. S. Shayler and J. K. B. Illingworth	Blind flying of V/STOL aircraft with particular reference to take-off and landing. AGARDograph 46. June, 1960.

APPENDIX

Derivation of Control Equation

The basic circuit for the derivation of the control equation is that shown in Fig. 6.

LIST OF SYMBOLS USED IN THIS APPENDIX

A, B, C, D	Constants
C_1	Capacity of integrating condenser
G	Rate-gyro constant
j	Current through gyro coil
j_1	Current through integrating condenser
j_2	Current through leak resistance
R_1	Gyro coil resistance (including trimming resistance)
R_2	Leak resistance
S	Stick angle
V	Autostabiliser output voltage
θ	Aircraft attitude
τ	Time constant of 'leak circuit'

The electric-spring gyro functioned so that the current through the coil was proportional to the rate of rotation of the aircraft, and

$$j = G\frac{d\theta}{dt}. \tag{4}$$

Also the voltages across the condenser and the leak resistance were equal, so that

$$\int \frac{1}{C_1} j_1 dt = R_2 j_2$$

or

$$j_1 = C_1 R_2 \frac{dj_2}{dt}. \tag{5}$$

And the output voltage V was the sum of the voltages across the gyro coil and the leak resistance, or

$$V = R_1 j + R_2 j_2 \tag{6}$$

while

$$j = j_1 + j_2 \tag{7}$$

therefore

$$V = R_1 j_1 + (R_1 + R_2) j_2 = C_1 R_1 R_2 \frac{dj_2}{dt} + (R_1 + R_2) j_2 \tag{8}$$

and

$$G\frac{d\theta}{dt} = C_1 R_2 \frac{dj_2}{dt} + j_2. \tag{9}$$

From equations (8) and (9)

$$V - GR_1 \frac{d\theta}{dt} = R_2 j_2$$

and

$$(R_1 + R_2)G \frac{d\theta}{dt} - V = C_1 R_2{}^2 \frac{dj_2}{dt}.$$

So that

$$C_1 R_2 \frac{dV}{dt} - C_1 G R_1 R_2 \frac{d^2\theta}{dt^2} = (R_1 + R_2)G \frac{d\theta}{dt} - V$$

or

$$V + C_1 R_2 \frac{dV}{dt} = (R_1 + R_2)G \frac{d\theta}{dt} + C_1 G R_1 R_2 \frac{d^2\theta}{dt^2}. \tag{10}$$

Now V the output voltage of the gyro circuit, is related to the attitude of the aircraft by a relation

$$\frac{d^2\theta}{dt^2} = \text{constant} \times \text{control-valve deflection} = AS - DV$$

or

$$DV = AS - \frac{d^2\theta}{dt^2}$$

and

$$D \frac{dV}{dt} = A \frac{dS}{dt} - \frac{d^3\theta}{dt^3}.$$

Substituting in equation (10) we get

$$AS - \frac{d^2\theta}{dt^2} + AC_1 R_2 \frac{dS}{dt} - C_1 R_2 \frac{d^3\theta}{dt^3} = DG(R_1 + R_2) \frac{d\theta}{dt} + DGC_1 R_1 R_2 \frac{d^2\theta}{dt^2}$$

or rearranging,

$$C_1 R_2 \frac{d^3\theta}{dt^3} + (1 + DGC_1 R_1 R_2) \frac{d^2\theta}{dt^2} + DG(R_1 + R_2) \frac{d\theta}{dt} = AS + AC_1 R_2 \frac{dS}{dt}.$$

This is identical with equation (3) of Section 2.3.2 with the values of the constants in that equation being

