The Digital Computer as a Helicopter Flight Simulator

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DR J A J BENNETT (*Chairman, Lecture Committee*) occupying the Chair

The CHAIRMAN said Mr Harrison was Chief Aerodynamicist of Westland Aircraft Ltd The subject was rather novel in the Association's lecture programme They had become accustomed to the idea of automation in industry and to the use of an automatic pilot, but somehow the conception of an automatic aerodynamicist, or the use of a black box in the Design Office, had not been given the attention it deserved Whether they liked it or not, however, for certain purposes there was no doubt that the human brain could well be replaced by an electronic brain, and Mr Harrison would show why this was so in helicopter investigations

MR J M HARRISON

SUMMARY

A method suitable for dealing with extended longitudinal manoeuvres is outlined, based on a step-by-step integration process It is shown how the necessary calculation is carried out on a digital computer, using a programme consisting of two parts A general part is applicable to any manoeuvre, and a special part idealises the pilot's action in performing the particular manoeuvre under consideration Using two illustrative examples, it is demonstrated how the method can be used to deal with problems which usually come under the heading of performance, but nevertheless involve handling qualities Some numerical results aid in the illustration

INTRODUCTION

When the treatment of the stability and control of a helicopter is first examined by an investigator with experience of fixed wing aircraft, it is likely that he will try to use the classical approach which works so successfully in

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that field He will find, though not after encountering and circumventing difficulties due to extra complications, that such methods work quite well within certain limitations Experience shows that calculated responses are valid only within the first few seconds of initiation, which, while limiting the scope, still leaves a reasonably wide variety of manoeuvres which can be dealt with adequately, and makes an exhaustive study worth while They are chiefly those which involve only a small change in forward speed, or rotor speed If it is required to examine a response over a longish period, or one involving large variation of parameters, the assumption of linearity on which classical method is based is best abandoned

It is the purpose of this paper to describe how two typical manoeuvres which come under this category can be tackled The reason for choosing these two particular manoeuvres, the power-off landing, and the take-off will become apparent at a later stage in the presentation In the process to be described, the motion is limited to the longitudinal mode, which is possible because the necessary control movements to maintain zero rates of roll and yaw, and angle of sideslip, have negligible effect on the longitudinal motion This does not imply that it is impossible to allow for cross coupling As is well known, in certain types of manoeuvres there are potentially embarrassing cross-couplings, which it might be desirable to investigate The method to be described is readily capable of extension to deal with such a situation In the following treatment, the number of degrees of freedom is limited to five, after first describing a simpler system having only two

The Descriptive Model

The geometry of a single (main) rotor helicopter is depicted in Fig 1 The coning angle is not represented, as it affects only two of the equations of motion to the second order, and has been neglected in the analysis Although there is in general a small offset of the flapping hinge from the

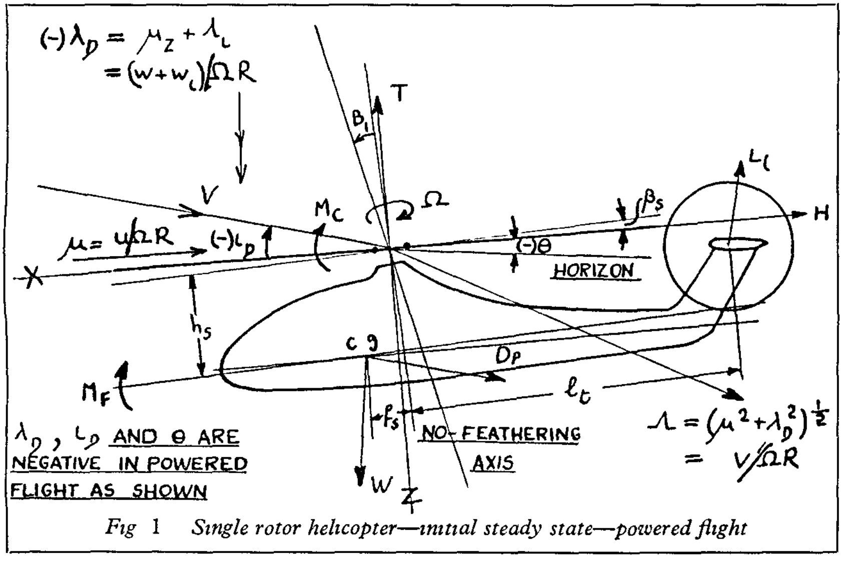

Fig 1 Single rotor helicopter—initial steady state—powered flight

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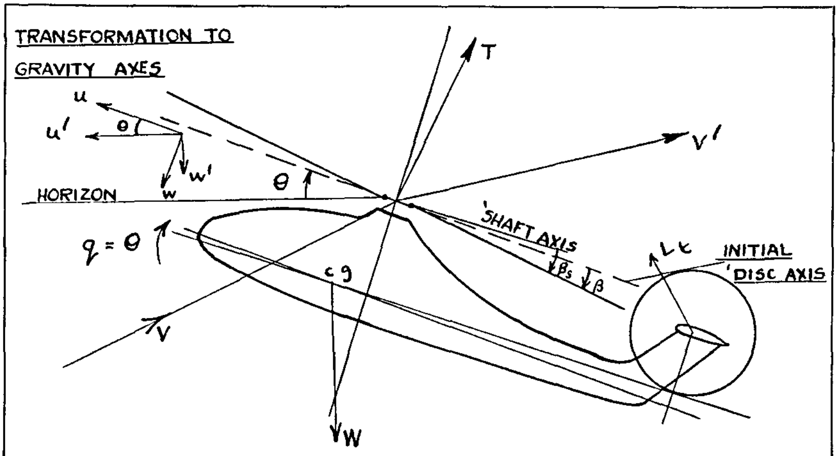

