NOTATION

T	rotor thrust vector
$W = mg$	weight of helicopter
η	fore-and-aft tilt of rotor thrust vector relative to line joining rotor hub to C of G
h	distance from rotor hub to C of G
θ	angle of pitch of fuselage
u	increment in forward velocity of C of G
η_u	fore-and-aft tilt of rotor thrust vector due to increment in velocity u
a_u	derivative of rotor tilt with respect to u
a_q	derivative of rotor tilt with respect to angular velocity of pitch of fuselage
M_η	derivative of angular acceleration in pitch with respect to η
k_y	radius of gyration about the pitch axis
η_s	fore-and-aft cyclic control input
K_θ	coefficient of θ in control law
K_q	coefficient of θ in control law
K	coefficient of θ datum in control law for " Cruising " autopilot
K_x	coefficient of x in control law
K_u	coefficient of u in control law
n	time constant of leaky-integrator network in seconds
x	linear displacement of helicopter from point of hover in fore-and-aft direction
x_u, x_w, etc	non-dimensional derivatives as in standard fixed-wing notation
$\hat{t}$	unit of time in airseconds
$p \equiv \frac{d}{dt}$	

MR M C CURTIES

PART II Flight Development

Introduction to the Flight Experiments

In the first part of this paper the theoretical considerations underlying the design of an automatic control system for helicopters have been discussed This second part describes some flight experiments carried out at R A E , Farnborough In addition to demonstrating the validity of the theory presented, there has emerged from the flying a clear conception of the design features needed in a practical system for every day use by the average helicopter pilot

One of the more interesting aspects of the experimental programme has been in the fact that the results were achieved almost entirely from flight tests At the time when this work was commenced, aerodynamic information of the test aircraft was scanty Thus whilst the theoretical form of the control law was known, the optimum values of the control parameters could only be roughly forecasted and the actual values were obtained in flight Similarly the desirable operational features of a system were also appreciated

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during the flying and here the importance of the part played by the test pilots cannot be stressed too strongly

Before describing the actual work which is the subject of this paper it is worth recalling that the first helicopter flying with an automatic pilot in this country took place in 1951 The experiment was intended mainly to get aerodynamic information The equipment, a fixed wing auto-pilot developed at R A E for a special application, was fitted into a Bristol Sycamore A control law in which cyclic stick was applied proportional to angular position and rate of the fuselage was used and satisfactory stabilisation was achieved over a wide speed range Apart from showing that a autopilot could fly a helicopter, little more was achieved at this stage, there being at that time no formal requirement for a helicopter system The experiments were not completed because the helicopter was written-off in a flying accident, not associated with the use of the auto-controls Whilst the autopilot used was particularly suitable for flight experiments, the control facilities afforded the pilot were rather primitive and the system could not be regarded as a real helicopter autopilot

Later, when a requirement was established for a helicopter automatic control system, more emphasis was placed on the operational characteristics

In view of the importance of obtaining early flight experience, the test aircraft, a Whirlwind (S 55) loaned by the Royal Navy, was fitted up with an experimental set of equipment using, in the main, " off the shelf " components For example, the rate gyros and magnetic amplifiers were components of fixed wing autostabiliser equipment, whilst the Yaw Servomotor was a component designed for a pilotless target aircraft Vertical and heading gyros for another fixed wing autopilot were added later

Most of the standard equipment was supplied by Louis Newmark Limited, who also designed and manufactured the necessary additional components specifically for the helicopter, a Ministry of Supply development contract being placed for this purpose

The installation of the experimental equipment was carried out by Westland Aircraft Limited who were responsible in particular for the design of the Servomotor installations which naturally involved some alterations to the flying controls Aerodynamic information has also been supplied by the aircraft contractor

After about 100 hours flying had been completed a large measure of success had been achieved both with the basic problem of stabilisation and in appreciating the important design features