$$\tau = C_1 R_2$$
$$B = DGR_1$$
$$C = DG/C_1.$$

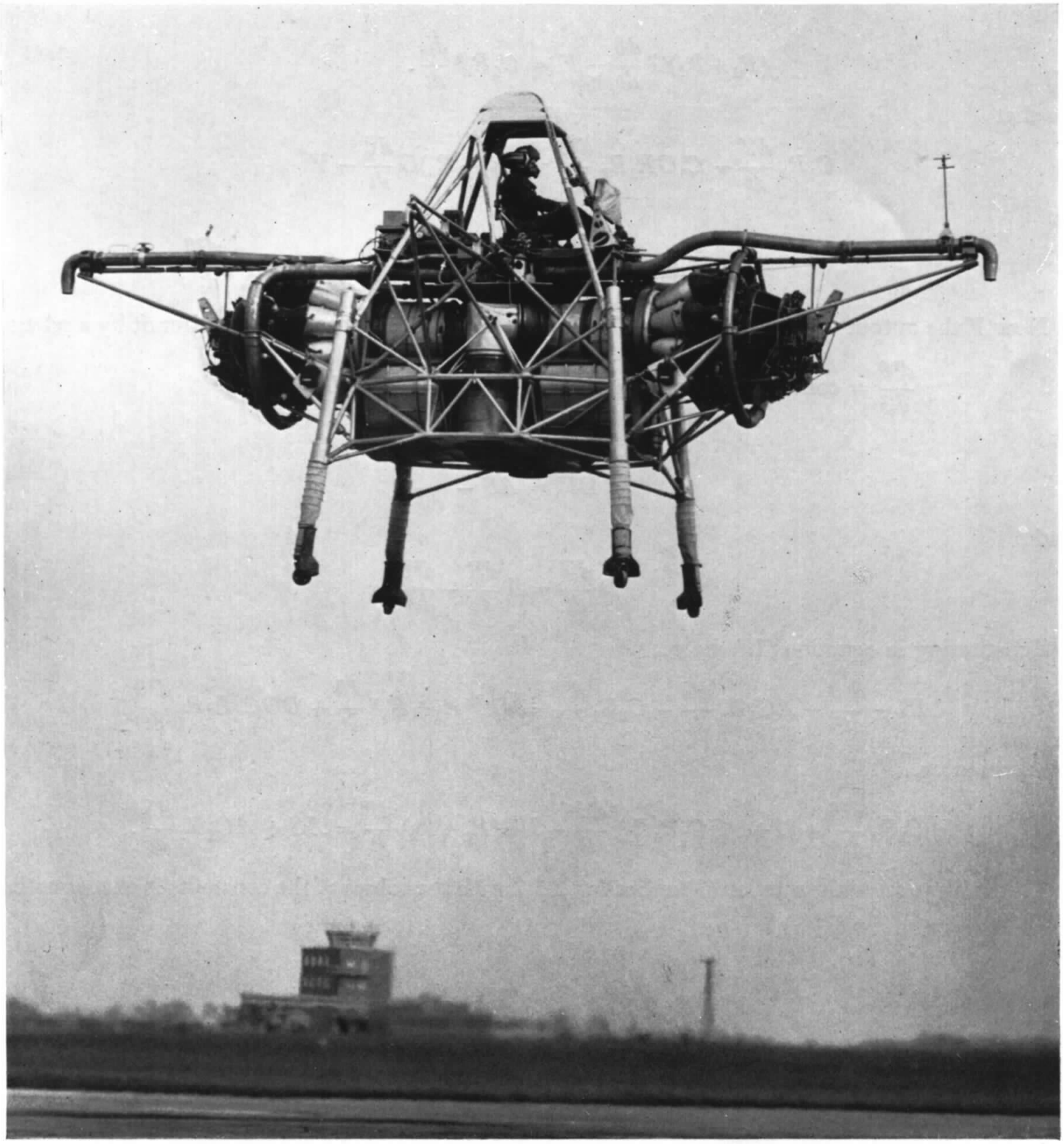
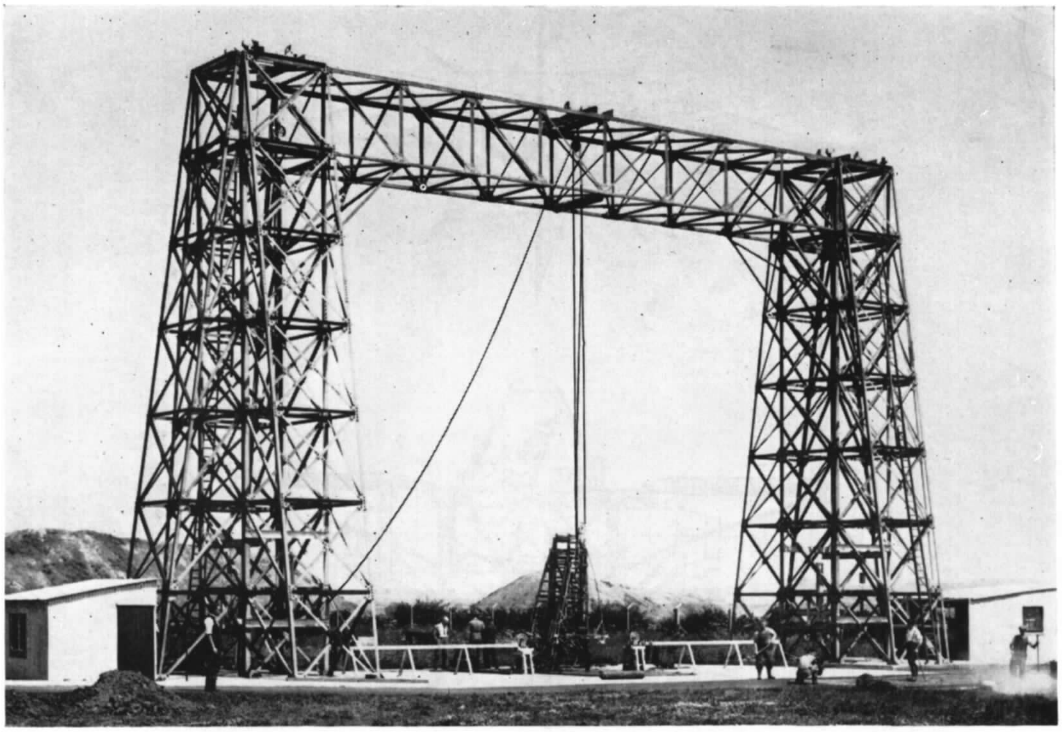