Fig 2 Single rotor helicopter—state during power-off manoeuvre

centre of rotation, the blades can thus be regarded as sweeping out a disc, instantaneously, and the containing plane will be called the disc plane The initial equilibrium position of the disc plane is used to define the axes of reference and contains the X axis pointing in the direction of flight The Z axis is normal to the disc and points downwards This system of axes is chosen for economy of computative effort The initial state is described by the following equations

$$W \cos \theta - T \simeq O \qquad (1)$$

$$D_p \cos i_D + W \sin \theta + H = O \qquad (2)$$

$$M_f + M_c - T (f_s - h_s\beta_s) + Hh_s - L_t (l_t + f_s) = O \qquad (3)$$

$$Q_R + \frac{\eta P_E}{\Omega} = O \qquad (4)$$

$$M_A \simeq O \qquad (5)$$

The first three equations describe the equilibrium of the helicopter, the fourth the equilibrium of the rotor about its shaft axis, and the fifth the equilibrium of an individual blade about its flapping hinge This latter moment is the longitudinal or sine component of flapping, and to a close approximation, for a small offset of the hinge, is entirely aerodynamic in origin After a disturbance, the helicopter and rotor are, in general, in a state of acceleration, the helicopter in translation along the X and Z axes, and in rotation about the Y axis , the rotor in angular motion about the shaft, and each blade about its flapping hinge The position at some stage of a manoeuvre is shown in Fig 2 In particular the attitude of the heli-

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copter has changed, and the disc has " flapped " through a small angle β Resolving, again with respect to the disc plane, the state of equilibrium is now given by

$$\frac{W}{g}(w - uq) + T - W\cos\theta \simeq O \qquad (1a)$$

$$\frac{W}{g}(u + wq) + (T\beta + D_p \cos i_D + H) + W\sin\theta = O \qquad (2a)$$

$$Bq - M_f - M_c + T(f_s - h_s\beta_s) - Hh_s + L_t(l_t + f_s) = O \qquad (3a)$$

$$I_R\Omega - Q_R - \frac{\eta P_E}{\Omega} = O \qquad (4a)$$

$$2\,I_B\Omega\,(q + \beta) - M_A = O \qquad (5a)$$

At any given instant, the various components of each equation can be expressed as functions of the dependent and independent variables Thus, *e g* , using elementary strip theory

$$T = f_1\,\{\theta_0, B_{1D}, u, w, w_i, \Omega\} \qquad (6)$$

The above equations are recognisable as the classical equations of motion, although usually (5a) is treated on a quasi-static basis, and (4a) is ignored in the linearised approach, whereby, partial differentiation of each equation with respect to the variables in turn, gives rise to the familiar aerodynamic derivatives The procedure is well known and should need no further enlargement The treatment accorded here is the equally well known step-by-step integration process Each component acceleration is defined by the identity of the appropriate equation (1a)—(5a) and is assumed to remain constant over a small finite time interval New values of the variables are arrived at by a simple integration , thus, *e g* , after the nth time interval

$$w_{n+1} = w_n + w_n\Delta t \quad \text{etc} ,$$

It has been found from experience that, as long as the time interval is kept sufficiently small, this is a sufficiently accurate process for practical purposes In addition, if the linear velocities u and w are now transformed with respect to gravity axes, further integration leads to a definition of the flight path The new values of the variables obtained as above can be used to revaluate the component accelerations and so on, in a cyclical process If computation is manual, changes in the independent variables, representing control inputs, may be introduced arbitrarily by inspection Difficulty arises however when computation is automatic, for it is then impracticable to use other than automatic means for this purpose How this problem is dealt with will be deferred to a later paragraph

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SIMULATED POWER-OFF LANDING

As an illustrative case, a simple two degree of freedom model will be used to simulate a power-off landing Only vertical velocity w and rotor speed Ω will be allowed to vary, and the initial angle of the disc to the horizontal will be assumed small so that

$$T \simeq W$$

The initiating disturbance is a complete and instantaneous power failure The motion will thus be triggered off by an unbalance of torque in the rotor shaft leading to

$$\dot{\Omega} = \frac{Q_R}{I_R}$$

where Q_R is the aerodynamic torque component previously balanced by the now non-existent engine output The resulting acceleration is therefore negative, and the thrust decays, leading to a downward acceleration given by

$$\dot{w} = g\left(1 - \frac{T}{W}\right)$$

New values of Ω and w are obtained by integration, and then, by transformation to gravity axes, the height loss by a similar process On the second cycle a complication arises, because a change in velocity of flow through the rotor implies a change in induced velocity

The standard method of dealing with this situation is to equate the blade element expression for the thrust (6) to the momentum expression, leading in general to a quartic in the induced velocity parameter It will be described later how this equation is solved by iterative methods

To return to the computative process , the " pilot's " reaction after an arbitrary delay, conventionally taken as one second, is to drop the collective pitch lever rapidly to the bottom stop

The step-by-step process indicates that downward acceleration builds up rapidly at a rate depending on the forward speed After an initial decay to a minimum value, which depends on the delay time and initial pitch setting, amongst other things, the rotor speed starts to build up rapidly As the maximum rotor speed is approached, collective pitch is increased progressively until the vertical velocity falls below a level which the undercarriage is capable of absorbing The height lost in this process gives a point on the safety envelope

THE GENERAL MANOEUVRE

Such a manoeuvre is a special case and describes approximately a pilot's reactions to engine failure in a speed band near to the minimum power speed It would not dangerously over-simplify the problem if the speed spectrum were divided into high speed, low speed, and intermediate bands The latter has been covered in the above description When caught out by engine failure in the high speed band (say from 50 knots upwards), the accepted procedure is to absorb kinetic energy due to forward speed by decelerating without losing height The first reaction is to reduce collective pitch as described above, followed immediately by a backward moment of the stick to raise the nose The result is two-fold, an increase in thrust and accelerating torque, both due to an increase in disc and blade incidence By judicious manipulation of the stick, level flight can be maintained whilst the backward component of the increased thrust decelerates the helicopter rapidly Meanwhile, stroking of the collective pitch maintains rotor speed within the prescribed limits It is possible if the initial speed is sufficiently high to " balloon," and regain some of the height lost in the first few seconds of the manoeuvre As a safe landing speed is approached, the stick is eased forward, dropping the nose to a suitable landing attitude, and height control is transferred to collective pitch at the expense of some of the kinetic energy stored in the rotor If there were plenty of height available, initial flare-out could be followed by a transition to autorotation at minimum sink speed, or optimum gliding distance speed, according to circumstances Such cases are not to be dealt with here