The Experimental Equipment

Before embarking on any experimental investigation of the problem of automatically controlling helicopters, a study was made of the reasons for the existence of a requirement for an auto control system By talking to Service users and by observing the various tasks for which the helicopter was being used, it became apparent that in the characteristic instability of the machine lay the heart of the problem Whilst different operators appeared to want the equipment to perform different tasks, the reasons seemed common to all cases The instability of the aircraft demanded a level of pilot concentration which resulted in early fatigue and loss of efficiency in tasks involving accurate flying, as for example, in continuous hovering

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over a point It made almost impossible certain other functions such as instrument flight

Whilst it is generally possible to design devices to carry out in an aircraft particular functions or manoeuvres automatically, the diversity of the roles of the helicopter in this case indicated a different approach to that of the usual autopilot

It was decided that in the first place an attempt would be made to add artificial stability to the helicopter by means of suitable " Black-Boxes " and thus make it easier to fly The pilot would still retain overall control The argument was that the pilot's task in any condition of flight could be broken down into two parts

(1) Determining the flight path
(2) Stabilising the aircraft

If the second of these could be done automatically, then the first could be done more readily by the pilot, however complicated the overall task Furthermore, by building a " stabiliser " system to meet this requirement, the basis would be provided for a more complete autopilot if the need for such was proved

Whilst it was appreciated that the helicopter had an additional control as compared with the usual fixed wing aircraft, it was thought sufficient at first to concentrate on a three axis system in which automatic control was to be applied to cyclic pitch (fore and aft and lateral) and to the yaw pedals

Fig 5 shows a block diagram of the pitch channel of the original experimental installation With the exception of some minor differences, which will be mentioned, this channel can be considered as typical

The main features of the system which had to be decided were (*a*) The choice of the detecting element , (*b*) the servomotor arrangement (Series or

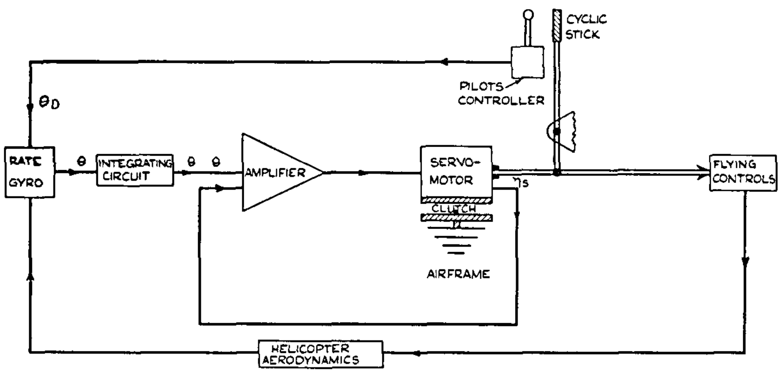

FIG 5 BLOCK DIAGRAM OF FIRST EXPERIMENTAL SET (PITCH CHANNEL)

Parallel) , (*c*) the means of introducing pilot's demand signals, *i e* , to enable him to fly the helicopter with the system working It should be noted that the choice of (*b*) affects (*c*)

As has been discussed in Part I of this paper the rate gyro appeared to be the most suitable detecting element In a system in which freedom to manoeuvre was to be left unimpaired, the use of a position gyro with its implied long term datum was considered to be a disadvantage It has been shown that this disadvantage is not present when the angular position signal necessary for stabilisation is obtained from a rate gyro using the " leaky-integrator " technique

The choice of servomotor installation was a more difficult one to make The system proposed in the early stages was basically a stabiliser, not an autopilot There was, therefore, using the fixed wing precedent, a case for the use of a limited authority series (or differential) arrangement for the servos However, the alternative, a parallel system, seemed more attractive There were two main reasons for this Firstly, it was considered that the percentage of total control travel needed for stabilisation would be greater in a helicopter than in fixed wing aeroplane and thus the servo authority needed would be greater A series servomotor with a large percentage authority is recognised to be a potential difficulty in the event of a servo failure at or near the end of its travel, when the pilot is left with asymmetrical control authority Secondly, it was known that the system would possibly become a full autopilot in the course of development and the parallel servo arrangement seemed better suited for this conception

