



PILOTED SIMULATION STUDIES OF HELICOPTER AGILITY

by

B. N. Tomlinson

G. D. Padfield

Royal Aircraft Establishment, Bedford, England

**FIFTH EUROPEAN ROTORCRAFT AND POWERED LIFT AIRCRAFT FORUM**  
SEPTEMBER 4 - 7 TH 1979 - AMSTERDAM, THE NETHERLANDS

PILOTED SIMULATION STUDIES OF HELICOPTER AGILITY

by

B. N. Tomlinson  
G.D. Padfield

Royal Aircraft Establishment, Bedford, England

SUMMARY

The need for helicopters to operate close to the ground and near obstacles has prompted a critical look at design features which affect performance and handling qualities in this environment. Some experiments using a ground-based flight simulator have been conducted to investigate this subject and to obtain data on helicopter agility. These experiments required the development of a general mathematical model capable of representing helicopter flight, including gross manoeuvres, from hover to cruise and validation by comparison with flight tests. An exacting low level flying course was created on a model ground terrain and formed the primary task for the six pilots involved in the experiments. The paper describes these aspects and then goes on to describe how a set of rotors, differing in blade flapping stiffness and inertia (Lock number), were represented and flown over the agility course to investigate the effects of rotor design. Some of the theoretical consequences of these variations will be outlined and the results of piloted flights in the simulator described.

*Copyright*

©

*Controller HMSO London*

1979

1 INTRODUCTION

It is widely recognised that helicopters need to be more agile to operate in a military role close to the ground and near obstacles. At and near the hover, helicopters need to be able to bob up and down rapidly and precisely and to point accurately in any desired direction. Away from the hover, helicopters need to be able to fly forward very close to the ground in order to make maximum use of features for concealment. They must also be able to avoid obstacles, and make rapid transitions and quick stops. In a loose sense, then, these qualities comprise agility.

Agility is concerned with flight path control. This includes control in the vertical plane, the ability to change direction and the ability to accelerate and decelerate along the flight path. The word "agility" is used, rather than the phrase "nap-of-the-earth", since the latter phrase is sometimes taken to mean terrain hugging flight at speeds below 40 knots.

We have investigated several areas of agility but will deal in the present paper with handling qualities and manoeuvrability in the horizontal plane close to the ground and at speeds from 60 to 100 knots.

At its simplest, changing direction in forward flight requires a roll and stop manoeuvre to tilt the thrust vector and thus accelerate the helicopter sideways, plus the ability actually to generate the necessary load factor. Thus handling qualities related to the roll axis are involved, in terms of such measures as achievable roll rates, time constants and stability. We shall also see later that pitch attitude control, in order to maintain height, is also important. Performance is also involved, since without the ability to maintain speed or generate the desired accelerations, agility is reduced. Time to complete certain specified manoeuvres, such as roll reversals or wing-overs, has been used in the past as a measure of agility, but has been criticised<sup>1</sup> as being unsuitable for three reasons. Results depend on pilot skill. It assumes that the aircraft completing the manoeuvre in the shortest time is the most manoeuvrable, which is not necessarily true, and such manoeuvres do not provide information of direct use in the design process. Despite such criticism, our view is that in the controlled environment of a piloted simulation such an approach is valid, but it is important that the task is clearly defined.

As with fixed-wing aircraft, a significant amount of helicopter handling qualities research can be conducted in a piloted flight simulator. The advantages of doing so include the ability to assess a variety of design features before effort is devoted to engineering and flight safety considerations.

At the Royal Aircraft Establishment, we have conducted several studies of helicopter handling qualities, using a piloted flight simulator. Early tests were concerned<sup>2</sup> with the handling of specific helicopters and served to demonstrate that simulation of helicopters could accomplish a variety of tasks, albeit with some limitations<sup>3</sup>. Most recently, simulation studies have been conducted to investigate the nature of helicopter agility.

The initial phase of these studies<sup>4</sup> aimed to develop and validate a general mathematical model, capable of representing helicopter flight, including gross manoeuvres, from hover to cruise. Various rotor configurations could be set up by simple parameter changes and the studies demonstrated that agility was a suitable and feasible topic for simulator investigation. The second phase

extended the initial work by detailed examination of a limited range of manoeuvres, again examining the effect of rotor characteristics on agility. To provide a suitable flying environment in which to examine agility, an exacting low level course was created on a model terrain. This course consisted of a series of bends, with intervening straight stretches. Two sets of triple bends received most attention.

This paper briefly discusses the helicopter mathematical model and its validation by comparison with flight, describes the flight simulator and then illustrates a selection of results from the agility experiments.

## 2 ELEMENTS OF THE SIMULATION

### 2.1 Structure of the mathematical model

A non-linear mathematical model was created to represent the major features of helicopter flight within normal operating conditions in an identifiable manner. The model was of the total-force, rather than derivative, type. It allowed for large manoeuvres and exhibited the principal aerodynamic and dynamic cross-couplings. Aerodynamic interference effects were neglected, however, so that phenomena normally associated with these were absent.

The main rotor was modelled by assuming a disc representation with attitudes defined by longitudinal and lateral flapping angles and coning. Blade flapping and incidence angles were assumed small and lag and torsional motions were not included. A centrally hinged, straight, rigid blade was assumed for deriving the aerodynamic loading and the effects of blade elasticity and inertia on the hub moments were defined in terms of the flapping frequency ratio  $\lambda_B$  and Lock number  $\gamma$ . Rotor aerodynamics were derived from incompressible, inviscid, two-dimensional theory and reversed flow effects were neglected. The induced flow field, assumed instantaneous, was treated as uniform with a linear fore-and-aft variation superimposed. A combination of blade element and momentum theory produced the required analytic expressions for the aerodynamic loading.

A simplified model of a helicopter free turbine engine was included to provide a rotor speed degree of freedom. The governor model took the form of a second order non-linear differential equation in engine torque, responding to a combination of rotor speed error and acceleration.

As for the main rotor, blade element and momentum analyses were used to develop the tail rotor thrust and torque expressions, though blade flapping effects were neglected and a uniform inflow was assumed.

The sole contribution from the tailplane was a normal force, derived from two dimensional theory and tunnel tests, that produced a pitching moment about the centre of gravity. The fin was treated in a similar manner.

The force and moment contributions from the body were synthesised from a collection of available wind tunnel data covering the complete range of body incidence angles.

A rudimentary undercarriage supported the simulated helicopter on the ground but it was not intended that the landing and take off phases of a sortie should be represented as faithfully as the flight modes.

Conventional collective lever, cyclic stick and rudder pedals produced blade collective, cyclic and tailrotor pitch respectively through a system of control actuator lags. Provision for a range of control interlinking was included together with the normal cyclic phasing. An autostabiliser was also implemented, with a variety of parameters which could be set to give different forms of control law.

The digital computer form of the model reflected the structure described above. Easily changed parameters enabled specific characteristics to be set up. The helicopter modules were combined with standard kinematic and axis resolution modules<sup>5</sup> to create the complete program which was executed repetitively 20 times per second using a Runge-Kutta fourth order integration method.

## 2.2 The flight simulator

The single seat cockpit of the Flight Research Division's simulator at RAE Bedford was used for the experiments (Fig 1). A photograph of the interior in its helicopter configuration is shown in Fig 2.

A view of the outside world was produced by a closed circuit television system, in which a TV camera tracked across a 700:1 scale model landscape, carried on a continuous belt, in response to position and attitude signals from the computer. The picture so produced was displayed to the pilot via a black and white monitor viewed through a collimating lens, giving a typical field of view of about 35 deg in pitch by 45 deg in azimuth. The outside world display imposed an additional pitch movement limitation visually of  $\pm 25$  deg. Peripheral attitude cues were provided by a skybowl horizon projector which produced a shadow horizon on the walls of the dome surrounding the cockpit. Rotor flicker was simulated by mounting a rotating grid in the skybowl above the pilot's head.

Motion cues were provided in pitch, roll, heave, and yaw and a low ambient level of vibration was augmented, as a function of 'g' and speed, to indicate that high normal accelerations were being used. A view of the cockpit and motion system<sup>6</sup> is shown in Fig 1.

Audio cues consisted of engine roar, turbine whine and rotor slap with the latter triggered by the same control function as the vibration cue mentioned above.

## 3 VALIDATION EVIDENCE

The validity of the simulation for performing agility experiments has been tested both qualitatively, through general pilot impressions, and quantitatively by comparison with flight data. These exercises have exposed the strengths and weaknesses of the mathematical model and the visual and motion system. When manoeuvring close to the ground, the main areas of criticism of simulation fidelity were the restricted field of view, both in pitch and azimuth, and the limited heave motion cues. These limitations led to difficulties with flight path (height and track) control compared with experience in a real helicopter. However, the addition of a bold white line defining the track, and a corridor of foliage (described in more detail in section 4.4) to aid height perception, compensated to a large extent at least for the visual limitations.

Quantitative comparisons were made with flight results for Puma and (to a more limited extent) Lynx, both unstabilised. The Lynx has a hingeless rotor

with  $\lambda_{\beta}^2 \approx 1.2$  and  $\gamma \approx 8.2$ , and the Puma an articulated rotor. These comparisons included trims and responses to step control inputs at selected speeds. Overall comparison with Puma flight data was considered good<sup>4</sup>. Cross-coupling from pitch into roll and vice versa did not agree well, as one might expect without a hinge offset model, but these cross-couplings were fairly small in general.

Comparison of the simulator with Lynx flight results did not create as high a level of confidence in the model. Fig 3 illustrates typical comparisons of the response to longitudinal and lateral cyclic stick inputs at 100 knots. Whereas pitch rate response to longitudinal cyclic shows good agreement the same is not true for the roll response to lateral cyclic. The oscillatory character of the roll rate response measured in flight suggests that substantial sideslip developed in the short term and this is thought to originate from a low value of the ratio  $n_v/l_v$  in the raw aircraft. Other data, not shown here, indicate strong pitching and rolling moments being produced following a step pedal input and these couplings, presumably again due to sideslip, are much smaller in the model. Further flight and theoretical experiments are planned to investigate these phenomena.

The primary areas of disagreement revealed by the Lynx comparisons are predictions of cross-couplings and roll control response. The Lynx data were not available until after the simulation was completed and therefore did not influence the experiments. The areas of discrepancy require attention but it is felt that the conclusions drawn in this paper are not materially affected by the comparisons but their range of application is more limited.