The problem posed in the low speed band is somewhat different There is little kinetic energy of translation available moreover, the aircraft is operating on an unfavourable part of the power curve The first objective is to convert potential energy due to height to kinetic energy by easing the stick forward, causing the helicopter to accelerate horizontally The initial rate of descent is high until, as speed passes through the intermediate band (say 30—40 knots), a backward movement of the stick causes the nose to rise, into initial flare-out configuration The remainder of the procedure is as for the high speed cases Needless to say, the height loss from a low speed configuration is comparatively large

The Computational Procedure

It was found by experience that a minimum of five degrees of freedom had to be admitted when the above manoeuvre was simulated, using a step-by-step process

It was intended to treat blade flapping as a quasi-static process, but the small time constant made this impracticable without the time intervals being reduced to an uneconomically low value It was soon realised when the method was being proved by hand, that a digital computer would be necessary if any worthwhile results were to be achieved soon enough to provide non-obsolete information The time required per cycle rose from five minutes in the case of the two degrees of freedom model to half-an-hour To make matters worse it was necessary to reduce the time intervals from 0 2 to 0 1 secs Another, and what at the time seemed a formidable problem now arose how to introduce the control inputs required to bring about the desired manoeuvre Before dealing with this aspect it is convenient to describe the computer which was actually used to produce the curves of Figs 6, 7 and 8

The I B M 650 Computer

It is intended to give a sketchy description of the computer from the layman's point of view, merely sufficient to make the details of the programmes clear The particular computer, the I B M 650 was somewhat of a Hobson's choice, but nevertheless an eminently satisfactory one Among its most attractive features is the ease with which it can be programmed The particular programmes to be described were written in collaboration by two mere amateurs after a modicum of instruction, and required surprisingly little vetting by professionals This is a particularly important point, raising a principle which also applies to analogue computers The engineer should be able to use these tools with a minimum of supervision from the relevant specialists, otherwise the former is frustrated to some extent by communication difficulties, or the latter has perforce to spend valuable time gaining working knowledge in a number of fields

The computer system embraces three units, a power unit, a read-punch unit, and the computer The power unit whose function is apparent from its name can be glossed over All information is fed into, and extracted from, the system through the read-punch unit using standard Hollerith type cards Pre-punched cards are fed into a hopper and disappear one by one into the maw of the machine Blank cards previously loaded into another hopper are swallowed one at a time at irregular intervals, to reappear neatly punched with the answers A printing machine is available to decode the perforations The key units of the main computer itself are a revolving magnetic drum which is the store or memory, and the arithmetic unit consisting of a twenty digit accumulator, and a ten digit distributor Before any operations, the programme and necessary numerical data must be stored on the drum, via the read-punch unit The drum has a capacity of 2,000 " words " each of ten decimal digits, and each having an addressable location For purposes of computation, the data is fed via the distributor to the accumulator, where all operations are performed, and returned, again via the distributor, to the drum The final answers are read off the drum and punched out by the read-punch unit Operations are initiated using various controls on a console located in the computer, and subsidiary controls on the read-punch unit The console, distributor, and accumulator are all addressable, allowing the two latter to be used incidentally as an auxiliary store

The programme consists of a sequence of instructions which differ from pure numbers in that they are coded into blocks of 2—4—4 digits The first block of two digits contains the operational code about which more anon The next four contain the data address, the location of the number in which the operation is to be performed, and the last four, the instruction address, the location of the next instruction Programming may be described as the art of writing a series of instructions, so as to cause the system to solve a particular problem with the greatest accuracy, consistent with economy of effort It can be seen that any process once initiated, is self perpetuating through the medium of the instruction address

The operational codes referred to above fall under six generic headings , arithmetic, shift, store, branch, read and punch, and miscellaneous In each case, one of the four arithmetic operations are involved in the arithmetic codes and require no further comment The shift operations are used primarily to re-locate the decimal point in a number after a multiplication or division The store operations enable information to be moved about at will, for intermediate results to be racked temporarily for future reference, and for final results to be made available for punching Branch instructions are the means by which computers make logical decisions, and are probably responsible for the term " electronic brain " Read and punch should be self explanatory More complicated operations can be synthesised into sub-routines For most computers there exists a library of those in common use , *e g* , sine, cosine, square root, logarithm, exponentials, etc These for the I B M 650 are suitably inscribed on cards with instructions for their insertion into the main stream

An example taken from the general part of the longitudinal motion programme will serve to illustrate a few of these features, and at the same time explain the iterative procedure for reconciling the thrust and the induced velocity The requisite equation in non-dimensional form is

$$\frac{C_T}{as} = f_2 \{\theta_0, B_{1D}, \mu, \mu_Z, \lambda_i\} = - k\lambda_i\Lambda \qquad (7)$$

Fig 3, a block or flow diagram of the procedure, is almost self explanatory, but a few remarks will not be remiss When a block contains a calculating instruction, it is implied that the result is stored for future reference