It was therefore decided that the arrangement would be a parallel one, with full authority since unrestricted manoeuvring was required whilst under automatic control This scheme seemed particularly suitable in the yaw axis where in the single rotor helicopter large changes in yaw pedal position can be required as a result of changes in main rotor torque

In order to provide safeguards for the failure and runaway cases, electrically operated clutches were incorporated in the system so that instant disengagement or easy overpower was available to the pilot in all axes

The third design feature mentioned above was considered in conjunction with the servomotor configuration In a parallel system the pilot's controls reflect continuously the action of the automatic stabiliser since they are not disconnected from the control run and the servo is effectively working through them If it is assumed, for example, that some steady flight condition in the helicopter has been set up by the pilot and the automatic control equipment switched in, then it is the equipment which decides at any given instant where the stick or controls should be The system attempts to maintain the initial flight condition For the pilot to change the condition he must introduce a control movement It is not desirable that he should merely overpower the system to do this and means have therefore to be provided for him to fly through the system

At the time when the experiments were commenced, it was the current practice in the fixed wing field to introduce pilot's demand signals through a remote controller sometimes in the form of a " miniature stick " This system has the obvious advantage that there is no alteration necessary in the main controls and the controller can usually be placed in a convenient position to hand The main disadvantage is that it is necessary for the pilot to transfer from one control to another when changing from automatic flight to manual This is important if a failure of the automatic system occurs and the runaway case in particular has to be considered

In spite of the fact that this type of controller was readily accepted in fixed wing aircraft, objections to its proposed use were raised in the early

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discussions by experienced helicopter pilots, representing the potential users These objections appeared to be mainly psychological ones associated particularly with the possibility of failure of the equipment The general validity of these objections was recognised especially in view of the desire to use the proposed equipment throughout the whole range of operating conditions of the helicopter including hovering near the surface There was moreover certain evidence in existence of " unfortunate occurrences " associated with the use of miniature sticks in helicopters in the U S A where work on the helicopter auto-control problem was commenced somewhat earlier than in this country

It seemed therefore that there was a need to devise a scheme in which the autopilot controller was integrated with the main flying controls and various suggestions were put forward As the problem seemed to demand more than superficial examination it was decided that a miniature controller would be used in the early experiments to get the flying started This would enable the stability work to proceed and it would also be a means of obtaining first hand information on the operation of the controller and the reaction of pilots to it

The controller, which was constructed, consisted of a small stick some 3-4 inches high, which could be moved in the same way as a normal control stick Electrical signals were produced proportional to the displacement of the stick and these were used to demand rates of pitch and roll through the appropriate rate gyros

Rotation of the knob on the top of the stick in azimuth demanded a rate of yaw

With the basic system as described above, flying was commenced and the programme went ahead with satisfactory speed

It is useful to consider the flying programme in two phases —

(i) The stability investigation

(ii) The development of the system

Whilst obviously each phase affected the other there was a fairly well defined time in the programme when the emphasis of the work changed, and the flying will be discussed under these headings

The Stabilisation Experiments

It was particularly gratifying to find that the system, even with its roughly estimated control parameter values, functioned on the very first flight, and a short period of hands-off flight was achieved It was later discovered that the system was, in fact, not critical and stable flight could be achieved over a wide range of values of the control parameters

In the early stages of the flying, investigations were carried out into the basic control and controller laws and into the amplifier unit circuitry by which the laws were to be produced Some of these steps are worth recording

Whilst as has been demonstrated, a helicopter stabiliser should apply cyclic stick proportional to fuselage angular position plus rate, some early experiments were carried out in which the rate term only was used The results were interesting The periodic time of the unstable oscillation was increased, and whilst in theory the damping of this mode was not improved,

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in practice hands-off flight was achieved with a steady long period oscillation of some $\pm 3°$ amplitude instead of the uncontrolled divergence