Finally Fig 4 shows a comparison between the simulated Lynx and the real aircraft flying the large triple bend, which was marked out on the airfield at Bedford with the same geometry as the course in the simulator (see section 4.4). In spite of the differences in roll response discussed above the agreement shown in Fig 4 for roll-related variables is very good. Pedal movement agrees well, with some not unexpected displacement of the mean. Longitudinal correlation is not nearly so good, as might have been expected from the coupled responses previously discussed. The normal acceleration comparison in Fig 4 suggests that, during the turns, the required 'g' was established earlier in flight, a feature that could be explained by the limited motion cues in the simulation reducing pilot perception of height loss. Unfortunately height error was not obtained during the Lynx flight as the radio altimeter gave spurious readings after 45 deg of bank and the low visibility precluded the use of kinetheodilites. Records obtained when flying the triple bends with both Puma and Gazelle, however, show height variations comparable to those obtained in the simulator.

#### 4 BACKGROUND TO THE SIMULATION EXPERIMENTS

##### 4.1 Configurations

The primary parameters varied during the experiments were the blade flapping stiffness coefficient  $K_{\beta}$  and inertia  $I_{\beta}$ . A matrix of six rotors was defined based on the resulting variation in the non-dimensional parameters  $\lambda_{\beta}$  (blade flapping frequency ratio) and the Lock number  $\gamma$ . This matrix is shown in Table 1 and includes the configuration identity A2, C3 etc. Some early experiments were performed to select optimum values for cyclic phasing, longitudinal stick gearing and the amount of collective to longitudinal cyclic interlinking. These experiments are described in section 5.1. The remaining parameters defining the raw configurations were held constant during the trials at

values representative of a Lynx-like helicopter. Operational weight was 9500 lb. To give an indication of the effect of variation of the primary parameters in the longitudinal and lateral responses, short term rate responses to one inch cyclic stick inputs at 100 knots for the configurations are displayed in Figs 5 and 6. They illustrate the range of control and rate sensitivity (angular acceleration and velocity per inch of stick movement, respectively), basic pitch and roll time constants and cross-coupling considered during the simulation. How these different features affect handling qualities will be discussed in more depth in section 5.2 but several points are worth developing at this stage. The first observation to be made identifies the general character of the primary responses as classical rate responses, particularly the roll response. The evidence supplied by the Lynx flight results in Fig 3 suggests that the short term response to lateral cyclic can contain an oscillatory component that would be expected to degrade attitude control. This type of response is familiar<sup>7</sup> in both fixed and rotary wing stability and control and, as mentioned earlier, is often attributed to the combination of low directional stability ( $n_v$ ) and high dihedral effect ( $\lambda_v$ ). The absence of any appreciable dutch roll content in the roll response of the present agility configurations simplifies the study of handling qualities to the extent that short term roll control is dominated by the subsidence mode. The present experiments are therefore restricted in terms of lateral handling qualities and improvement in the mathematical model is clearly needed in this area.

#### 4.2 Roll response

Lock number is seen (from configurations C1, C2, C3 in Fig 5) to have a pronounced effect on both roll rate sensitivity and time constant, with both increasing as blade inertia and hence damping decreases, *eg* C3; 13 deg/s/in, 0.175 s and C1; 30 deg/s/in, 0.4 s. Variations in  $\lambda_\beta^2$  change both the damping and control power in approximately the same proportion and hence the rate sensitivity varies only slightly between A2 and D2, as is also shown in Fig 5. On the other hand the time constant reduced from about 0.5 s for A2 to 0.25 s for D2. This characteristic behaviour is more or less preserved from hover to high speed.

In this paper lateral handling qualities will be discussed within the framework of the roll time constant/rate sensitivity diagram which is permissible when the short term response is dominated by the roll subsidence mode. The present agility configurations are located on this diagram in Fig 7 along with some relevant handling boundaries, and two current military helicopters, the YUH-60 (UTTAS) and YAH-64 (AAH). The Edenborough-Wernicke criterion<sup>10</sup> was specifically developed for armed helicopters flying nap-of-the-earth tasks and this augments the Mil Spec 8501A criteria<sup>11</sup> by specifying a lower rate sensitivity (14 deg/s/in) and a maximum time constant (0.25 s) for satisfactory handling qualities. Contemporary simulation research conducted at NASA Ames in this area claims<sup>12</sup> that this boundary is probably too restricted, without identifying a wider boundary, and suggests that auxiliary features, *eg* cross-couplings, can degrade handling qualities inside the satisfactory boundaries.

The wider boundary in Fig 7 is the 3.5 pilot rating boundary obtained for fixed wing fighter aircraft<sup>13</sup>. The results of Ref 13 are used to support the requirements laid down<sup>14</sup> in Mil Spec 83300. While reviewing the work in Ref 13, Bisgood<sup>15</sup>, makes the point that in the major portion of the regime investigated, "the contours of the boundaries define limits to the capability of performing certain operational bank manoeuvres", and goes on to show that theoretical results for a bank and stop manoeuvre correlate well with the experimental boundaries of Ref 13. The point made by Bisgood is raised here because of its

relevance to agility. It will be shown in section 5.2 that limits to agility can also be described in terms of characteristic manoeuvres but that the boundaries are probably far narrower than those described in Refs 13 and 15.

#### 4.3 Pitch response

Turning now to the response to longitudinal cyclic inputs, we see in Fig 6 the effect of the primary parameter changes in the pitch, roll and yaw rates. Increasing rotor stiffness (A2 to D2) increases the basic pitch rate response but also the cross-coupling effects. Lock number appears mainly to influence the pitch response, but not the cross-couplings. In considering these results, it is important to realise that short term pitch response is strongly affected by forward speed. Whereas in the hover control sensitivity remains constant with  $\lambda_{\beta}^2$  and the short term pitching response is determined by the pitch damping and control power, the response becomes more complex as forward speed increases, with incidence changes coupling with the pitching motion. Resulting speed changes begin to introduce non-linear effects after only a few seconds, as illustrated in Fig 8. The normal acceleration and pitch rate response, normalised by the size of input,  $\eta_1 C$ , are shown here for rotors A2 and D2. The axis scale refers to the largest input case. Two notable features of the response are relevant to the present study. Firstly, with the softer rotor (configuration A2), negligible differences in response character are observed for the different inputs. For D2, however, the character changes dramatically after about  $1\frac{1}{2}$  s with a sharper response peak occurring much earlier for the larger inputs. Also, for the stiff configuration (D2), the larger the input, the more the response departs from being a rate type and pilot appreciation of pitch control is expected to change. Linear theory will, of course, predict the type of response produced by the smaller inputs in Fig 8 and hence handling qualities criteria based on analytical models may well be at variance with pilot opinion of applied flying tasks where the pitch response continues to be important after about  $1\frac{1}{2}$  s.

Fig 9 shows how a selection of other variables, relevant to agility, develop during the first few seconds after a one inch cyclic step, portraying the increased transient manoeuvrability for the stiffer rotors for the same control gearing. To achieve the same flight path (height change) as a D2 with an A2 configuration would clearly require a substantial increase in control gearing and would be produced at the expense of considerably greater longitudinal flapping. The same level of manoeuvrability comparison can be made with regard to decelerating turns in the horizontal plane as discussed in Ref 16.

#### 4.4 The tasks

The tasks discussed in this paper involved flying through two sets of bends which formed part of a larger scheme. This total scheme, illustrated in Fig 10, consisted of a winding 'Serpent' course, designed to evaluate primarily lateral-directional handling qualities, and a series of hurdles placing emphasis on longitudinal handling qualities. For the Serpent course the path to be followed was defined by a white line marked on the ground and additional constraints were imposed in the bends by a corridor of trees, some 60 ft (20 m) high and 150 ft (45 m) wide, apparent in the photographs of the triple bends shown in Fig 11.

This paper examines in detail flight round the two sets of triple bends, the geometry of which, shown in Fig 12, was determined by the kinematics of

flight in 2 g turns at 60 and 100 knots. Fig 13 illustrates flight paths in turns at these two speeds and several angles of bank. At 100 knots, reduction of bank angle causes a substantial increase in the air space required to effect a 180 deg turn. The lower speed also has a dramatic effect. Fig 14, a general chart of turn rate and radius of turn versus speed and bank angle, brings out in particular that 2 g turns at low speeds involve high turn rates (20-30 deg/s) which are translated, in aircraft terms, into demands for high yaw and pitch rates. This latter point will arise again later when discussing the results. It is also important to appreciate from Fig 14 how rapidly the normal acceleration level to maintain balanced flight builds up once the bank angle exceeds 60 deg.

Bank angle (deg)	48.2	60	66.4	70.5
Normal acceleration (g)	1.5	2.0	2.5	3.0 .

Flight round the large triple bend at 100 knots demands close to the maximum sustained performance typical of current operational helicopters without special features to assist agility, such as lift or thrust augmentation or a high solidity rotor.

An implication from this discussion is that, for speeds of 100 knots, 60 deg banked turns are desirable to give adequate turning performance but are probably close to the maximum that could be specified as being acceptable to a pilot in flight close to the ground.

The pilot's task in negotiating one of the triple bends was to follow the white line while keeping his height below 50 ft (15 m) above the ground. To aid height assessment a light, located centrally on the main instrument panel but easily detectable while looking outside, was triggered to come on whenever the helicopter rose above the set height. The pilots found this simple device to be a useful indicator and felt it imposed a realistic and necessary stress. For each new helicopter configuration, the pilot was allowed to fly as many runs as necessary to assess the configuration, at the end of which he summarised his comments and gave a pilot rating using the well known Cooper-Harper scale<sup>17</sup>, shown in Table 2. Depending on the configuration's characteristics, as many as six runs might be required before the pilot was satisfied. There is considerable evidence of learning and it is not unreasonable that the pilot should have time to adapt his method of control to suit the new configuration.

Trace records of key variables such as control positions, body rates and attitudes, speed, height and 'g' were taken during each run. Digital samples of these and many more variables, including rotor behaviour, were also stored in the computer for subsequent analysis. These records, together with the pilot's ratings and his detailed comments formed the basis for the assessment described in this paper.