FIG. 1. The Rolls-Royce Flying Bedstead.



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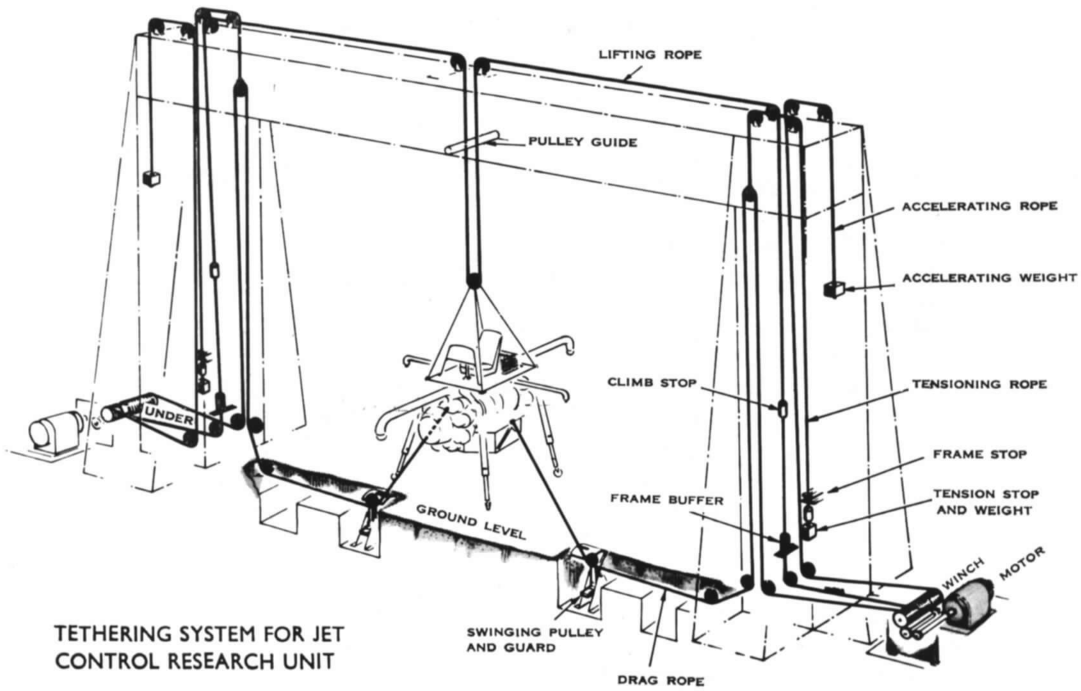


FIG. 2. Gantry and gantry cable system.

