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HELICOPTER AGILITY IN LOW SPEED MANOEUVRES

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ABSTRACT

A series of agility flight trials has been conducted at RAE Bedford as part of a general programme of studies into helicopter handling and control. The specific aims of the trials were to establish test techniques for measuring an aircraft's agility performance in low speed manoeuvres typical of the NOE mission enviornment, and to investigate those factors which inhibit the pilot from exploiting the full potential of the aircraft. In particular, the intention was to examine the influence of the aircraft's handling characteristics on task performance and pilot workload and to determine those features which promote good agility performance.

Special mission related tasks, or Mission Task Elements (MTEs) have been developed which represent typical discrete manoeuvres to re-position the aircraft from hover-to-hover in both sideways and forward flight. Test points involving different step sizes have been flown at different levels of task aggression, where the level of aggression was determined by the initial attitude at the acceleration stage of the manoeuvre. Pilots were required to maintain a given level of task performance throughout the tests and to fly each case at increased aggression, to the limits of the aircraft's performance, until the minimum task time had been established. Two RAE research aircraft were flown in the tests, a Puma HC Mk I and a Lynx AH Mk V. Both aircraft were fully instrumented and flight path coordinates were measured by a kinetheodolite tracking facility. Two subject pilots were involved and a questionnaire was used to record their opinion with regard to the task cues, workload, task performance and the vehicle dynamics.

This Paper discusses the background to the trials and presents results for two different tests, a roll axis 'sidestep' manoeuvre and a pitch axis 'quickhop' manoeuvre. The concept of helicopter agility is discussed and an Agility Factor (A_F), derived from the ratio of a theoretical 'ideal' task time and the actual task time, is proposed as a measure of the aircraft performance the pilot is able to exploit. The handling qualities criteria proposed in the Mil Spec 8501 revision are also discussed, in particular the roll and pitch control criteria for moderate amplitude manoeuvres. Results for the two different aircraft and pilots are compared, including the agility factors achieved and estimates of the bandwidths attained, together with the pilots' comments and their ratings for handling qualities and workload.

1 INTRODUCTION

Manoeuvring at low speed and close to hover, the helicopter demonstrates its unique versatility as a flight vehicle. In safety critical situations, skilled pilots can exercise precise flight path control in limited available airspace, eg Nap-Of-the-Earch (NOE) combat, shipboard operations and rescue missions in confined spaces. However, in these operational situations current helicopters are not particularly agile in this flight régime. The limited low speed manoeuvre envelope combined with typical thrust to weight ratios (T/W) less than about 1.05 have given pilots little freedom to fly aggressively. The requirement for future rotorcraft to be more agile in battlefield operations over wider ranges of atmospheric conditions (eg hotter, higher, gustier) has stimulated a number of studies into how manoeuvrable a helicopter can usefully be in low speed flight and the development of related quantitative criteria. Would, for example, a 10 or 20% hover thrust margin lead to significant improvements in task performance and, if so, could it be easily exploited or what kind of problems might inhibit pilots from using such a level of performance?

As an hors d'oeuvre to the main section of the Paper, Fig 1 presents a set of Cooper-Harper pilot ratings for a Puma flown in a sidestep task as a function of task time. The latter was decreased by the pilot using greater bank angles and flying more aggressively as he attempted to minimise the time for the hover-to-hover sidestep. As shown, the workload rises rapidly and handling ratings deteriorate through the three levels (satisfactory → adequate performance not achieved) over a critical time range. Bank angles used in this range increased to 30° ($T/W = 1.15$) for the lowest task times. However, at these task limits, the sluggish roll control and reduced visual cues led to considerable pilot compensation but, above all, the handling qualities associated with the poor engine response and rotorspeed governing forced the ratings into and beyond the Level 3 range in at least one case. Of course the Puma was never intended to be flown so aggressively and it comes as no surprise to find this light-support helicopter falling short in what is essentially a combat helicopter task. Nevertheless a clear result emerges from these tests, that exploitation of performance can be inhibited by handling deficiencies and the need to monitor flight envelope limits.