## 5 AGILITY IN THE TRIPLE BENDS

### 5.1 Auxiliary parameters

This section describes the rationale adopted for the selection of values for longitudinal stick gearing and collective/cyclic pitch interlink, both of which vary with speed for the basic Lynx configuration, and the cyclic phasing angle. Within these studies, pilot opinion varied over as wide a range as when the

primary parameters were varied. But this was expected and it is thought that the constant values chosen are a suitable compromise. One assessment pilot only was available for this optimisation.

Varying phase angle for the C2 configuration between -15 deg and + 45 deg produced the pilot rating pattern shown in Fig 15 for the large triple bend task. The asymmetry in the results about the nominal 15 deg value reflects a preference for aft/left to forward/right wrist movement by the assessment pilot, who quickly adjusted to both  $7\frac{1}{2}$  deg and 30 deg of phase shift. A value of 15 deg was therefore chosen as an overall compromise even though the C2 optimum value for roll at 100 knots lay between 20-30 deg.

The interlink between collective lever input and longitudinal cyclic pitch was chosen to give a zero pitching moment with collective at approximately 60 knots, *i.e.* the design speed for the small triple bend.

In some helicopters, longitudinal cyclic stick gearing is a function of collective lever position but for these tests it was constant. However it was necessary to establish a suitable value for this gearing for each rotor configuration, in terms of degrees of cyclic per inch of stick movement.

Stick travel was nominally 10 inches (250 mm), constrained by the space available in the simulator cockpit. Three values of stick gearing were set up: 1.6, 2.3 and 3.1 deg/in. For the purposes of the present discussion, these are referred to as G1, G2, G3 respectively. When varying gearing, the total cyclic range is, of course, affected and it is important that a suitable neutral value is determined to provide adequate manoeuvring authority for both forward and back stick movements.

To evaluate alternative gearings, one pilot (pilot A) flew each of the rotor configurations of Table 1 with each gearing, using the large triple bend as the task. Stick activity and helicopter motion were recorded as usual and pilot opinion ratings awarded.

The variation of pilot rating with stick gearing for each configuration is illustrated in Fig 16. For variation of rotor stiffness at constant Lock number (configuration A2, C2, D2), pilot rating did not change markedly with stick gearing (Fig 16a). For the softest rotor (A2), rating improved slightly with increased gearing. For C2 and D2 the general trend is a decline in rating with gearing.

Fig 16b shows variation of pilot rating with gearing for three rotors of constant, fairly high, stiffness, but varying Lock number. Here the variation of rating with gearing is quite dramatic, the same rotor being given ratings of 1, 2 at its best, with gearing G1, and 6, 7 at its worst (gearing G3). Indeed, the pilot was amazed that "just changing stick gearing could have such a drastic effect". The general trend again is that increasing the gearing degrades the handling qualities.

The conclusion from these tests was that gearing G1 (1.6 deg/in) would suit all rotors. Why this should be so is not really clear, as plotting rating against control sensitivity, expressed as  $\text{rad/s}^2/\text{in}$ , thus including the effect of stick gearing changes on the response, does not produce a unified picture (Fig 16), there being still a clear effect of rotor types on the optimum control sensitivity.

## 5.2 Assessment of the rotors and their agility characteristics

The simulated helicopter was flown with each of the rotors defined in Table 1 and assessed by three pilots in the triple bends without any auto-stabilisation, *ie* in its 'raw' condition. Each pilot's ratings, according to the scale<sup>17</sup> shown in Table 2, are displayed in Fig 18 as a function of flapping frequency ratio and Lock number. Shaded areas indicate the range of ratings given. Pilots B and C chose to fly the large bend (designed for 100 knots) at a lower speed than pilot A, a point of significance for agility that will be developed later. The data are incomplete due to the limited time available with pilots B and C. Distinct trends are nevertheless apparent and overall the pilots preferred the stiffer rotors with a mid range Lock number. Pilot A flew the large triple bend at several collective settings defining different entry speeds. Fig 18 shows how his ratings became uniform as entry speed decreased, a feature related to the increased time available for manoeuvring and compensation. At lower speeds, not only are the bank angles required smaller but the distance covered during pilot's reaction time are shorter and this should be reflected in the level of agility demanded.

Fig 19 shows the roll rates used during the reversals by pilot A as a function of speed. Only configuration C2 was flown at these lower speeds. The full lines denote the hypothetical rates required to complete the roll reversals in just 2 s, a value thought to be a typical characteristic time for this manoeuvre. At 100 knots the rates actually used vary from about 70 deg/s with C3 to well over 100 deg/s with C1 and A2. Time constants for the rolling mode at these extremes were about 0.2 s and 0.5 s respectively and the pilot demanded full control for both C3 and A2. With configuration C3 the pilot complained of the barely adequate control available whereas with A2 overcontrolling resulted from the longer time constant. At 90 knots the rates required from the different configurations were much more uniform and this situation is expected to be preserved at the lower speeds where the rates used follow more closely the bank angle curve. It appears that, above about 90 knots, this pilot began to compensate for the differences in rate sensitivity (roll rate per inch of stick) and time constant and differences between the configurations began to emerge.

An important feature here is the ratio of the time constant of the aircraft's response to the characteristic time of the manoeuvre. A deterioration in pilot opinion is expected to accompany an increase in this ratio with the increased workload required for attitude control. This expectation is certainly borne out by speed variation (manoeuvre time) and configuration changes (time constant), but the actual deterioration felt is very pilot dependent. For example, the roll rates used by pilots B and C at 90 and 80 knots were 10-20 deg/s higher than used by pilot A, at the same speed, who also gave a better pilot rating. Fig 20 shows pilot A's ratings for C2 at four different speeds. The deterioration in rating at 40 knots was attributed to the more difficult height control necessitating collective activity.

A graphic portrayal of the effect of forward speed on the task of flying the large triple bend is shown in Figs 21 and 22. Fig 21 shows that the track achieved at each speed (100, 80 and 60 knots) is practically indistinguishable from the others. Fig 22, however, depicts the pilot's control activity, plotted as hand movement. As speed falls, control activity shrinks dramatically.

For the 60 knot triple bend both pilots A and B indicated a preference for the stiff rotor D2 and clearly regarded this task as the more difficult.

This is particularly apparent from pilot A's ratings in Fig 18. Roll rates used during reversals are included in Fig 19 and indicate a wider range of values for the different configurations. The pilots demanded full cyclic for C3, C1 and A2. The higher roll rates used reflect the shorter characteristic manoeuvre time for this task. At this lower speed, the task is made more difficult by the higher pitch and yaw rates necessary in turns, as brought out earlier in Fig 14, and is compounded now by the additional dimension of having to make extensive use of collective pitch.

It is apparent from the results described above that both speed and configuration type have a strong influence on the roll handling qualities that feature while exercising the agility levels demanded by the triple bend manoeuvres and hence on pilot opinion. Unfortunately simulation time was not available to fly a wider range of configurations. An attempt was made to define boundaries on the roll handling qualities diagram discussed in section 4.2. Some variations on the basic configurations were briefly flown yielding evidence to suggest that configurations near the 3.5 pilot rating boundary of Ref 13, shown in Fig 7, may well give ratings which are closer to the 6.5 boundary for the large triple bend task. Also the preferred configuration would seem to be between C2 and C3 rather than C2 and D2, *ie* with a somewhat lower rate sensitivity than C2 and D2. Further systematic work is clearly needed to define boundaries and preferred regions on this diagram. The problems associated with completing such a picture are complex since the boundaries will be dependent on the particular manoeuvres being flown, *ie* on the level of agility. It is not hard to imagine a complete picture, such as Fig 23 with several different contours, each a 3.5 pilot rating boundary for a particular 'Level' of agility. Fig 23 is speculation and operational requirements will certainly need to be drawn on to define the types of manoeuvre associated with each level.

For most of the flying the longitudinal characteristics were not optimised and hence height control featured large in the overall pilot opinion. One pilot, before finding suitable visual references, commented that the workload in controlling height was very high, aggravated by the weak heave motion cue. He was adamant that height was the most important single variable, with agility becoming important when one tries to fly lower and faster where good height control is essential.

Precise height control near the ground involves a careful coordination of rotor thrust and bank angle. When the former is accomplished with longitudinal cyclic then the character of the pitch response and the degrees of cyclic harmony becomes as important as the roll characteristics. Pilot C felt that all of the raw configurations were unsatisfactory ( $PR \geq 4$ ) for the tasks mainly because of the high workload in controlling pitch and hence height. Fig 24 illustrates the problems this pilot had with height control. After allowing the 'g' to reduce while in the first bend (a) he found the helicopter 'swooping down' during the first reversal (b). He then maintained a high thrust by pitching up, only to climb when in the second bend (c). The 'g' was then reduced and increased again before the second reversal causing the helicopter to climb while reversing roll for the second time (d). This pattern repeated during the last bend (e). Similar problems were experienced by all three pilots on occasions. Height control was regarded as most critical during the roll reversals when the highest lateral cyclic activity occurred.

Cross-coupling from roll into pitch clearly will affect co-ordination during reversals but pilot criticisms were not consistent regarding this feature.

In particular their criticisms were often compounded by the immediately preceding control activity as discussed above.

No systematic investigation into the effects of cross-coupling was made during the simulation and the most positive comments came when these were practically eliminated during the control system study (described in section 5.3). It is felt that efforts to understand these effects in raw configurations should be maintained since cross-coupling derivatives are notoriously badly predicted by theory (see section 3) and there exists some scope for reducing these.

An additional problem for the pilots when flying at steep bank angles related to the distinction between pitching and yawing motions. Once identified, the yawing reaction from torque fluctuation was criticised, particularly when pulling out of left roll reversals where the counterclockwise reaction caused the helicopter to yaw towards the ground. Pedal activity was highest at this time. The yaw oscillatory mode, with a period of about 2-3 s, was practically invariant for the different configurations and this motion dominated the response to pedal. All pilots compensated for the restricted field of view by using pedal to skid around the turns (slipping out) hence enabling them to see further around the course. This, not entirely artificial, technique resulted in a more favourable opinion of the configurations for which full lateral cyclic was used, eg A2, C3 and C1.

### 5.3 Control systems

Most of the results described so far have been with 'raw' helicopter configurations in order to gain insight into the inherent effect of rotor characteristics on handling qualities. Some exploratory tests were also conducted to evaluate the potential improvements in handling qualities which could be obtained from a control system, and to give some indication of the type of control system which might be required.