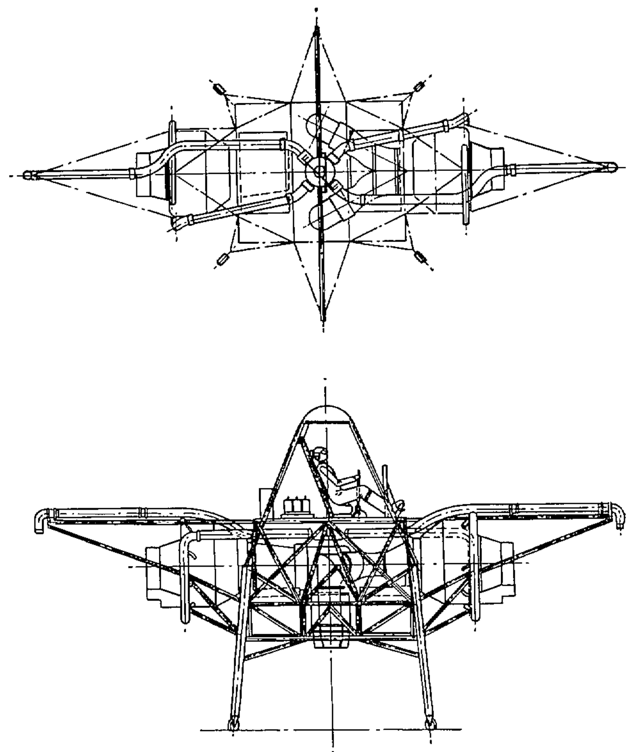


FIG. 3. General arrangement of Rolls-Royce Flying Bedstead.

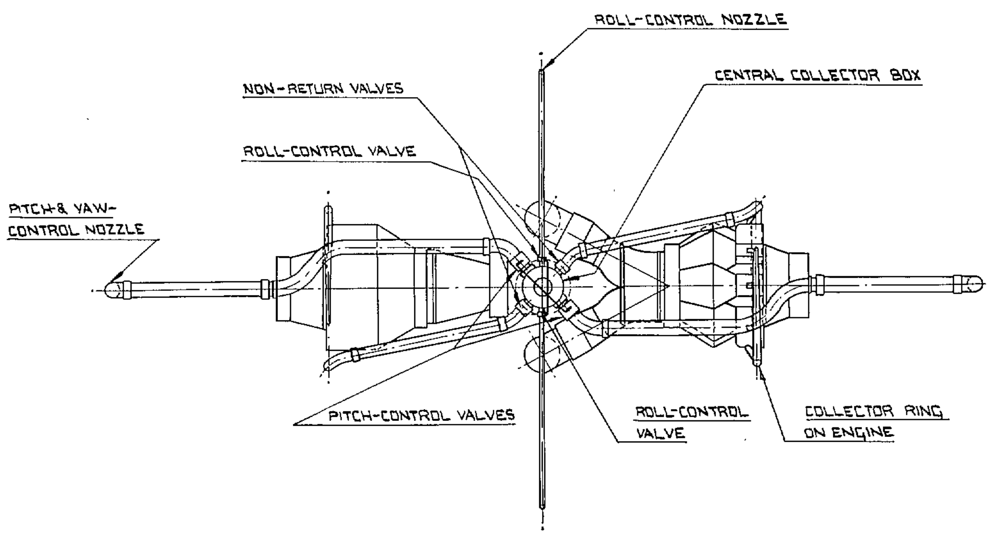


FIG. 4. General arrangement of control air bleed and ducting system.