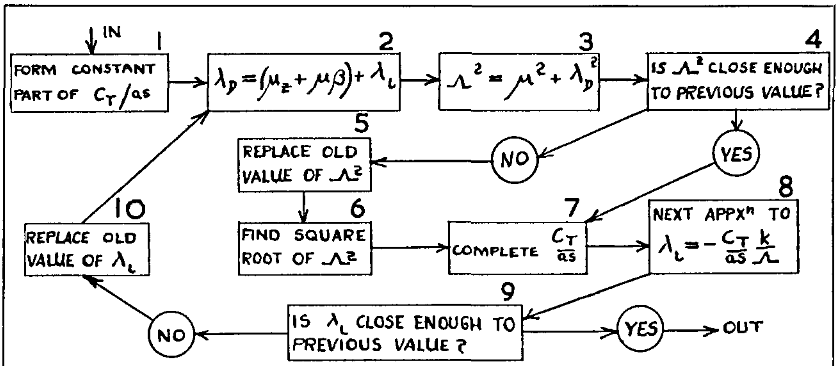

Fig 3 Iterative loop in " equations of motion "

The thrust coefficient is partially calculated, omitting the term involving the induced velocity Block 4 is a branch instruction to compare two successive approximations, the comparison in this instance being made by subtracting one from the other, and using zero or non-zero as a criterion The degree of accuracy required for practical purposes can be achieved using a shift instruction, thus saving computing time The loop within a loop is also a time-saving device, since Λ converges much more swiftly than λ_i in most configurations Blocks 5 and 10 are store instructions to renew stale data Block 6 is a library sub-routine Provision for ground cushion effect which is made in this loop, is not shown here

An interesting feature of the machine coming under the heading of miscellaneous codes is the table look-up facility An empirical curve which is difficult to fit analytically may be stored in tabulated form against its argument The feature is used when computing the fuselage and tailplane pitching moment contributions The effective downwash factor is tabulated against the tangent or cotangent of the wake angle In this case the facility has an added advantage that the successive values of the argument need not be evenly spaced, so that it is possible to attain greater accuracy in regions of rapid change

The General Programme

Common to every complete programme is the main part which is logically divisible into two sections These are called " Equations of Motion " and " Integration " The titles are intended to be descriptive The first section commences with the iterative loop of Fig 3 The thrust coefficient and induced flow having been reconciled, the normal acceleration follows A few operations later the vertical acceleration is evaluated using (1) The computation sequence moves progressively through (2a) to (5a), although the order from this point is a matter of choice It is intended that the two main sections shall be as general as possible To this end, provision is made for dealing with ground cushion effects, and the presence or absence of a tailplane Among the refinements yet to be considered are the admission of a further degree of freedom in coning, and provision for an auxiliary wing The former would be of importance when investigating manoeuvres which could result in the blades contacting the droop stops

The integration section is fairly straightforward The eight integrations necessary for producing fresh values of the dependent variables are performed, along with the calculation of sundry squares, products, and non-dimensional forms required in the first section Other data used in various feedback sections are produced at convenient points One of the most important functions is the evaluation of sin θ and cos θ, and the transformation of axes made prior to the integration of the flight path The closing operation before entering the feedback section is to put the clock on by one increment of time

The Feedback Section

The feedback section is in some ways the most important part of the programme In servo-mechanism terminology the general programme represents the transfer function of the helicopter In conjunction with the feedback section it forms a closed loop, hence the designation The actions of the pilot are represented in the two examples to be described, and since these to some extent are to be arbitrary it may puzzle some people as to why such a method is used, when the elaborate network required is revealed Because of the fantastic speed at which a computer can operate (even the more complex operations are completed in thousandths of a second) it is impracticable to introduce even arbitrary data manually Since the pilot to some extent functions like an automaton, it is possible to represent him ideally as such The feedback section can be used in addition to represent such hardware as auto-pilots, auto-stabilisers, and automatic engine controls, and leads to a unified approach to the problem of programming

Feedback for Power-off Landing

Although at the inception, the basic outline of the programme was apparent, the final form was arrived at after refinements were added as a result of (sometimes) bitter experience It is intended to describe only the final form which eventually emerged The diagram of Fig 4, it must be

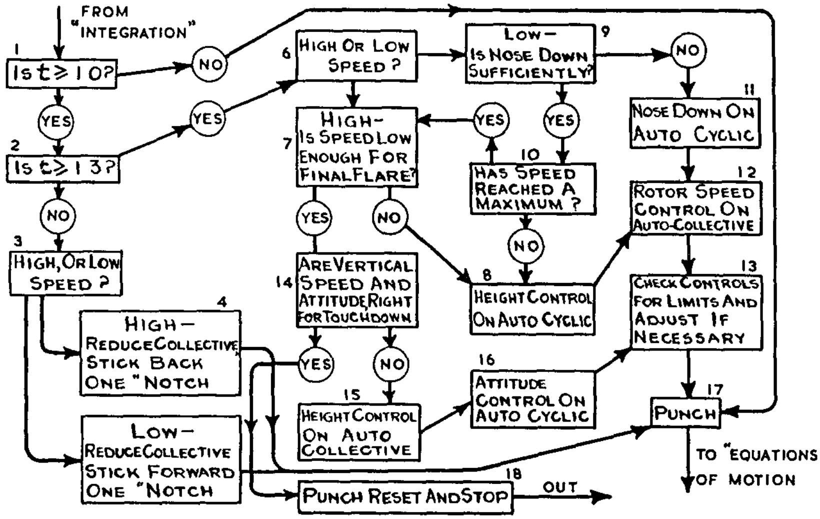

Fig 4 Feedback for power-off landing

understood, is extremely sketchy, and does not constitute a working form suitable for direct transformation into a written programme Such a diagram would take up to four times the amount of space First it is assumed that the power decays instantaneously which is reasonable, as a time lag is allowed for the pilot to register the failure and react accordingly One second is deemed sufficient for this and a further 0 3 secs for initial recovery action, which takes the form of prescribed arbitrary motions of collective pitch over full range, and cyclic pitch over three degrees