What do pilots want from a control system? Their requirements include precise control over flight path, exercised through attitude control, with a low workload stemming from low compensatory control activity, and minimal cross-coupling resulting from controls or manoeuvres. Particular questions are concerned with whether an attitude or rate type of response is preferred, and with the control authority required.

In the following sections, three forms of control law will be discussed: additional rate damping, attitude stabilisation and rate command, attitude hold.

#### 5.3.1 Attitude systems

One pilot (C) assessed additional rate damping in pitch and roll versus attitude stabilisation, with configuration C2. His preference was for attitude control in both axes, which he rated at 3. Fig 25 compares records from two runs round the large triple bend, one with attitude stabilisation in pitch and the other with rate damping, in both cases with attitude control in roll. Longitudinal stick activity and pitch attitude are both much steadier with the attitude system (Fig 25a), and autostabiliser requirements were less. The pilot commented that lateral cyclic stick activity was also reduced, solely as a result of the changes in pitch behaviour. The characteristic variation in pitch rate, necessary to maintain height, is well brought out in Fig 25.

Comparing now an attitude system in roll with a simple autostabiliser providing additional rate damping, notable features of the time histories in Fig 26 are the distinctive patterns of lateral cyclic movement for the two control configurations. Furthermore, stick activity is less and the roll behaviour is steadier with the attitude system.

An important consequence of the improved handling qualities resulting from stabilisation was that the pilot was prepared to fly the triple bend task some 10 knots faster, *ie* at a mean speed of 95-98 knots instead of 86-90 knots, without degradation in pilot rating (Fig 27). Further speed increase, to 110 knots, degraded his rating to five and elicited severe comments that the speed was too high. In fact, he considered the task was approaching the limit of his ability, in particular his ability to receive and process information from the outside world, and he could not envisage improvements to the control system which would make the task more acceptable. Speed and height time histories for these cases are illustrated in Fig 28, grouped according to collective pitch setting. Height control has suffered at the higher speeds.

After trying various combinations of attitude and rate control systems, this pilot commented that, even though not optimised, such systems "had the dramatic effect of eliminating cross-coupling effects and resulted in a significant reduction in pilot workload and an ability to fly faster through the obstacles while remaining below 50 ft".

Following this assessment of pitch and roll attitude systems, two other pilots examined several systems providing *roll* attitude autostabilisation only. Characteristic responses to a step input of lateral cyclic stick (at the pilot) are illustrated in Fig 29, for the various configurations, which have been given the identifiers C21, C22 etc. The response of the raw helicopter (with C2 rotor) is also shown. In all cases the input is sized at 10% of total travel. With the attitude systems, a step stick input produces a near constant roll attitude. The configurations differ in the final attitude achieved and in the time taken to reach it.

Principal comments, which should be related to the responses in Fig 29, and the associated identifiers C21 etc, are summarised below.

C24 was criticised for inadequate authority. Full lateral stick deflection gave a bank angle of about 65 deg, which, not surprisingly, was not acceptable in a task calling for 60 deg of bank. This configuration was rated 4-7.

C23 was criticised for being too sensitive and responsive, although the two pilots were not fully in agreement, pilot A rating it at 5-8½, and pilot B at 4.

C22 was the best, with C21 similar. Pilot B thought that C21 had the minimum desirable initial roll rate.

Pilot A commented that having a roll attitude system also reduced the problems in the pitch and yaw axes, although there were no direct changes to the behaviour in these axes, which were not stabilised in any way.

All pilots showed a clear preference for the addition of roll attitude stabilisation to the raw aircraft. With the attitude system the pilots considered it was possible to achieve much greater precision in the flight path, whereas

with the raw helicopter continual compensation was necessary and despite significantly more stick activity during roll reversals, flight path control was less precise.

### 5.3.2 Rate command, attitude hold (RCAH)

A further form of control system examined, albeit only very briefly, was one in which, for no stick movement, roll attitude hold properties were the same as described above, but for manoeuvring stick displacement now commanded a *rate of change* of datum roll attitude.

Pilots were keen to retain the roll attitude hold facility, already examined, for its value in turns and in suppressing cross-coupling, but thought that a rate response character might in fact be preferable for manoeuvres and would overcome the limitations of a pure attitude system.

Two particular configurations were evaluated by pilots A and B. Fig 30 illustrates a flight by pilot A through the triple bend and compares behaviour with a rate command system with the best of the attitude control systems. The run with the rate command system exhibits smoother roll rate and bank angle behaviour, generally lower roll rates, good control over normal acceleration and somewhat reduced demands on autostabiliser authority. Flight speeds are generally similar but height control with the rate command system was not as good as with the attitude system, although the achieved heights are lower.

Pilot A gave a pilot rating of 3 to the rate command system. He gave a PR of 2 to the attitude system, although on repeating the configuration *after* the RCAH system only gave a PR of 3. Pilot B, however, rated the RCAH system better than the attitude system.

### 5.3.3 Summary of control systems studies

Table 3 summarises the pilot ratings of the three pilots for the raw helicopter and the attitude and rate command control systems. The pilots were agreed that either control system type was a distinct improvement over the raw helicopter. Pilot A for example, was adamant that the raw helicopter was not nearly as good as the rate command system, despite the numerical pilot ratings not being enormously different.

The best attitude system reduced pilot workload (as reflected in the pilot rating) and offered an increase in performance (shown most dramatically for pilot C in the higher speed at which he could perform the task). The principal disadvantage of an attitude system in roll was the need to maintain a stick displacement in a turn. This was tiring unless the stick forces were light or the stick trim was disconnected. In pitch, it would be difficult to match an attitude system to the necessary manoeuvres over the whole flight envelope, such as acceleration and deceleration manoeuvres or diving attacks.

Although only a brief examination of a rate command system was possible, initial results were very encouraging. The pilots considered that they felt more in control with a rate system which will stop at an attitude when the stick is centralised. With an attitude system, they were not sure what attitude would result from a given control movement and the rate of change of attitude depends on the speed of movement of the hand. Although a rate system in principle requires more stick movement to effect a given manoeuvre, *eg* two movements for a roll and

stop versus one with an attitude system, the pilots did not consider this to be a serious criticism of a rate system for agility. The advantages of a rate system are suitability for a wider range of manoeuvres and potentially the promise of a lower authority.

A good control system in the context of agility should provide attitude stabilisation to minimise control activity in the 'steady' phase of manoeuvres such as turns, elimination of cross-coupling during manoeuvres (pitch response due to rapid rolling is particularly disturbing) and turn co-ordination in both yaw and pitch which is sufficiently effective to cope with rapid rolling. The maintenance of height during rapid rolling manoeuvres is a major problem: the pitch rate variation required has already been mentioned. These are areas for further study.

## 6 DISCUSSION AND CONCLUSIONS

This paper has described some piloted simulation experiments conducted to explore the nature of helicopter agility and in particular to evaluate the influence of rotor flapping stiffness and inertia on a helicopter's handling qualities and agility. As the range of topics discussed has been wide and varied, some of the main points are reviewed here.

The influence of the principal rotor parameters on the helicopter's response to longitudinal and lateral cyclic controls has been examined as a background to the pilots' qualitative assessments. These responses have shown that, for the stiffer rotors, the increased transient pitch response and associated speed response, for a given control deflection, makes assessment of pitch handling qualities by theoretical methods more complicated than for soft rotors. Short term roll response, and its relationship to handling qualities, is, however amenable to theoretical analysis, at least when dominated by the roll subsidence mode.

Agility has been explored by testing the ability of the simulated helicopter, with each rotor configuration, to negotiate triple bend sequences marked out on a special course, while keeping height below 50 ft. Tight constraints were imposed on how accurately the track was to be flown. These tasks, set up as an idealisation rather than as a truly realistic operational demand, were very exacting and successful. They were well defined, especially in the simulator with the corridor of trees and direct indication of height excursions above 50 ft, and were also readily set up in real life (but without the trees) for full-scale flight tests.

Piloted simulation has been shown to be a valuable tool for assessing helicopter handling and agility. Despite limitations in the field of view and ground detail of the TV-type outside world display, pilots could fly the desired manoeuvres in a consistent manner at ground clearances of 20-50 ft and speeds up to 120 knots. Such vigorous flying tasks do, however, make major demands on simulator motion systems and visual displays, and there is a clear need for improvement, firstly in field of view and secondly in amplitude of motion. Restricted field of view, low picture resolution and limited heave motion together resulted in pilots having poor perception of height changes in the simulator. However, it did appear that the same order of height variation was experienced in real flight. Once pilots had become familiar with the task, the white track line and corridor of foliage compensated to some extent for these limitations. Indeed, the agility course created on the model terrain especially

for these present tests was particularly valuable and suggests that, by creation of another appropriate terrain, operational concepts could also be explored by piloted simulation.

Deficiencies in the mathematical model have been identified by comparison with flight test results from a Puma and Lynx. Improvements in modelling are required, particularly in relation to cross-coupling effects.

Agility is a combination of performance and handling qualities. Performance provides the ability to manoeuvre and sustain the required normal acceleration, *eg* up to 2g or more at 100 knots, and good handling qualities give the pilot the confidence to use the available performance in this demanding regime of flight close to the ground. Despite major changes to the response of the simulated helicopter, accuracy achieved in the triple bends, measured in terms of track following, did not differ markedly, except for those few cases where the bends could not be negotiated at all. These cases were limited by the time required to develop the necessary bank angles rather than by the ability to generate absolute levels of normal acceleration. The primary effect of different rotors was on the pilot's ability to control the helicopter's attitude. Banking was necessary in order to turn, but also to correct for height error; pitching in order to maintain height; and yawing to suppress sideslip, but also sometimes deliberately to induce it, either to see better or to enhance the roll performance. It was not possible to negotiate the bends successfully without use of pedal.

Results from the present tests of alternative rotors have shown that agility is strongly influenced by rotor blade flapping stiffness and inertia, the principal parameters varied. Although numerical results in absolute terms must be treated only as an informed guide, the tests showed that flapping stiffness, quantified by flapping frequency ratio ( $\lambda_\beta$ ), in the region of  $\lambda_\beta^2 = 1.2$  and Lock number ( $\gamma$ ) in the range  $\gamma = 4-8$  formed the best compromise for the raw helicopter. Low stiffness rotors (*eg* A2 in the present context) cannot roll quickly enough and high stiffness rotors (*eg* D2) are too responsive and prone to pilot induced oscillations. During the vigorous manoeuvres involved in flying the triple bends, soft rotors such as A2 have to flap much more than the stiffer rotors to produce similar rotor head moments, which may impose design problems in terms of canopy and tail clearance. Such rotor limits, including retreating blade stall, are important factors to be taken into consideration, and need a mathematical model in which they can be effectively included. In our tests, rotor flapping and maximum blade incidence were monitored but did not inhibit the rotor's performance in any way.