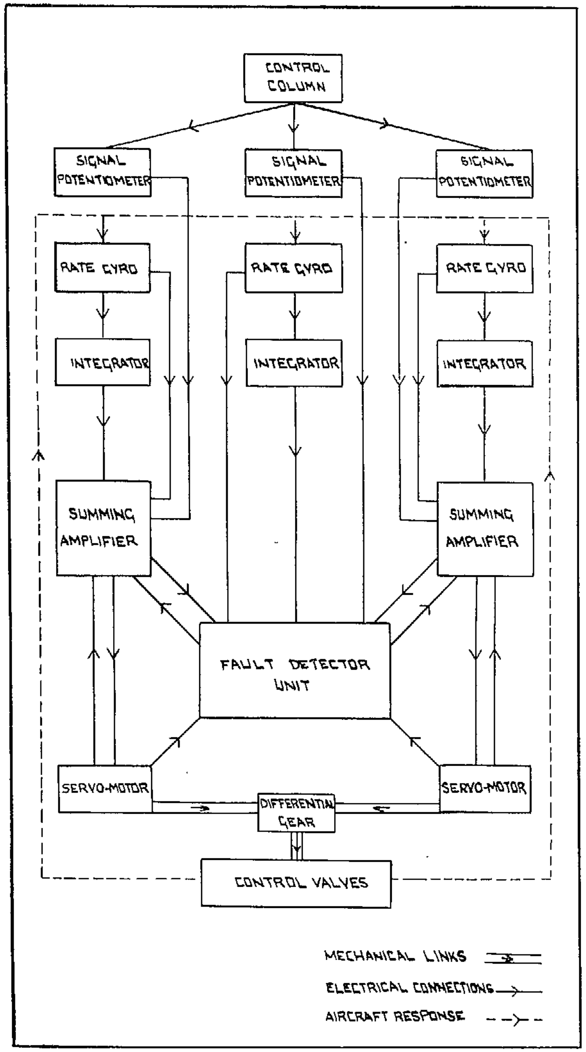


FIG. 5. Block diagram of autostabiliser.

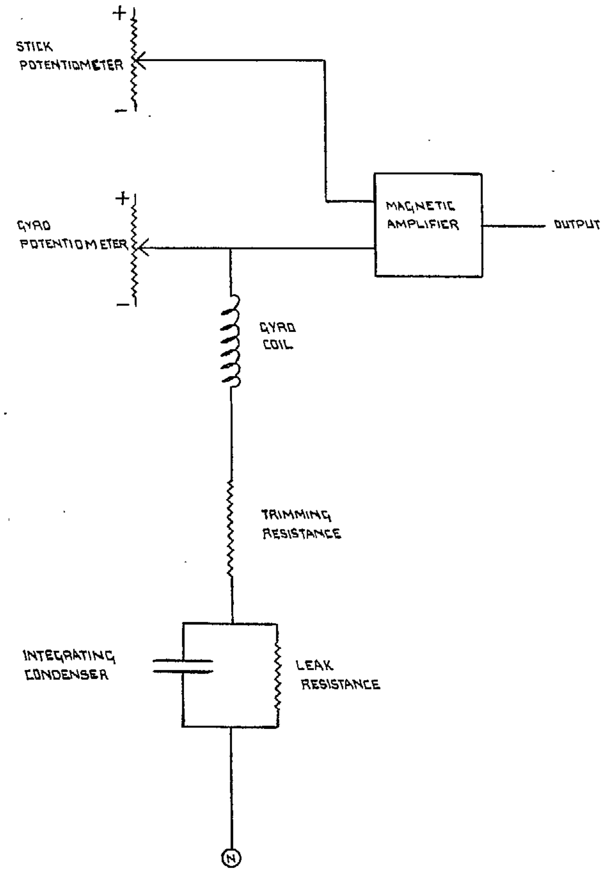


FIG. 6. Schematic diagram of gyro integrator circuit.