If the above results were to some extent encouraging, the initial use of the control law indicated by the theory was disappointing With the equipment as originally built the introduction of the angular position signal into the control equation caused a divergent oscillation, the effect being present even with small signal strengths The cause was eventually found in the use, in the system, of the classical method of obtaining the integrated position signal from the rate signal by means of a motor Non-linear effects associated with the design of the integrator were believed to be responsible for the trouble On changing over to integration by means of a passive network a dramatic improvement in performance was achieved This change, together with the use of phase advance networks in the control circuits to compensate for system and aerodynamic lags in the overall loop, made possible the use of much tighter control with a resulting high standard of stabilisation

Whilst the difficulty discussed above was of little significance in the programme as a whole it is mentioned as an illustration of the kind of unexpected troubles which are met when theory is put into practice

Also of interest was a trial of a different controller law For general use, as has been explained previously, it was decided that the controller should demand an angular rate of response of the helicopter This was chosen as a " natural " law familiar to the pilot and having a strong resemblance at least to fixed wing aircraft

It was proposed that for hovering it might be advantageous if a displacement of the controller produced an angular displacement of the helicopter instead of the angular rate, *i e*, the attitude of the helicopter would be a linear function of stick displacement It was thought that this control law would help the pilot in the task of maintaining a fixed position relative to the ground

In practice the scheme was unpopular This was partly due to the fact that it was unusual and partly because of the conscious mental effort required to decide on how to use the controller when it could provide two different effects depending on the control mode selected It was accordingly abandoned

The position at the end of this stage of the tests was that satisfactory stabilisation had been achieved using the theoretical control law discussed and " hands-off " flight was possible throughout the entire speed range

The miniature controller had proved effective Pilots without previous experience of the system were able with little practice to carry out all normal flying including take-off, hovering and landing, using the remote stick and collective pitch lever only There was however always somebody in the second pilot's seat and it was considered that for service use something better was needed The steps taken to meet this problem are discussed in the following section

System Development

Once satisfactory stabilisation had been achieved the main effort was directed to investigating the proper design features for a helicopter system

Some ideas had begun to take shape during the earlier stages and one feature of interest, yaw compensation, was introduced almost at the beginning of the experiments

In the yaw channel the control law used for stabilisation was similar to that adopted in fixed wing practice Considering the characteristics of the helicopter in yaw to be similar to that of an aerpolane, control was applied proportional to fuselage angular rate only, there being no integrated position signal to define the fuselage heading Consequently it was necessary when changes of power or speed were made, for the pilot to maintain the heading using the yaw controller, just as he would have to do when flying without stabilisation Partly because the yaw controller, described previously, was slightly awkward to use it was decided that it would help the pilot if some automatic compensation was fed into the yaw channel when changes of collective pitch, and hence power and rotor torque, were made It was found that by putting a simple potentiometer pick-off to measure collective pitch stick position and by feeding its signal into the yaw channel, surprisingly accurate compensation could be achieved It became possible to fly the machine "feet-off" through the range of power conditions from auto-rotation to hover with only a small change of heading without the use of a heading signal in the system This feature was particularly appreciated by pilots and is now always shown as a " Circus Trick " when demonstrating the equipment in flight

Of greater fundamental importance was the change over to main control flying and the elimination of the miniature stick Whilst it had been demonstrated that entire flights could be carried out with the remote stick it was agreed that it did not meet the requirements for Service use It was felt that there should be as little difference as possible between the flying technique needed when the stabiliser was working and when it was not, with the exception of course that when the helicopter was made stable, less continuous effort was needed by the pilot

The most promising solution to the problem of several considered, seemed to be the use of force sensitive pick-offs in the controls themselves Such devices had previously been developed for similar applications in fixed wing aircraft and for measuring control forces A cyclic stick and a suitable link in the yaw control run were modified at R A E to try out the scheme It was arranged that when the pilot applied a force to the appropriate control in the usual way, the stick or yaw link deflected slightly, proportional to the