Forward speed is a major parameter in agility, affecting both workload and performance. In the present tests, the large triple bend was designed to be flown at 100 knots, more to expose the potential weaknesses of individual rotors than as a practical speed. In fact, the large triple bend could certainly be flown at 80-100 knots as a practical proposition but, involving as it did bank angles of 60 deg or more, the demands of such manoeuvres were close to the limit of pilot acceptability so close to the ground and near obstacles. To go faster with the same flight path would require higher 'g', for example 2.8g at 120 knots instead of 2g at 100 knots, and would demand higher roll rates to reach the necessary bank angle. To maintain adequate clearance between the rotor and the ground would then dictate a minimum height of not less than 30 ft. Flying more slowly reduces control activity and turn radius but at the expense of increased time for a sortie. Operational factors must then be taken into account.

Agility manoeuvres require crisp response to longitudinal and lateral cyclic inputs. At 100 knots, maximum roll rates achievable certainly need to exceed 60 deg/s and demands for 80-100 deg/s are likely. These numbers are a function of speed. It has been shown that, for flight through the large triple bend, peak roll rates decrease as speed drops but in the circumstances of tighter manoeuvres, such as the small triple bend, very high roll rates, up to 150 deg/s, are called for even at 60 knots. Maximum pitch rates demanded are typically 20-30 deg/s. Large attitude excursions, to more than 60 deg in roll and 40-60 deg in pitch are necessary. All axes of response are important: pitch and roll for primary manoeuvrability and yaw to maintain balanced turns and to counter reaction from torque fluctuations, which may be significant in gross manoeuvres even at fixed collective settings.

Agility could be quantified by defining a range of manoeuvres as a series of paths in space and assigning a level of agility to each path, taking into account the speed at which it could be flown. This amounts to defining agility kinematically. It would then be possible to relate levels of agility to specified operational roles and to identify the handling qualities which affect the attainment of these levels. Many of these aspects can be investigated by simulation.

No helicopter is agile without good performance but agility really comes from the speed and precision with which manoeuvres can be initiated and the required flight path sustained at low workload. A control system can enhance these areas. Additional rate damping, attitude stabilisation and rate command, attitude hold systems in pitch and roll were assessed briefly.

Attitude stabilisation was preferred to rate damping: its merits including provision of attitude stability and enhanced suppression of cross-couplings. Rate command with attitude hold was potentially even more promising as it still provided the advantages of attitude hold but with improved manoeuvring capability, and possibly lower authority demands. Specific benefits resulting from the addition of a stability and control augmentation system were reduced workload and an ability to fly faster. Pilots also thought that accuracy in following the desired track was improved. There is no hard evidence of this. Measurements suggest the track could be maintained to within  $\pm 15$  ft, *ie* less than the rotor radius, even with the raw configurations. What is apparent is increased pilot confidence, reflected in his willingness to fly this kind of task at all. A further benefit is the increased steadiness resulting from incorporation of a control system. If the pilot cannot maintain precise control, transient load factors may approach limiting values, or the likelihood of doing so may inhibit the pilot from manoeuvring in as carefree a manner as he might wish.

Present control systems are designed primarily with autostabilisation in mind, and for sustained manoeuvres of relatively limited extent. Further study is needed to design them to suit the particularly active and extreme manoeuvres which are now being demanded of the modern tactical helicopter.

The research described in this paper has demonstrated that piloted simulation can contribute to the description of helicopter agility and related handling qualities. Manoeuvres close to the ground, demanding bank angles of 60 deg or more, were flown by the assessment pilots with remarkable success. Although deficiencies exist in simulation fidelity for the very demanding tasks relevant to agility, they do not detract significantly from the main results of the experiments.

## REFERENCES

- 1 C.L. Livingston, M.R. Murphy; Flying qualities considerations in the design and development of the Hueycobra. Journal of the American Helicopter Society, Vol 14, No.1, January 1969
- 2 T. Wilcock, Am C. Thorpe; Flight simulation of a Wessex helicopter - a validation exercise. RAE Technical Report 73096 (ARC Current Paper 1299) (1973)
- 3 T. Wilcock, B.N. Tomlinson; Flight simulation in helicopter and V/STOL research. Second Flight Simulation Symposium, Royal Aeronautical Society, London, May 1973
- 4 G.D. Padfield, B.N. Tomlinson, P.M. Wells; Simulation studies of helicopter agility and other topics. RAE Technical Memorandum (1978)
- 5 B.N. Tomlinson; Sesame - a system of equations for the simulation of aircraft in a modular environment. RAE Technical Report 79008, January 1979
- 6 L.H. Warton; A four degree of freedom, cockpit motion machine for flight simulation. RAE Technical Report 72075, ARC R & M 3727 (1972)
- 7 E. Seckel; Stability and control of airplanes and helicopters. Academic Press New York, 1964
- 8 Dean E. Cooper; YUH-60A stability and control. Proceedings of the 33rd Annual National Forum of the American Helicopter Society, Washington DC, May 1977
- 9 K.B. Amer, *et al*; Handling qualities of Army/Hughes YAH-64 advanced attack helicopter. Proceedings of the 34th Annual National Forum of the American Helicopter Society, Washington DC, May 1978
- 10 H.K. Edenborough, K.G. Wernicke; Control and manoeuvre requirements for armed helicopters. Proceedings of the 20th Annual National Forum of the American Helicopter Society, May 1964
- 11 Anon; Helicopter flying and ground handling qualities; general requirements for MIL-H-8501A, September 1961
- 12 R.T.N. Chen, P.D. Talbot; An exploratory investigation of the effects of large variations in rotor system dynamics design parameters on helicopter handling characteristics in nap-of-the-earth flight. Proceedings of the 33rd Annual National Forum of the American Helicopter Society, Washington DC, May 1977
- 13 Brent Y. Creer, John D. Stewart, Robert B. Merrick, Fred J. Drinkwater III; A pilot opinion study of lateral control requirements for fighter-type aircraft. NASA Memo 1-29-59A, March 1959
- 14 Charles R. Chalk, *et al*; Background information and user guide for MIL-F-83300 military specification - flying qualities for piloted V/STOL aircraft. Technical Report AFFDL-TR-70-88, March 1971

- 15 P.L. Bisgood; A review of recent research on handling qualities and the application to the handling problems of large aircraft. Part II lateral-directional handling. ARC R & M 3458, June 1964
- 16 S. Attfellner, W. Sardanowsky; Meeting the manoeuvrability requirements of military helicopters. 2nd European Rotorcraft and Powered Lift Aircraft Forum, Bückeberg, FRG, September 1976
- 17 G.E. Cooper, R.P. Harper; The use of pilot rating in the evaluation of aircraft handling qualities. AGARD Report 567. NASA TN D-5153, 1969

Table 1  
MATRIX OF AGILITY CONFIGURATIONS

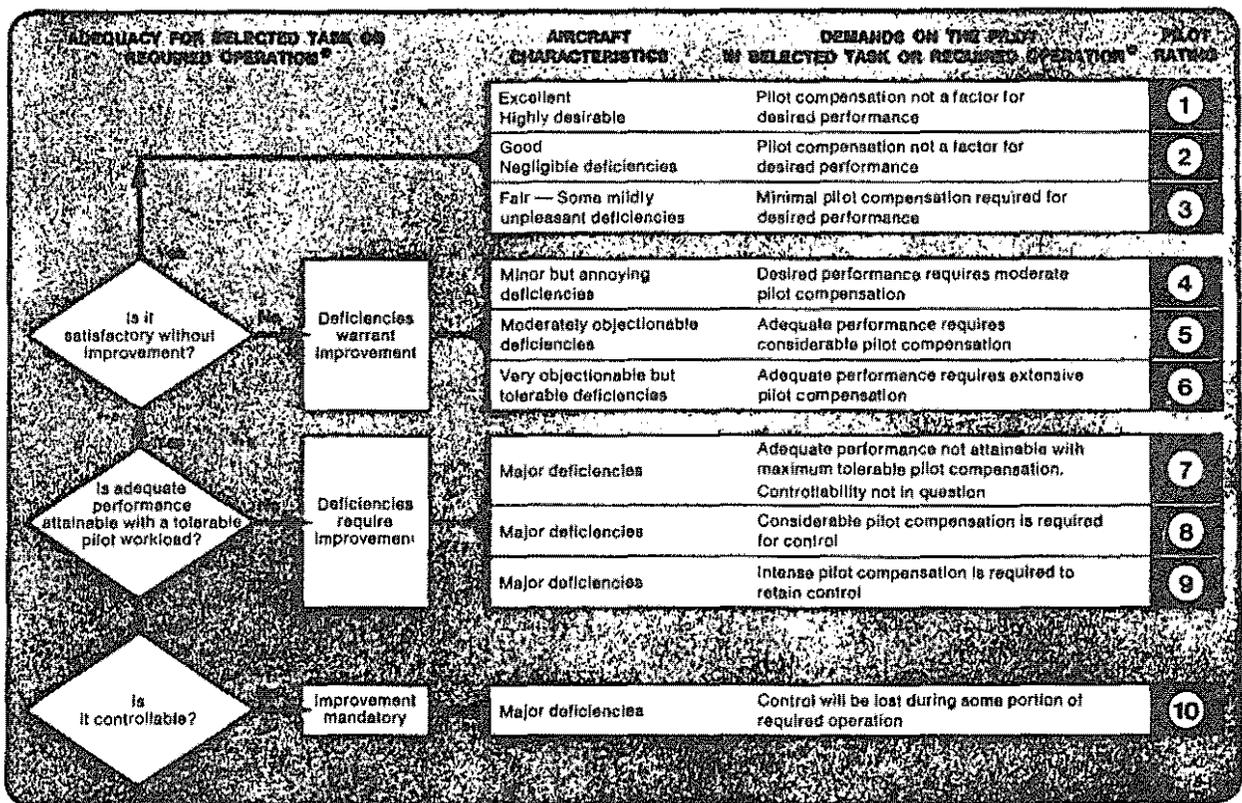
		C1	
		$\lambda_{\beta}^2 = 1.204$ $\gamma_{\beta} = 11.71$	
A2	B2	C2	D2
$\lambda_{\beta}^2 = 1.045$ $\gamma_{\beta} = 8.2$	$\lambda_{\beta}^2 = 1.136$ $\gamma_{\beta} = 8.2$	$\lambda_{\beta}^2 = 1.204$ $\gamma_{\beta} = 8.2$	$\lambda_{\beta}^2 = 1.272$ $\gamma_{\beta} = 8.2$
		C3	
		$\lambda_{\beta}^2 = 1.204$ $\gamma_{\beta} = 4.1$	