The feedback section starts with a question " Has the statutory one second elapsed ?" A branching instruction is used for the purpose It will be noted that free use has been made of such instructions, so that the diagram has the appearance of a marshalling yard The analogy is apt, for that is the way the programme functions Following a negative answer, entry is made into " Equations of motion " after first punching out the current values of the variables Following a positive answer the pilot reacts as described, provision being made for both high and low speed cases Marginal cases can be tried both ways to find the safer alternative A possible refinement which has been ignored is to allow the more urgently required collective pitch movement to precede the cyclic pitch Again information is punched out before moving on to " Equations of Motion " After 1 3 seconds has elapsed, arbitrary control movement is abandoned, and the automaton takes over The sequence is routed according to the speed band High speed leads to an automatic input of cyclic pitch to maintain level flight, and of collective pitch to keep the rotor speed within bounds This latter precaution is very necessary, because rotor speed is hypersensitive to changes in blade incidence It was found after some experimentation that a standard auto-pilot input is quite suitable for the former, and an auto-stabiliser for the latter The particular auto-pilot signal used, based on the vertical velocity and its derivatives, would be difficult if not impracticable to produce by a machine, which is of little importance since the intention is to represent, however ideally, a human pilot The input is of the form

$$B_1 = k_1w' + k_2w' + k_3 \int w'dt \tag{8}$$

The first two damping and stiffness terms are quite sufficient, when suitable gain values are chosen, to bring the " helicopter " to a straight path after a few seconds The last is a memory or positioning term required to regain level flight

Reference to Fig 4 will show that it is necessary during each cycle to check before the input is made, if the helicopter is ready for final flare out , in effect, if sufficient speed has been shed After the input it is necessary to check if the control limits have been exceeded, and to retrieve the situation in that event These meticulous precautions have to be taken, since contrary to belief in some credulous quarters, a computer cannot think independently, and will only follow instructions slavishly, however ridiculous they may be Checking the control limits serves the added function of testing the practicability of any manoeuvre

When forward speed is low enough to begin the final flare, height control is transferred to collective pitch at the expense of rotor speed control , at the same time the nose is dropped to a suitable landing attitude using cyclic pitch This involves two inputs of full auto-pilot type, similar to (8) The parameter in the latter case is the attitude angle θ In the last term positioning is dictated by integrating the differential between the instantan-

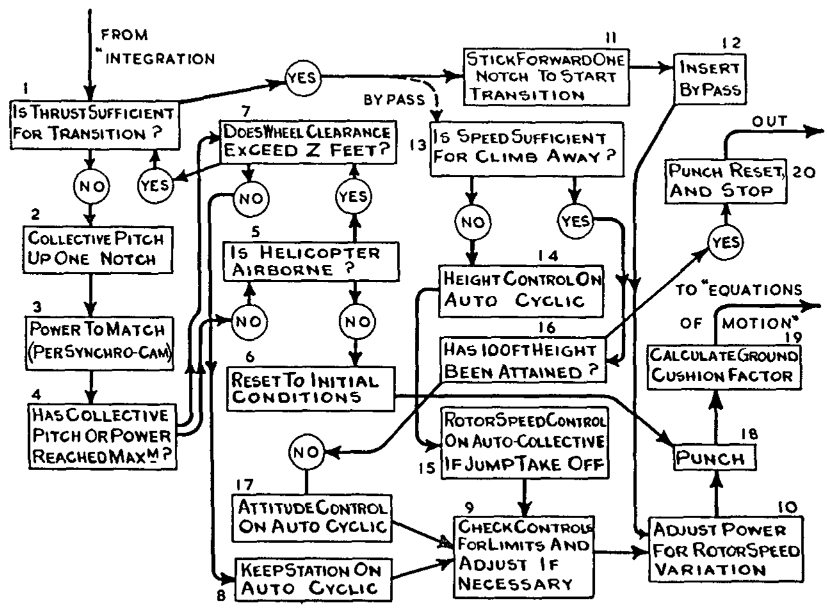

Fig 5 Feedback for take-off (manual control)