The constraints on agility in NOE operations have been of concern for some time. The results reported 20 years ago in Reference 1 first highlighted a range of fundamental helicopter characteristics that increase pilot workload. More recently, in Reference 2, the results of sidestep simulation experiments reveal the sharp degradation in pilot ratings as time loading or pressure effects become significant. This is certainly not a problem peculiar to old designs; additional results gathered in the RAE programme and also independently have demonstrated this. On the contrary, it is considered that new designs will be prone to the same limitations on agility unless steps are taken to configure future helicopters with tailored flying qualities and carefree manoeuvring. Agility will be affected by a host of factors summarised in Fig 2. The main concerns of the research described in this Paper are handling and performance but our flight results have confirmed previous findings that the complete pilot/vehicle system has to be carefully optimised to provide good agility.

The Paper examines the exploitation of agility in low speed Mission Task Elements (MTEs) and highlights features that can inhibit the pilot from using the full aircraft performance. Flight tests conducted with the RAE research Lynx and Puma will be described and results presented for side-step and quickhop discrete manoeuvres. Data are compared with the proposed US handling and agility requirements specification Mil Spec 8501.

The research results in this Paper form part of a larger programme of work aimed at deriving test techniques and design criteria to support the development of active control for future military helicopters.

2 AGILITY FOR LOW SPEED MISSION-TASK-ELEMENTS

At its simplest, agility relates to the level of excess thrust that can be generated and sustained, and re-directed safely with speed and precision; an agile helicopter can not only accelerate rapidly but can reach its maximum acceleration rapidly too. The level of excess thrust that can be generated varies considerably with flight condition. At higher speeds the rotor (aerodynamic) thrust limits can be approached through a combination of collective and by increasing the disc incidence, but in the low speed envelope, power limits normally mark the boundary to achievable thrust. Here, only transient thrust changes can be commanded by the pilot through his collective control but these can be very effective for accelerating over short distances. Initially, a 'bank, or pitch, and stop' manoeuvre is required and ideal sidestep and quickhop times can be derived (assuming instantaneous angular response and zero aerodynamic drag) from simple kinematics. The results are summarised in Fig 3, hence for a 100 ft (30 m) step and a T/W of 1.15 (initial bank of 30°), the ideal manoeuvre time would be 4.6 s. The maximum translational acceleration of 0.58 g is reached instantaneously for this simple case. Although this ideal time can never be achieved in practice, the time margin can be regarded as a shortfall in agility. The ratio of ideal time to achieved times can be used as a measure of this margin and is introduced here as the agility factor A_F (see Fig 3).

The agility factor is a measure of the usable agility of a given aircraft flying a given task. For the present purposes we wish to illustrate some important effects as the pilot uses more and more of the aircraft's inherent performance. We therefore define the ideal time on the basis of the maximum thrust to weight ratio being exploited. The agility factor can then be expected to vary as shown in Fig 4 with the theoretical limit rising to unity as the performance limit is reached. Handling deficiencies and entry and settling transients will account for reductions in measured agility factors and a flattening of the curve at high levels of task aggression. In a similar conceptual way, Fig 5 shows how pilot handling qualities and workload ratings (HQR/WLR) can be expected to vary with agility factor; over a critical range of agility factors time pressures on the pilot serve to expose vehicle deficiencies and ratings degrade rapidly. Ratings can deteriorate through the three levels so rapidly that, in this 'cliff edge' situation, the task can actually be abandoned by the pilot on safety grounds. High performance can therefore be wasted or unsafe to use unless measures are taken to ease the piloting task.

Influences on the time to maximum acceleration also need to be addressed. Actuator and engine response characteristics will govern the transient thrust magnitude response; aircraft angular motion characteristics will determine the re-direction response. Both are intimately linked with handling qualities but some way towards understanding the dynamic performance can also be achieved by looking at the manoeuvre kinematics. The three distinct phases of sidestep (acceleration, reversal, deceleration) can be seen on a phase plane portrait in the upper right of the 'task signature' in Fig 6. The diagrams show, not only the manoeuvre excursions, but also how rapidly the pilot has commanded the roll. Maximum rates used can be plotted against the bank maximum angle change as illustrated in the bottom right of Fig 6. The ratio of maximum roll rate to attitude change can be viewed as a measure of the aggression the pilot uses to accomplish the manoeuvre. Presenting data for a full range of mission task elements in this way provides a format for specifying performance aspects of roll control. This approach forms the basis of the roll and pitch requirements in the revision to Mil Spec 8501 (Refs 3, 4) and the criteria proposed by Heffley in Ref 5. The full picture is presented in Fig 7 showing how the manoeuvre demand limits vary with manoeuvre amplitude. For small amplitude precision tracking tasks the vehicle open-loop bandwidth defines the vehicle capability, while for maximum manoeuvres the control power (rate for full control) sets the limit. For moderate amplitude discrete manoeuvres, of which the quickhop and sidestep are typical, both bandwidth and control power can be expected to influence task performance and agility. With a simple first order equivalent dynamic system for roll and pitch dynamics the bandwidth can be directly related to the inverse of the roll and pitch time constants, or the equivalent system damping. This equivalencing provides some continuity with more traditional criteria based on damping and control sensitivity. The open-loop bandwidth is a more general parameter however, being the frequency at which the vehicle response is a defined margin from the 180° phase crossover, and embodies high order dynamic effects that spoil the validity of the first order equivalent model.