$\gamma$  ↑  
 →  $\lambda_{\beta}^2$

\* based on  $\Omega = 35$  rad/s

Table 2

**HANDLING QUALITIES RATING SCALE**



Cooper-Harper Ref. NASA TND-5153

\* Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

Table 3

SUMMARY OF PILOTS' RATINGS FOR THE LARGE TRIPLE BEND, C2 ROTOR

Pilot	Best 'raw'	Best attitude control system	Best rate command/ attitude hold system
A	4*	2	3
B	5	4	3
C	4½	3	-

\* given in the same sortie as his other ratings

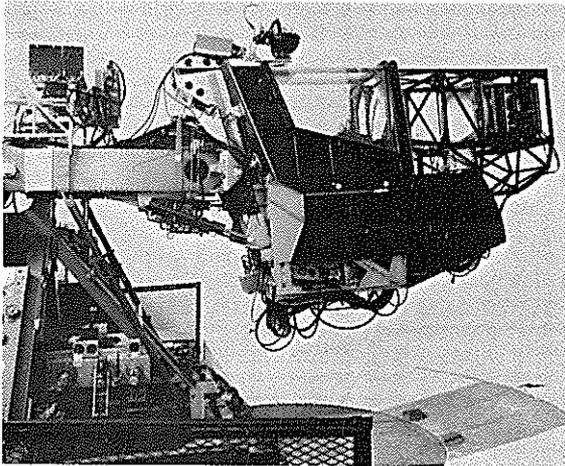


Fig 1 Cockpit and motion system

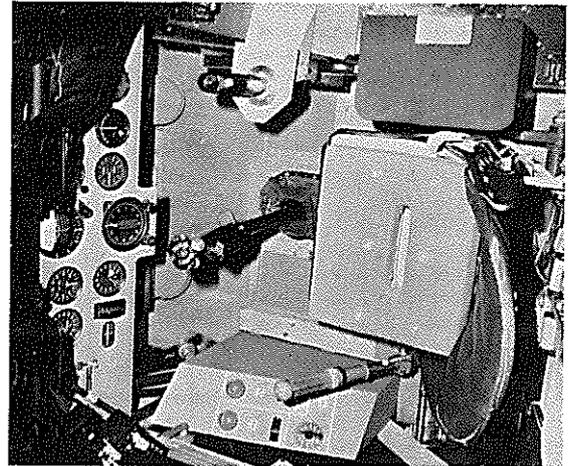


Fig 2 Simulator cockpit interior

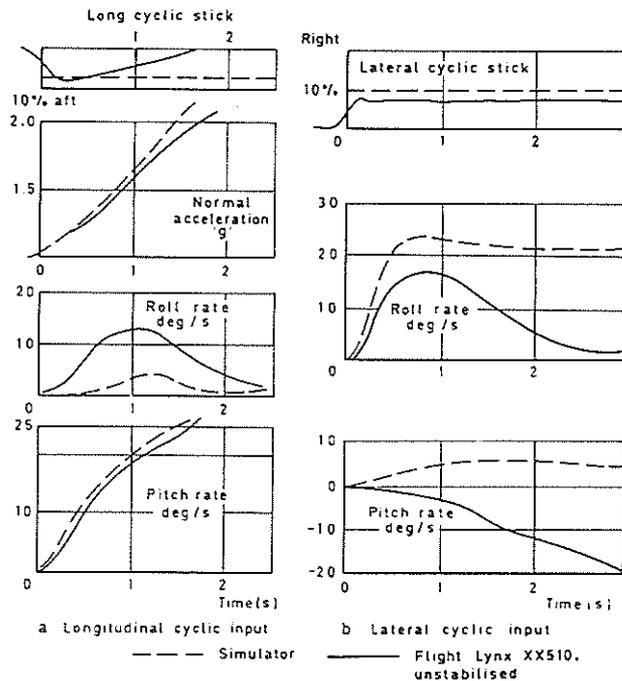


Fig 3 Flight and simulator comparisons — cyclic step inputs at 100 kn — Lynx

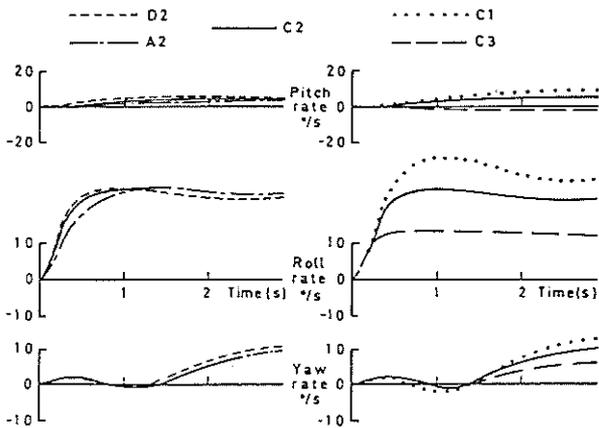


Fig 5 Response of agility configurations to one inch step in lateral cyclic ( $\theta_{1C} \sim 1.5^\circ$ ), 100 kn

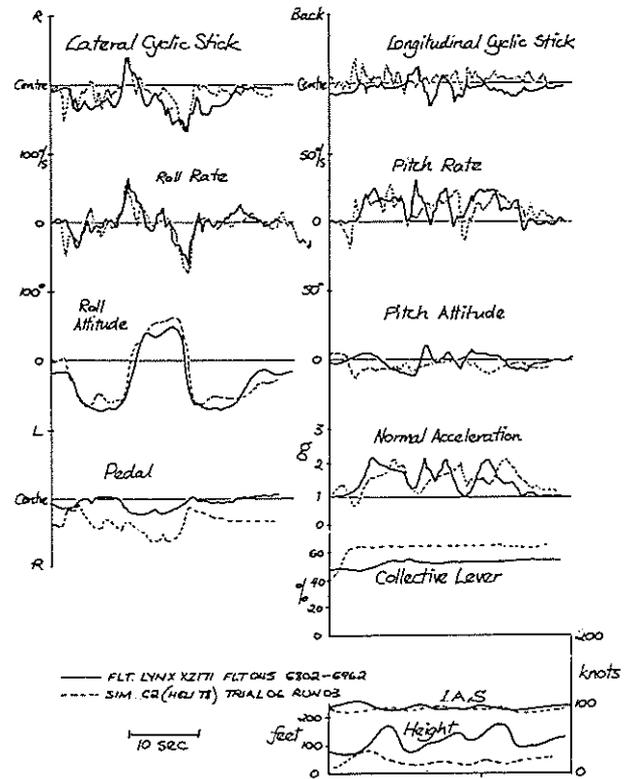


Fig 4 100 kn triple bend — flight and simulator comparison

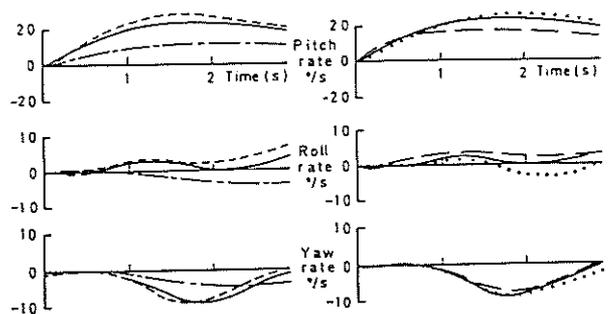


Fig 6 Response of agility configurations to one inch step in longitudinal cyclic ( $\theta_{1S} \sim 1.6^\circ$ ), 100 kn