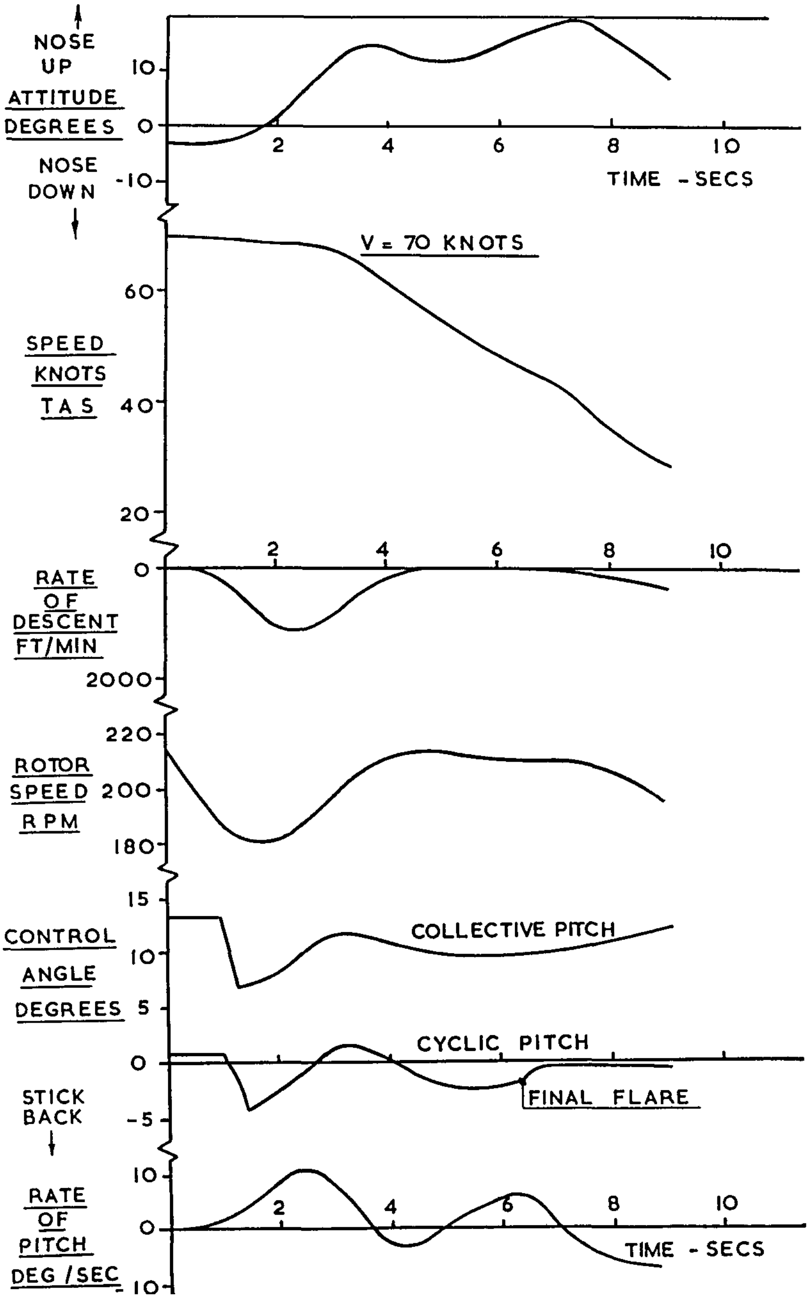

Fig 6 Simulated power-off landing of a typical single-rotor helicopter—high speed

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eous and desired attitudes Preceding these two inputs is a compound query as to whether conditions are suitable for touchdown , a sufficiently low vertical speed and a safe (slightly nose up) attitude Some tolerance is allowed to make the simultaneous fulfilment possible No attempt has been made to simulate penetration of the ground cushion, although this is a comparatively simple matter Following the two inputs, the controls are checked for limits as before When conditions are suitable for landing, the final instruction to punch, reset, and stop, are given The reset procedure ensures that the feedback section is restored to its initial condition before running another case, and is a device for stepping up computer output Such a procedure is necessary because to save computing time, certain switches and by-passes are inserted at appropriate intervals to cut out parts of the programme which are temporarily redundant

In addition to the foregoing sequence, an extra section is required for low speed cases and this is entered at the beginning of automatic operation In order to ensure a healthy nosedown swing, the automatic input is limited to a single stiffness term, based on the differential between pitching velocity and a desired mean By adjusting this mean, it is possible to attain the nosedown attitude to achieve a given maximum speed As the pitching velocity passes through this mean for a second time, transfer is made to initial flare, which is effected as for the high speed case Forward speed continues to build up to a maximum, when option is made for transfer to final flare

Illustrative Examples

High and low speed case histories are illustrated in Figs 6—8 The progress of the sequence can be followed on the control inputs The one second delay and initial ramp input are clearly seen Discontinuities are evident in both cyclic and collective pitch on transfer to final flare, which coincide with the selected flare-out speed In the low speed case a slight discontinuity is discernible in the cyclic pitch curve as transition is made to initial flare out It is noteworthy that, after the collective pitch lever is depressed, it has to be raised immediately to prevent overspeeding The sacrifice of rotor speed to prevent height loss in the final flare is clearly apparent On examination of the high speed curves of w', u', and θ in conjunction, the initial build up of vertical speed is seen to be checked within a few seconds, as the nose is lifted As the forward speed decays, the nose is raised still further until final flare, when, in response to the pulse input of cyclic pitch the nose drops fairly rapidly As the speed decays further the build up in thrust due to increased collective pitch is over-compensated by the loss in rotor speed, and vertical velocity tends to build up as touchdown is approached In practice the entry into the ground cushion would act as a check

In the low speed case, the nose swings down to a prescribed maximum, and then swings up sharply in response to the input of (8) Due to the unfavourable position on the power curve the initial decay of rotor speed is more marked than for the high speed case, and in spite of the much greater build-up of vertical speed, recovery is noticeably slower As the nose drops, there is a slight fall-off of forward speed, which is quickly checked before build up to a maximum In either case a marked lag in response is notice-