Both diagrams in Fig 7 represent different forms of the same design criteria. The procedure to establish the design envelope (vehicle capability) would begin with a specification of the required manoeuvre limit boundary, followed by a definition of the task margin, the extent of which will be driven by the increased agility required for emergency operations. The boundaries on Fig 7 define the inherent roll and pitch agility of an aircraft. High potential $P_{pk}/\Delta\Phi$ ratios should lead to an increase in agility factors. In practice, designs with high levels of such inherent agility, eg hingeless rotor helicopters, also suffer from high values of cross coupling which, unless suppressed, can, in turn, inhibit the pilot from exploiting the full performance.

Design criteria format similar to Fig 7 can be built up for both yaw and heave dynamics to complete the set over which the pilot has direct control. The excess thrust margin and manoeuvre criteria then form the essential elements defining a vehicle's inherent agility. The finer details of an aircraft's transient short-mid term response, its behaviour close to flight envelope limits and other issues raised in Fig 2 define the extent to which a pilot is prepared to exploit this agility.

3 FLIGHT TEST TECHNIQUES

For the purpose of the flight trials, the test technique illustrated in Fig 8 was adopted. The objective of the tests was to establish the time taken, the task performance and workload to re-position the aircraft from the hover to the hover over a range of different step sizes, in both sideways and forward flight, ie 'sidesteps' and 'quickhops'. A series of markers was used as a guide to the pilot and test points evaluated include sidesteps of 50 ft, 100 ft, 150 ft and 200 ft, and quickhops of 150 ft, 300 ft and 600 ft. The choice of distance was influenced by various factors, although first and foremost, those evaluated had to be representative of the NOE mission environment. For the sidesteps, there was a need to observe the aircrafts' sideways speed limit, hence the 200 ft maximum step size, whereas for the quickhops, the step sizes were selected to provide test points at transit speeds in the 0-45 kn range of the flight envelope.

3.1 Task definition

As discussed above, an important aspect of the tests was to examine the effect of pilot aggression on agility performance and in this respect it was considered that the time taken to execute the manoeuvre, coupled to a stringent requirement for task performance, would be a significant factor. Hence, in addition to the different step sizes, a range of different manoeuvre times was included in the task definition, where the time was to be related to the attitude used to initiate the manoeuvre. Starting from some relatively low attitude, say 5°, the requirement was for each step to be repeated, at increasing attitude, until the full aircraft performance had been exploited and the minimum manoeuvre time established. To maintain an 'even' task loading, pilots were encouraged to match the attitude used to arrest the motion to that used at the start of the manoeuvre. An additional consideration here was that the incremental approach would also be beneficial both to pilot confidence and his ability to exploit and assess the aircraft's handling qualities. The task performance requirement was to hold heading to within ±15°, height and track to ±5 ft and track over/undershoot to ±10 ft. In order to provide good height cues, the sidestep tests were carried out at 25 ft above ground level; for the quickhop tests this was revised to 50 ft to give added tail clearance during the stopping phase.