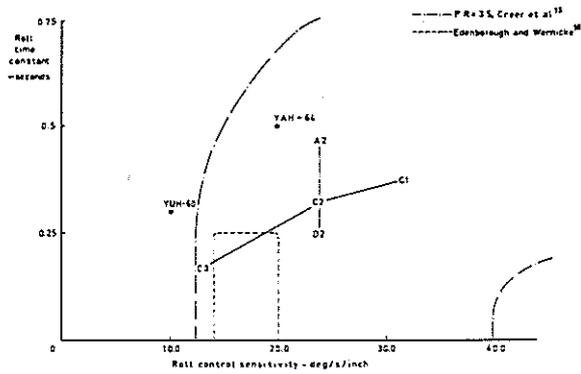


Fig 7 Short term roll response characteristics, 100 kn

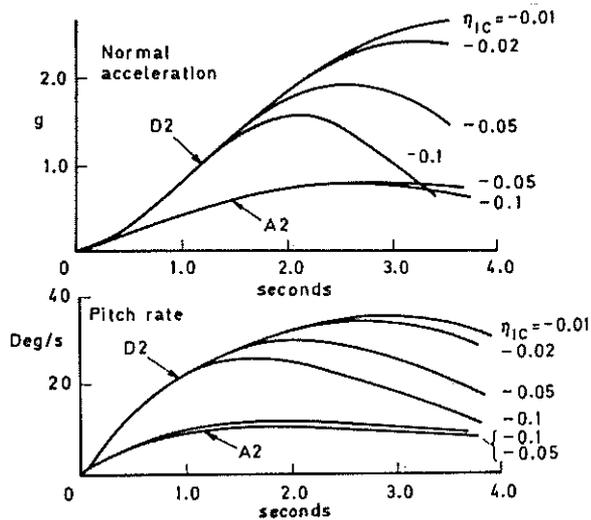


Fig 8 Response to different levels of longitudinal cyclic at 100 kn

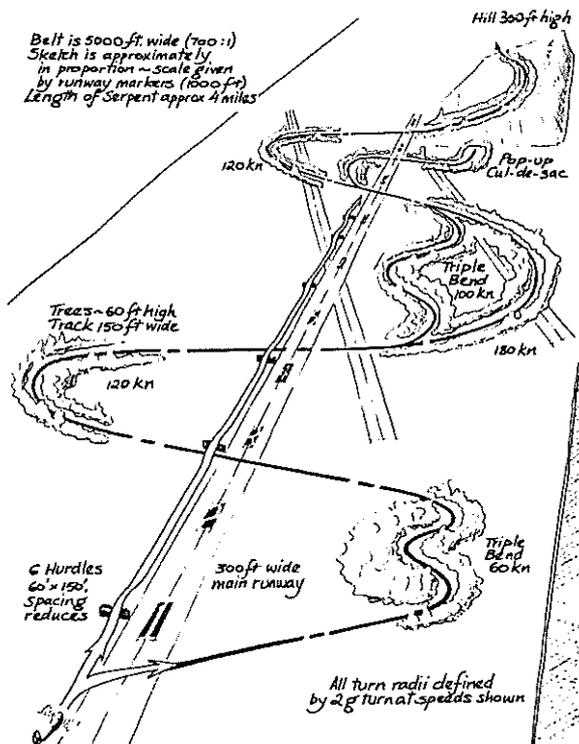


Fig 10 Sketch of agility course - the 'Serpent' and hurdles

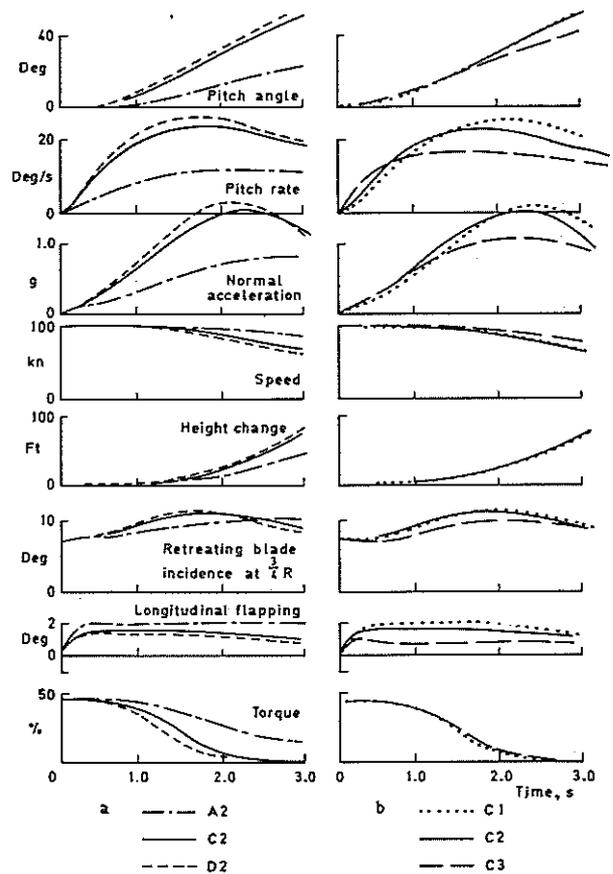
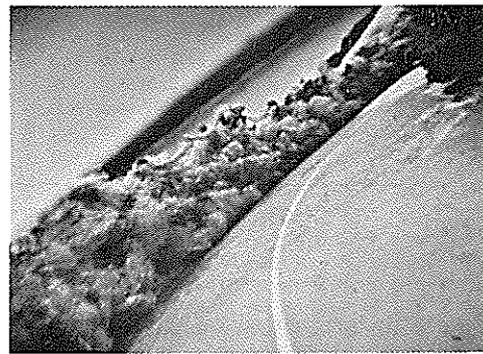
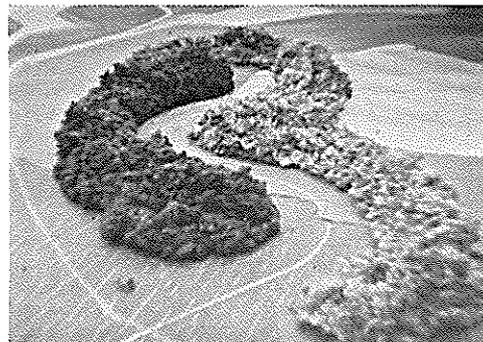


Fig 9 Response to one inch step input in longitudinal cyclic, 100 kn



b In the second triple bend



a First triple bend from above

Fig 11 Photographs of simulator terrain model

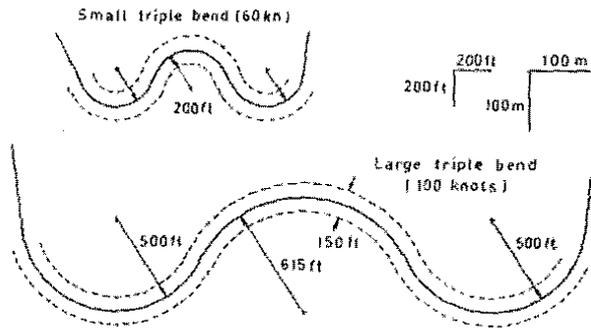


Fig 12 Geometry of triple bends

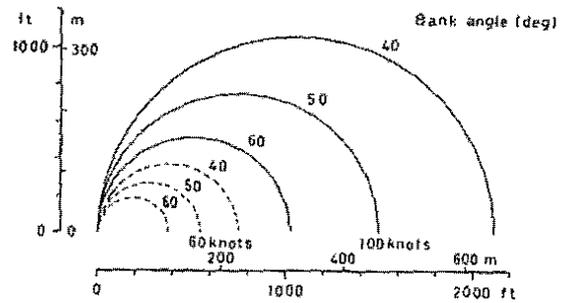


Fig 13 Flight paths in turns at 60 and 100 kn

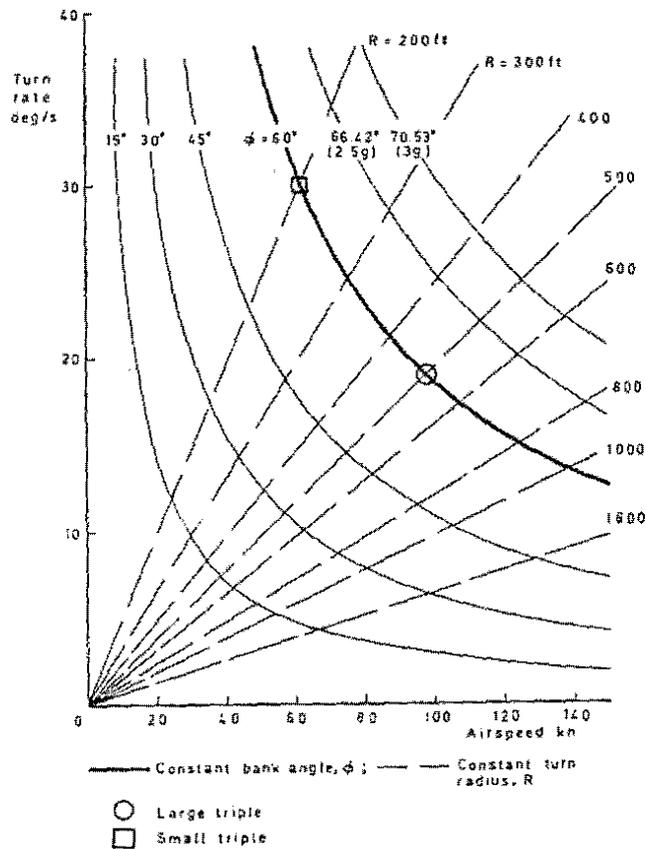


Fig 14 Kinematics of sustained turning flight

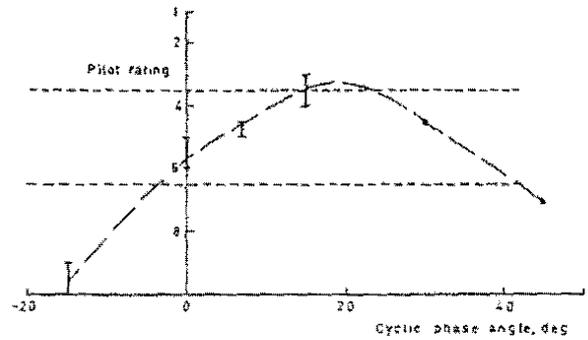


Fig 15 Effect of cyclic phase angle in pilot rating, configuration C2, 100 kn

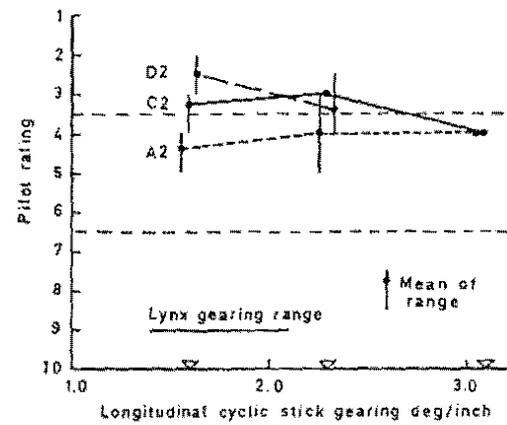
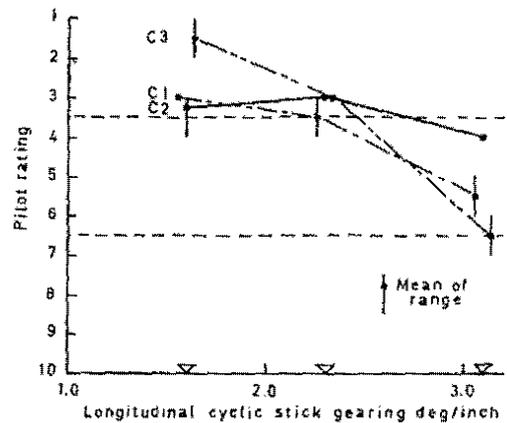


Fig 16 Effect of longitudinal cyclic stick gearing on pilot rating for various rotors, large triple bend, 100 kn