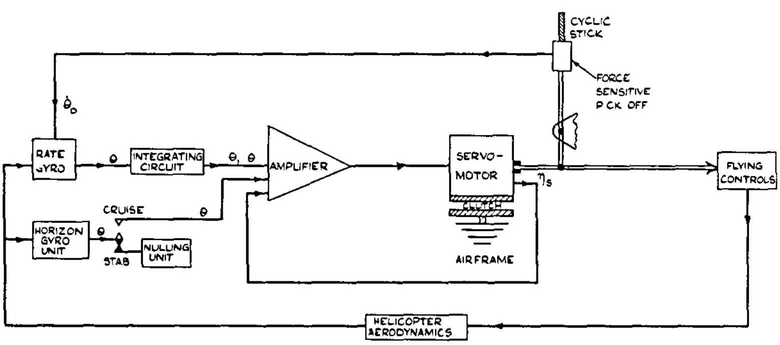

FIG 6 BLOCK DIAGRAM OF LATER EXPERIMENTAL INSTALLATION INCLUDING AUTOPILOT MODE (PITCH CHANNEL)

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force applied, and a corresponding electrical signal was produced This signal biased the appropriate rate gyro as before and a servo movement was produced which caused the control to move in the normal fashion This is illustrated in the block diagram in Fig 6

It was appreciated that trouble might be experienced with a coupling effect which results from the fact that the member on which the force sensitive pick-off is mounted is moved (by the servos) in response to its own signal A contributing factor is the inertia of the pilot's hand or foot

The expected snag did in fact occur in the form of a slight control " judder " particularly when a constant demand signal was required This was not particularly serious since steady control deflections are only needed in such manoeuvres as turns, trimmers being provided in the system to provide constant trim demands for normal flight

In the course of development the factors affecting controller design (feel and sensitivity) have been examined and the " judder " problem is now largely solved This has involved the investigation of such means as signal filter circuits and local hydraulic dampers associated with suitable maximum deflections and spring rates of the sensing members It has to a certain extent been a matter of experiment and it may be recorded that a second " Improved " cyclic stick produced after the first experimental model behaved much worse than the first The current design is much more satisfactory

So far the system, as developed, was purely a stabiliser During this development phase the engineering modifications were made for a simple cruising autopilot function, the stability of this mode having been investigated earlier

The facility introduced was a simple attitude and heading holder which would enable a straight flight condition set up by the pilot to be held indefinitely This required additional autopilot input signals in the form of real angular position signals These were obtained from suitably modified pilot's flight instruments, the artificial horizon and compass gyro It was arranged that in pitch and roll the signals would be nulled continuously by a small electro-mechanical servo, in the stabiliser mode, and switched on in the " cruise " mode only as relatively weak " monitor " signals, the datum being established at the instant of switching over In yaw the heading signal was used as a main control term in the " cruise " mode and here it was arranged that the yaw signal pick-off was de-clutched and centred mechanically in the " stabilise " condition

A third control mode called " hover " was evolved naturally from the other two It is usual when hovering to wish to maintain the heading, whilst positioning the helicopter in plan relative to the ground In the " hover " mode therefore it was arranged that the heading signal was used in the yaw channel (*i e*, the equivalent of " cruise ") whilst the pitch and roll channels remained as in " stabilise " Thus the pilot can position the stable helicopter using the cyclic stick, without the need to control yaw Collective pitch and throttle is of course still not automatic Nevertheless changes of height and plan position can be made at will without significant heading change In the case of single rotor helicopters with high pedal forces in the hover this considerably reduces fatigue

Operationally the cruise and hover modes are selected by the pilot by merely rotating a selector switch once the desired flight path has been established in the " stabilise " mode It is arranged that in " cruise " the controller pick-offs are inoperative so that inadvertent control demands are not caused if the pilot holds the stick Manoeuvring is carried out in the " stabilise " condition, co-ordination being left to the pilot A manoeuvre button is provided on the cylic stick which causes a temporary reversion to the " stabilise " mode from " cruise " so that changes in the flight condition, *e g* , levelling out after a climb, can be made without the use of the main selector switch This facility is also provided for the yaw channel in " hover "

At the end of this stage of the development, fairly clear ideas had emerged of the functional requirements for a helicopter automatic control system and a new set of experimental equipment was made embodying all the features so far described This equipment is still being flown