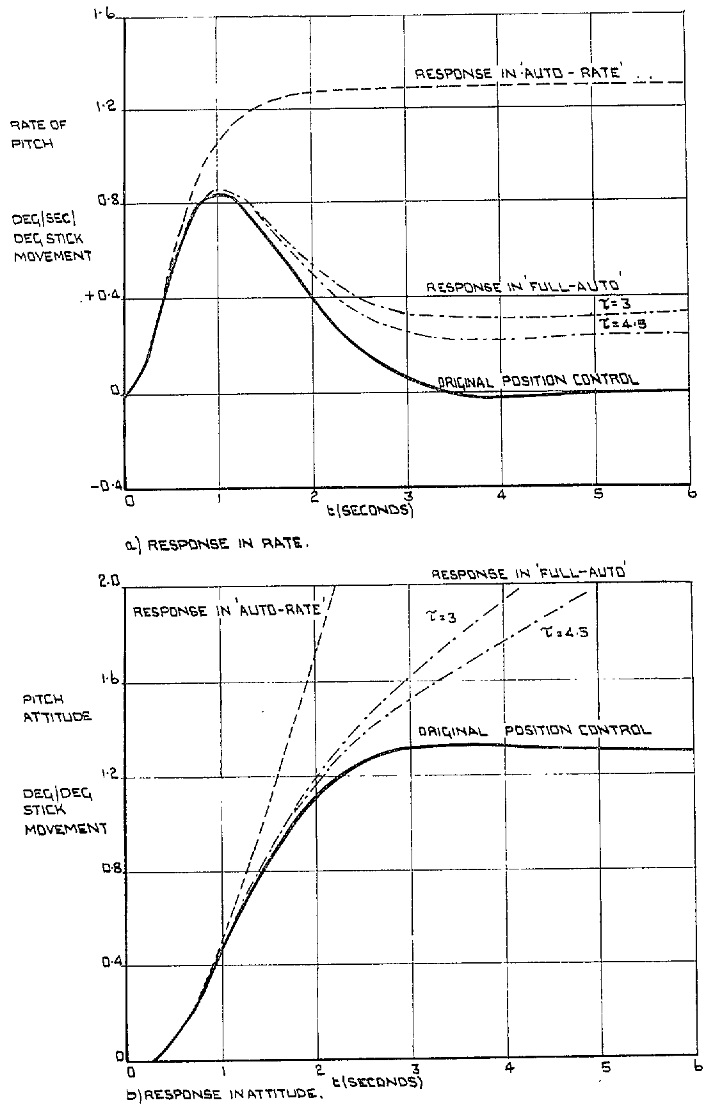


FIG. 7. Typical aircraft response to ramp control input applied in 0·5 seconds.

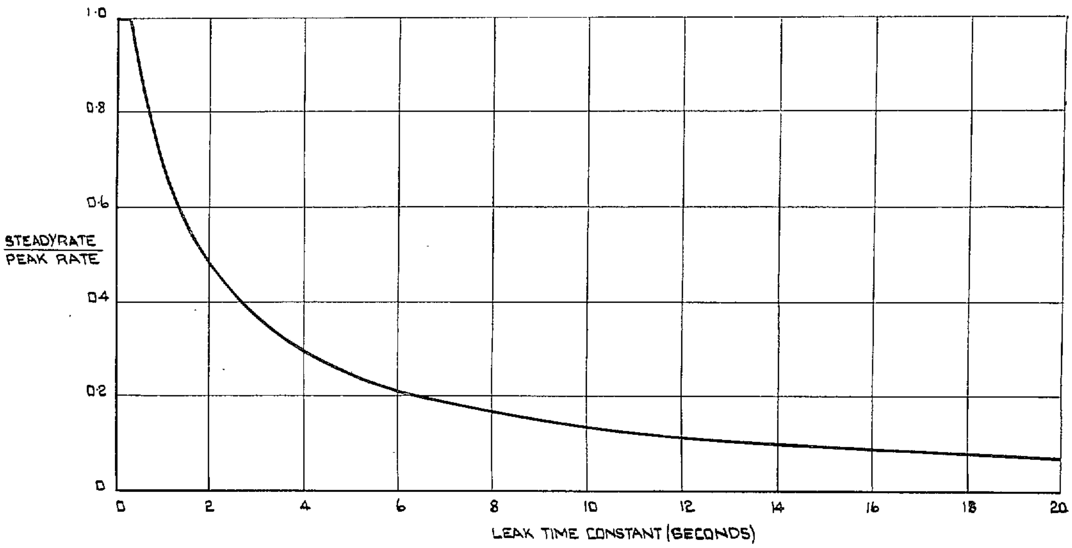


FIG. 8. Variation with leak time constant of the ratio of the final aircraft rate to the peak rate after a step control input.