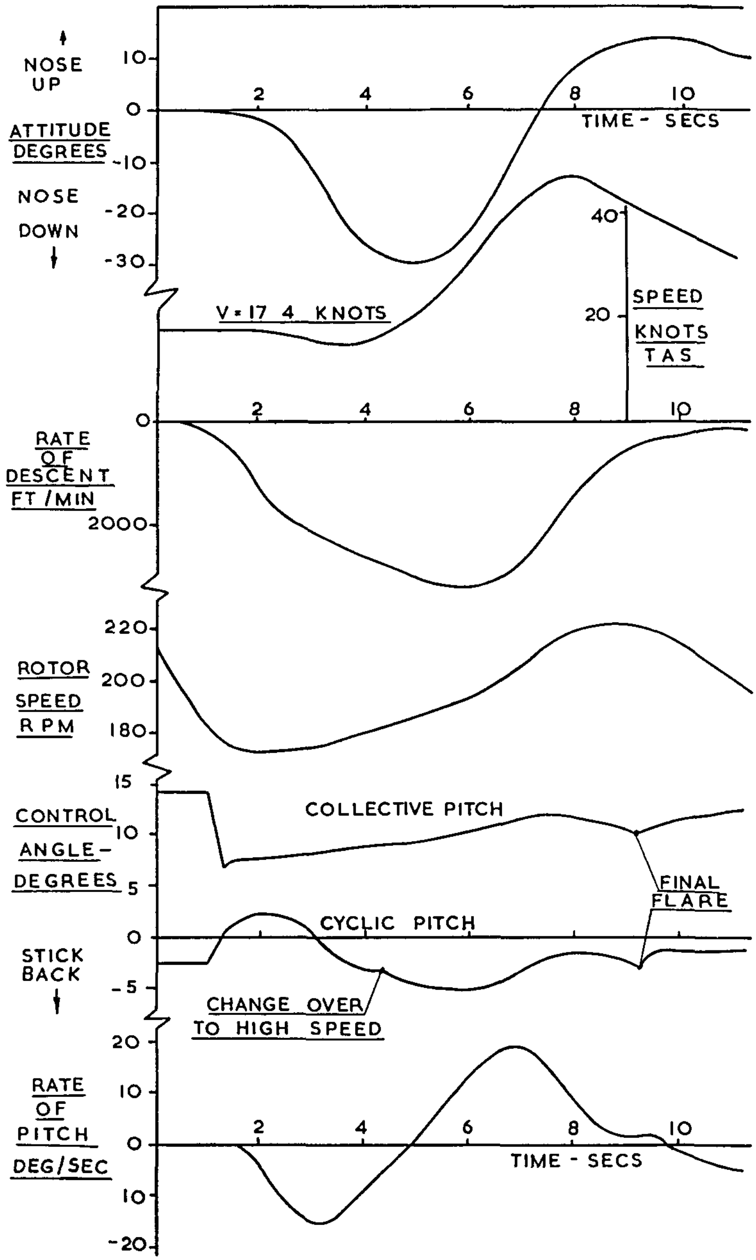

Fig 7 Simulated power-off landing of a typical single-rotor helicopter—low speed

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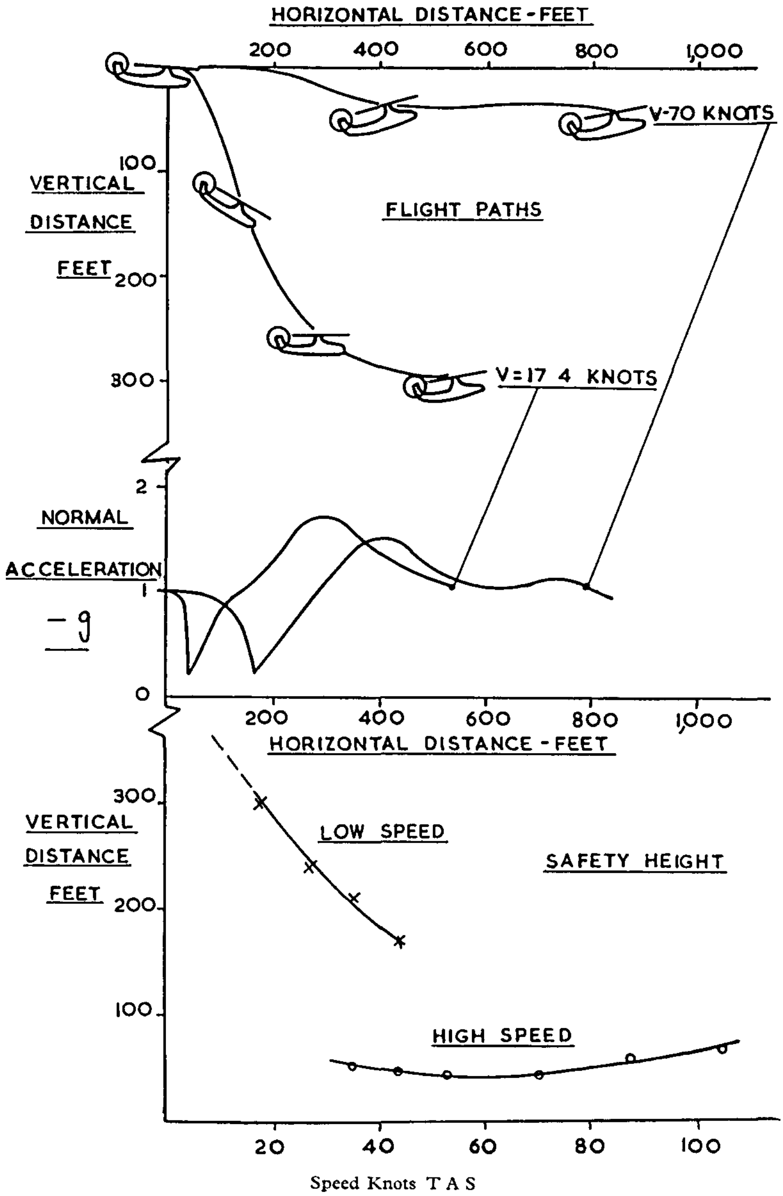

Fig 8 Simulated power-off landing of a typical single-rotor helicopter

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able, the maximum stick movement preceding the pitching velocity peak by more than one second It should be noticed too that in spite of the apparent violence of the manoeuvres, the normal acceleration stays within moderate limits throughout the manoeuvre

TAKE-OFF

Since the equations of motion (1) to (5) effectively cover performance as well as stability and control, there is no reason why the scope of the method should not be extended The power-off landing is a border line case and is as much a performance as a handling problem, which is one of the reasons why it was chosen as an illustrative example It has been used to show quite clearly how automatic control can be simulated as a by-product Take-off is primarily a problem of performance, although there are some handling difficulties involved, and is thus suitable for the second example First to describe the attack

The feedback appropriate to this problem is shown in Fig 5 and refers to a manually controlled engine The sequence is so arranged that most types of take-off technique, vertical, towering, jump and ground cushion can be simulated No attempt has been made to cover ground run take-off as yet