The Results Achieved

The experiments have shown that it is possible, as indicated by the theory, to make a simple and relatively light automatic stabilisation system for helicopters An automatic pilot facility can also be provided as an addition to the basic system with only a small increase in weight and complexity

The final experimental equipment was produced in a form suitable for pilot's evaluation from the operational standpoint and considerable experience has subsequently been obtained In general the equipment has been very favourably received Whilst, as has been indicated, the experimental sets were based on existing components and only limited effort was put in the early stages into engineering design, a high standard of reliability was achieved

The potential effect of such equipment on helicopter operations in the future appears to be considerable A few aspects may be considered

The helicopter is converted into a very stable machine and thus becomes easier to fly More of the pilot's attention can therefore be devoted to other tasks

The fatigue factor, particularly in tasks requiring very accurate flying is considerably reduced

Providing the equipment can be relied on, a reasonable standard of instrument flight becomes feasible for the average pilot This point is possibly one of the most important and is worth amplification In the course of the experimental flying both simulated and actual instrument flight has been practiced and some simulated Ground Controlled Approaches have been carried out Of particular interest here is the usefulness of the so-called " hover " mode Headings passed by the Ground Controller and established by the pilot are maintained without further effort, and the high standard of stability in the pitch and roll axes eases the problem of flying the correct glide path

A final claim that can be made for the equipment and which can be substantiated by flight records, is that the passengers enjoy a considerably smoother ride

Future Developments

Whilst it is not possible to discuss in detail the future development of the automatic control system certain possibilities can be indicated

The trends in the fixed wing field can be used as an illustration The main emphasis appears to be on the realisation of true All-Weather flight and here, because of the increased difficulty of the pilot's task in bad weather, the approach seems to be one of increasing automaticity Examples of this are in the development and use of automatic approach and navigation facilities linked with the basic autopilot by means of suitable couplers

Whilst the helicopter system, described here, has been designed to be as simple as possible it is capable of development in the same way as its fixed wing counterpart

However, with development comes increasing complexity, which unfortunately usually brings with it decreasing reliability

Because of the special nature of the helicopter it appears that " black-boxes " will, for some time, be used to provide stability and great reliance will have to be placed on the " black-boxes " in all-weather operation

Here lies the difficulty, more complexity and more reliability are needed together, and this is where engineering development must play its part Until an equipment can be produced that will never break down it might be necessary, in the civil field particularly, to accept some essential duplication with its attendant weight penalty

In conclusion the author wishes to state that any opinions expressed are his own and are not necessarily those of the Ministry of Supply He would also like to express his thanks to his colleagues at R A E for their comments and advice on this paper and for their help in preparing the diagrams and simulator records

Discussion

The Chairman said that the audience had heard a very interesting exposition of a very difficult subject and the authors were to be congratulated in having taken them through it in a very successful way It had been hoped that Mr B H Arkell, of the Sperry Gyroscope Co , would open the discussion, but he was temporarily indisposed and the Chairman had been asked to read his remarks, which raised the first questions in the discussion

Written contribution received from **Mr B H Arkell** (*Sperry Gyroscope Co*) (*Founder Member*) —

Mr Chairman, Ladies and Gentlemen I would like to begin by congratulating the two lecturers on having produced a paper of considerable interest to us all here tonight This subject has not been discussed in such great detail here before and I think that what we have heard tonight will give us considerable food for thought The development of this equipment is certainly a pioneering effort as far as this country is concerned and as such it is worthy of considerable merit

It is now generally conceded that, since helicopters are normally only neutrally stable, some form of artificial stabilisation is a desirable feature to introduce positive stability and so reduce pilot fatigue But I would like to utter one word of warning which is addressed more particularly to the helicopter designers I think it would be most undesirable if the introduction of automatic stabilisation had the effect of encouraging designers to place too much reliance on achieving stability by this means alone when some stability was attainable by aerodynamic means The best possible aerodynamic stability should still be a primary requirement Quite apart from the fact that the helicopter may at some time or another have to be flown without the aid of the automatic pilot, a very practical reason for making inherent stability a primary requirement is that the less work the " little black boxes " are called upon to perform, the lower will be their cost