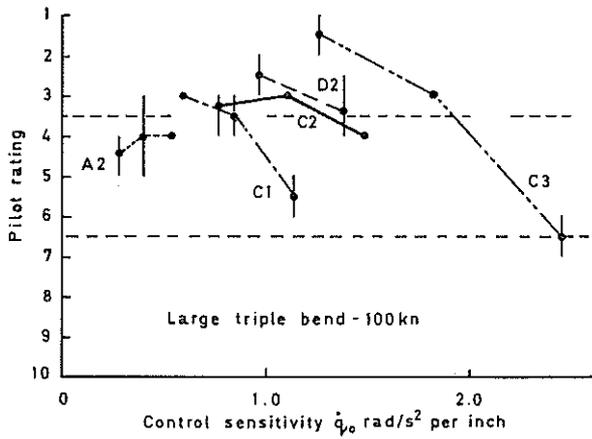


Fig 17 Pilot rating as a function of longitudinal control sensitivity

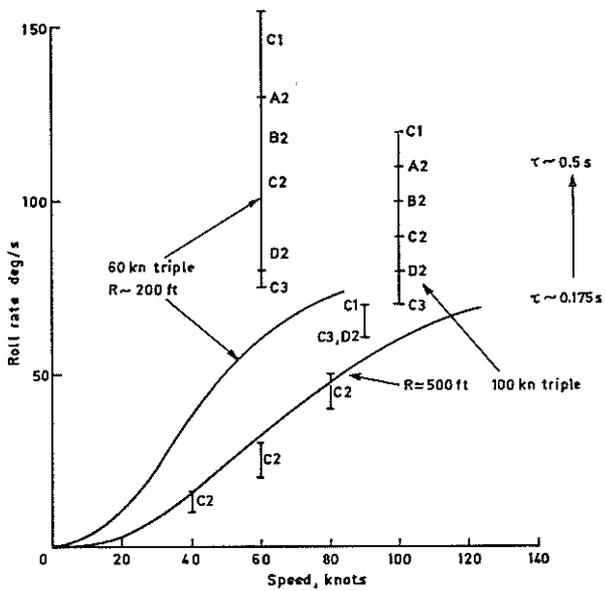


Fig 19 Rate requirements during roll reversals

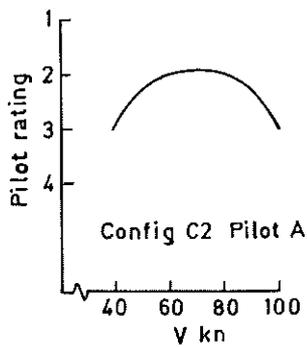


Fig 20 Effect of flight speed on pilot rating

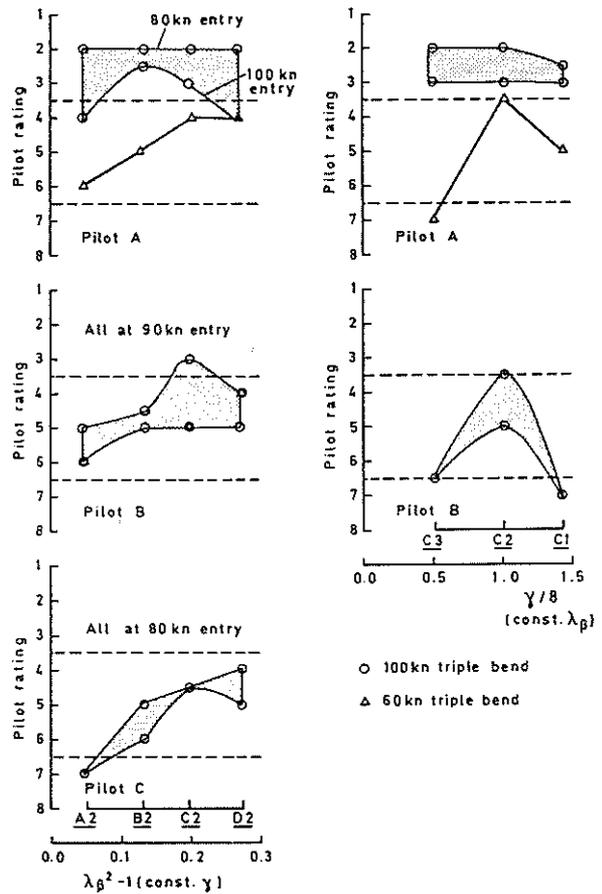


Fig 18 Effect of flapping frequency ratio and Lock number on pilot ratings for triple bends

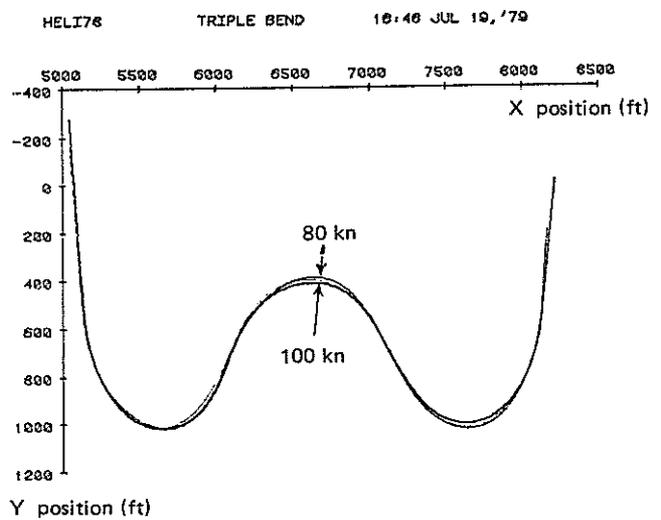


Fig 21 Negotiating the large triple bend at various speeds



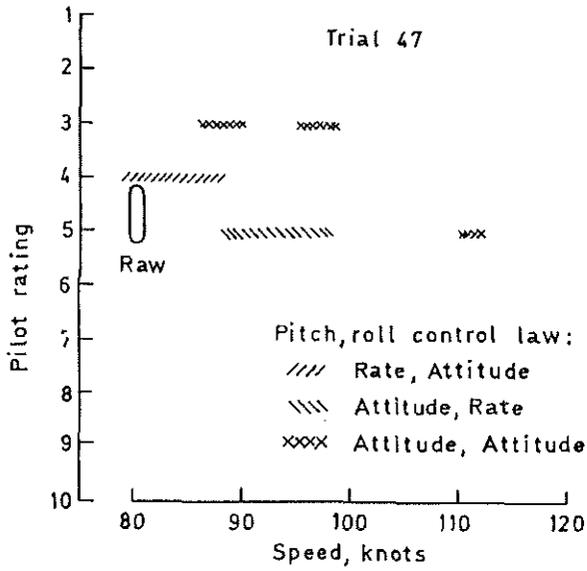


Fig 27 Effect of control system on mean speed through triple bend, C2 rotor, pilot C

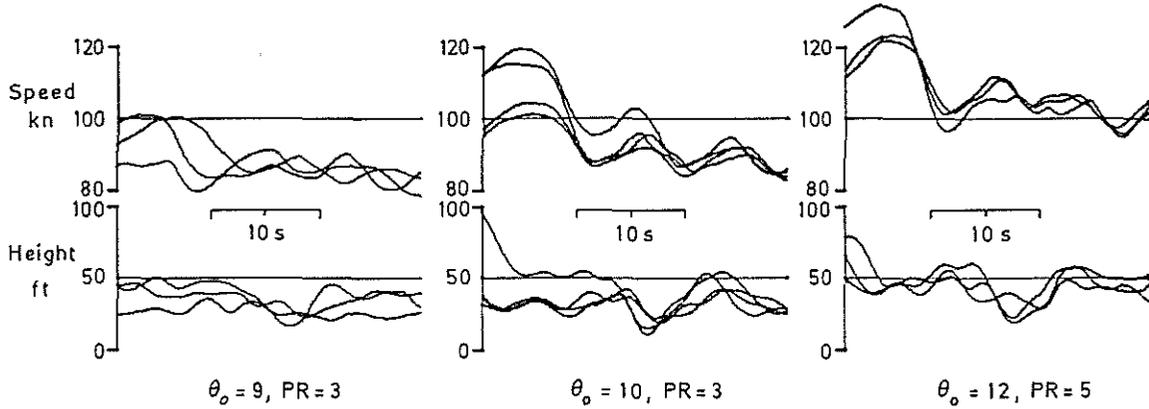
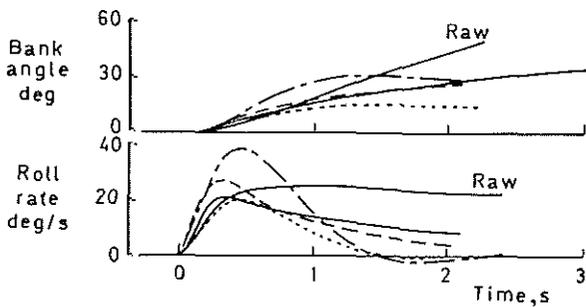


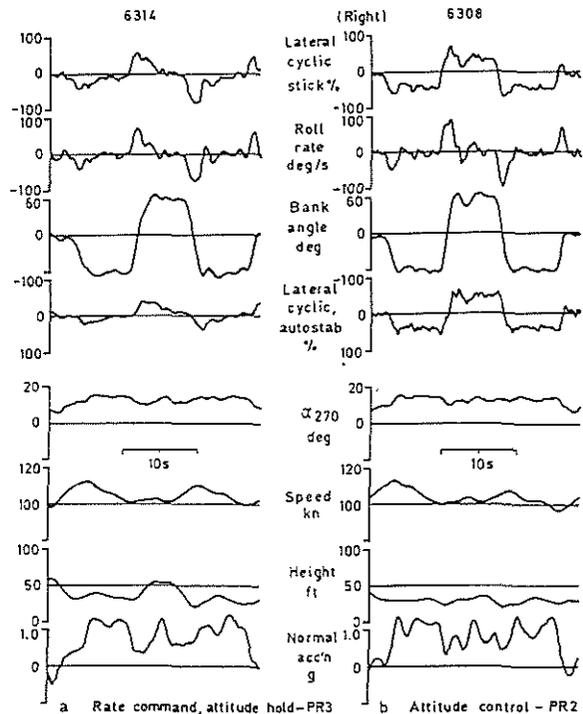
Fig 28 Speed and height variation in large triple bend at different mean speeds, pilot C, with attitude control in pitch and roll



Configuration	Rating	
	Pilot A	Pilot B
C 21 ———	—	4
C 22 - - - -	2-3	4
C 23 - · - ·	5-8 <sup>1</sup> / <sub>2</sub>	4
C 24 · · · · ·	4-7	6

Fig 29 Roll response of various attitude control systems, 100 kn, C2 rotor

Fig 30 Comparison of rate command versus attitude control in roll channel, large triple bend, pilot A



a Rate command, attitude hold - PR3 b Attitude control - PR2