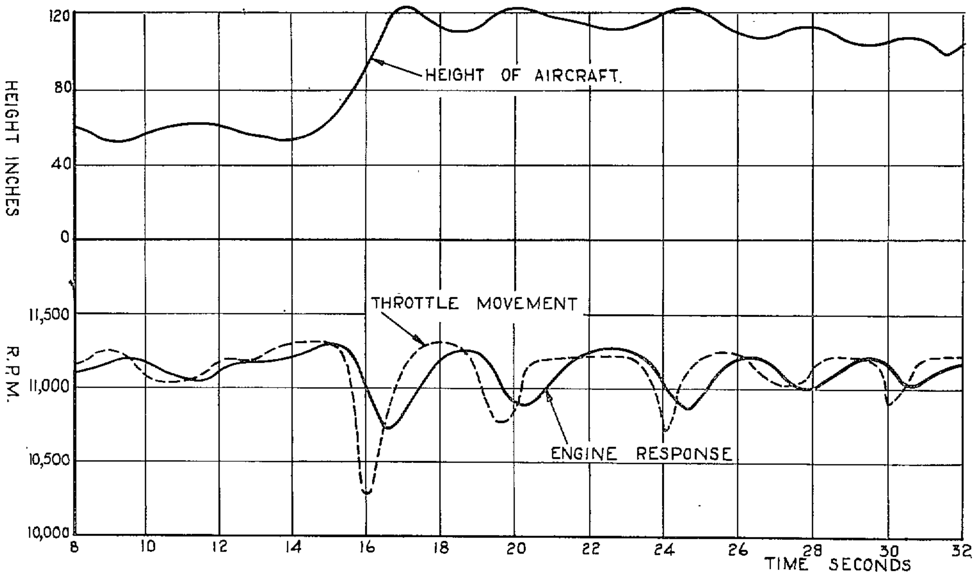


FIG. 9. Time history of demanded engine r.p.m., actual r.p.m. and aircraft height during hovering in the gantry.

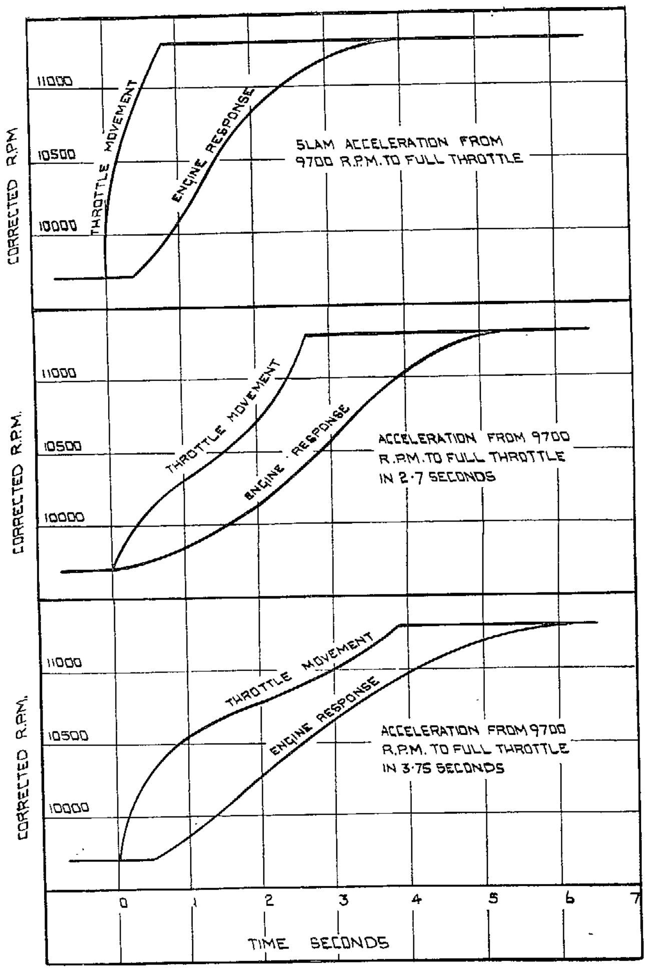


FIG. 10. Engine response to throttle movements.