At the start of the manoeuvre, it is assumed that the helicopter is stationary with rotor up to speed, and collective pitch on the bottom stop The preliminary question is asked " Is the thrust sufficient for transition ?" (to forward flight) Such a question might appear superfluous, if it were not remembered that it is asked on every cycle, and unless specially programmed to do so, the computer cannot exercise discretion Following a negative answer, the collective lever is notched up one place and the power is matched on the synchro-cam Things are arranged this way in anticipation of the introduction of automatic engine control at a later stage Block 3 would then be replaced by a section to simulate the engine response to a power demand, signalled by an increase in collective pitch By varying the size of the " notches " the effect of quick control movements can be investigated Block 4 allows a choice of take-off techniques For the more conventional patterns, branching would take place on maximum power, but in the case of jump take-off, maximum collective pitch would be used In lightly loaded cases the helicopter would be airborne with reduced power Blocks 5 and 7 allow for an entry into transition under these circumstances Until the " helicopter " is " airborne," the initial values of the parameters must be reset, otherwise the computer would naively register sub-terranean flight, hence Block 6 The exit from here to " Equations of Motion " is via punch and Block 19 , the latter devoted to the calculation of the ground cushion factor Entry into transition is expedited by an arbitrary input of cyclic pitch, which command is then by-passed forthwith On the next cycle the forward speed is examined before beginning auto-control as per (8), which is designed, as described previously, to maintain level flight In the case of a jump take-off, the rotor speed at this stage would be showing signs of decay, and as both power and collective pitch would be at a maximum setting, it would be necessary to institute rotor speed control on collective pitch Apart from this special instance, speed control is left to the inherent stability of the rotor-engine system The variation in torque demands of the rotor due to speed changes is taken care of automatically in " Equations of Motion " Block 10 ensures that the power output at a given throttle setting is adjusted accordingly The speed selected for climb away dictates the length of " ground run," and allows for variations from vertical take-off up to climb away at minimum power speed On the climb-away speed being reached, a height check is instituted, the take-off being deemed successfully achieved on the attainment of 100 ft of height The type of Control input is altered to bring the nose up to the desired flight path The input is essentially similar to that used in the final flare of power-off landing On 100 ft being reached, the sequence is routed through punch and reset, to stop These details and the checking of control limits require no further comment

Further Possibilities

The feedback programmes described cover the potentialities of this method of simulating flight manoeuvres fairly comprehensively It does not need much imagination to envisage the scope for ingenuity which exists, in view of the flexibility of the programming technique Just a few examples that suggest themselves are power-on landings and quick stops , switch back manoeuvres (to investigate blade stop clearance) , the N A C A pull-out criterion , pulse inputs to investigate dynamic stability and so on Some of these manoeuvres are such that an extension of the main programme would be necessary, but this should present no basic difficulty The amount of complication is dictated only by the cost, weighed against the necessity, or desirability, of a particular line of investigation, and the capacity of the computer, which in these cases has been hardly strained

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List of Symbols

A	Main rotor disc area	ft ^{2}
a	Left slope of blade section $\frac{dC_L}{d\alpha}$	
B	Helicopter pitching moment of inertia (see Fig 1)	lb ft /sec
B_1	Blade geometric longitudinal cyclic pitch angle (see Fig 1)	
B_{1D}	Effective aerodynamic longitudinal cyclic pitch angle $B_{1D} = B_1 + \beta s$	
C_T	Main rotor thrust coefficient $T/\frac{1}{2}\rho A s \overline{\Omega R}^2$	
c	Main rotor blade chord	ft
D_P	Helicopter extra — to — main rotor blade drag (see Fig 1)	lb
f_s	Displacement of helicopter c g normal to shaft axis (see Fig 1)	ft

List of Symbols

g	Acceleration of gravity field	ft /sec
h_s	Displacement of helicopter c g from rotor parallel to shaft axis (see Fig 1)	ft
H	Total drag of main rotor blades in disc plane (see Fig 1)	lb
I_B	Moment of inertia of one blade about flapping hinge	lb ft /sec
I_R	Polor moment of inertia of main rotor	lb ft /sec ^{2}
k	Constant	
L_t	Tailplane lift	lb
l_t	Displacement of tailplane aerodynamic centre normal to shaft axis (see Fig 1)	ft
M_c	Pitching moment generated by total blade centrifugal force, due to offset flapping hinge (see Fig 1)	lb ft
M_f	Fuselage aerodynamic pitching moment (see Fig 1)	
M_A	Aerodynamic longitudinal flapping motion for one Blade (see page 43)	lb ft
P_E	Engine power available	lb ft /sec
N	Number of blades	
Q_R	Main rotor aerodynamic torque	lb ft
q	Helicopter pitching velocity (see Fig 1)	rads/sec
R	Main rotor radius	ft
s	Main rotor solidity $\frac{Nc}{\pi R}$	
t	time	secs
T	Main rotor thrust	lb
V	Helicopter airspeed (see Fig 1)	ft /sec
V	Helicopter airspeed relative to rotor wake (see Fig 1)	ft /sec
$u\ v\ w$	Flight path velocity components with reference to disc axis (see Fig 2)	ft /sec
$u'\ v\ w$	Flight path velocity components with reference to gravity axis (see Fig 2)	ft /sec
w_i	Main rotor induced velocity (see Fig 1)	ft /sec
W	Helicopter all up weight	lb
β	Blade longitudinal flapping angle measured from initial disc axis (see Fig 1)	
β_s	Blade longitudinal geometric flapping angle (see Fig 1)	
η	Transmission " efficiency " factor Percentage of engine power available at main rotor	
θ	Longitudinal attitude of initial disc plane	
θ_o	Collective pitch angle	
L_D	Angle of attack of disc plane (see Fig 1)	
λ_D	Axial flow ratio with reference to disc axis (see Fig 1)	$\frac{W + W_i}{\Omega R}$
λ_i	Induced flow ratio (see Fig 1) $\frac{W_i}{\Omega R}$	
Λ	$(\mu^2 + \lambda_D^2)^{1}$ (see Fig 1) $\frac{V}{\Omega R}$	
μ	Advance ratio (see Fig 1) $\frac{u}{\Omega R}$	
μ_z	defined by $\lambda_D = \mu_z + \lambda_i = \frac{w}{\Omega R}$	
ρ	air density	slugs/ft ^{3}
Ω	Main rotor speed	rads/sec

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