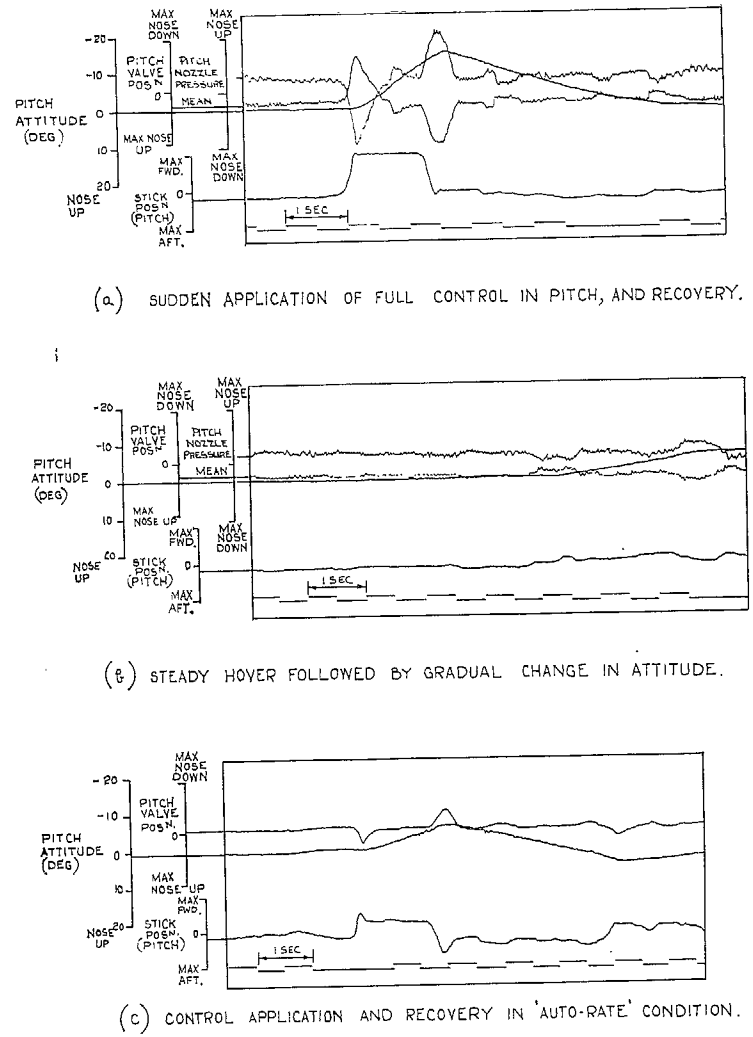
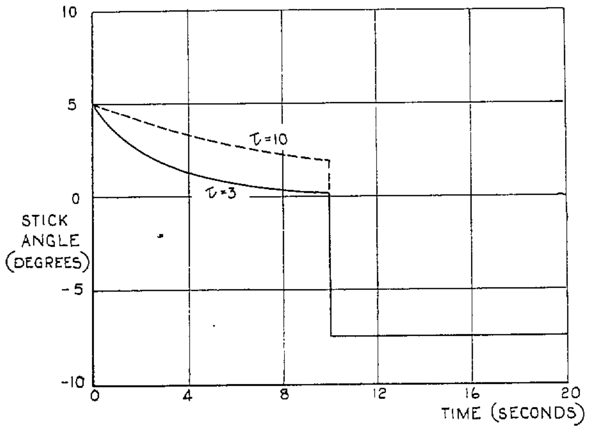
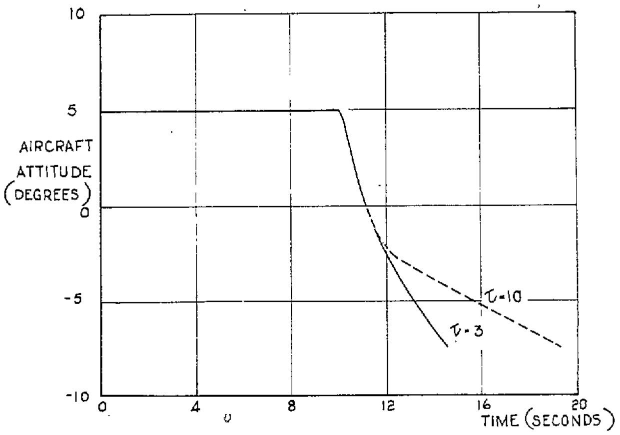


FIG. 11. Extracts from flight records.



(a) STICK MOVEMENT TO HOLD CONSTANT ATTITUDE, FOLLOWED BY STEP STICK MOVEMENT.



(b) AIRCRAFT RESPONSE TO STEP INPUT AFTER A PERIOD AT CONSTANT ATTITUDE.

FIG. 12. Effect of autostabiliser leak time constant τ on stick movement and aircraft response

(87645) 65/1418 K.5 8/63 Hw.

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