3.2 Aircraft configuration

Two different RAE research aircraft were flown in the trials, namely a Lynx AH Mk V (Fig 9a) and a Puma HC Mk I (Fig 9b). The Puma has a conventional articulated rotor with a hinge offset of 4° and an AUW of 6400 kg, whereas the Lynx has a hingeless rotor with an effective hinge offset of about 13%R and an AUW of around 4750 kg. The Puma has an augmentation system to provide stabilisation in pitch, roll and yaw and some initial testing was carried out to determine the configuration, either augmented or unaugmented, which gave the best task performance, in terms of the task time. While the results did not reveal any significant differences, pilots considered that the stabilisation reduced the workload, hence the Puma was flown augmented for the remainder of the trials. Similarly, the Lynx has an Automatic Flight Control System (AFCS) to provide stabilisation in pitch, roll and yaw, and stabilisation in pitch and yaw is further augmented by feedback loops from normal and lateral accelerometers to main and tail rotor collective respectively. The Lynx was evaluated both with and without the stabilisation engaged, although only the results for the unaugmented aircraft were available for inclusion in this Paper. In view of the likely effect of aircraft weight on manoeuvre power limitations, the intention was to test at least two different weight conditions. For the Puma, the standard sortie AUW was at 5500 kg and some checkpoints were also established at maximum AUW and a lower weight condition of 5000 kg. For the Lynx, the only results available to date were recorded at a sortie weight of 3850 kg.

3.3 Pilot experience

The two subject pilots used in the tests were both test pilots with considerable operational experience. Pilot familiarity had a marked effect on the task times achieved. To ensure consistent results sufficient time for practice was allowed. Actual testing commenced when the subject pilot deemed that his 'learning curve' had levelled out, based on his ratings and stopwatch timings. It is worth noting here that the use of 'on-line' data processing to derive task performance criteria, such as developed at the DFVLR and described in Ref 6, would help to remove some of the uncertainty in this area.

3.4 Data recording

For tests of the nature described in this Paper, it is of fundamental importance to be able to accurately monitor the pilots task performance and to record his comment and opinion with regard to the performance achieved. Throughout the tests, aircraft control inputs and responses were monitored and recorded using a Plessey MODAS digital data acquisition system and the flight path coordinates were recorded via a kinetheodolite tracking facility. Pilots used the universally accepted Cooper/Harper rating scale (Ref 7, Table 1) for handling qualities and, similarly, the Bedford scale for rating pilot workload (Ref 8, Table 2). In conjunction with the two rating scales, pilots were given a questionnaire to complete whereby they could record detailed comment regarding the control strategy, task cues and aircraft handling characteristics.

3.5 Operating conditions

Wind strength was an important consideration, for on most current aircraft types low speed, out-of-wind operations can be penalised by wind conditions even as low as 10 kn. This obviously has a major impact on all NOE type flight operations, so in order to allow the full performance of the aircraft to be tested, the intention was to minimise the intrusive effect of wind; the test conditions were therefore constrained to be carried out in less than 10 kn of wind. Furthermore, to remove the effect of wind assistance, tests were made with aircraft facing into wind for the sidesteps and across wind for the quickhops.

4 ANALYSIS OF RESULTS

4.1 General

In the event, the simple task elements described proved to be very exacting, not only in terms of piloting effort but also in terms of the demands on the aircraft's handling capabilities. However it has to be remembered that both aircraft were being taken well beyond the range of normal operational usage. As pilot aggression increased and the task times reduced, at some stage, the whole gamut of factors described in Fig 2 acted as constraints to hamper the pilot in his attempt to achieve the desired task performance. Above all, the flight tests demonstrated quite clearly the way in which pilot workload and task performance were strongly influenced by the aircraft's handling qualities and how the agility performance was inhibited. To help illustrate this point, Fig 10a&b show control time histories recorded for the sidestep and quickhop test points. Although the two tasks are primarily roll and pitch control exercises, in practice they are multi-axis tasks requiring large, carefully coordinated inputs from all controls.

Referring to Fig 10a, the sidestep was initiated by the application of lateral cyclic combined with coordinated application of collective to accelerate and maintain constant height, and also with the application of pedals to control the yaw. For both aircraft the handling limitations were most apparent in the deceleration phase and were associated with large and rapid variations in power demand, to control the height and re-establish the hover. For the Puma, the problems were caused by the poor engine response characteristics which created the potential for large rotorspeed droop and subsequent loss of height and yaw control. In contrast the engine response for the Lynx was better suited to the task and although transient rotorspeed droop was observed, the amount was relatively small and, notwithstanding some increase in pilot workload, serious control problems were not encountered in this axis. However, yaw control presented a problem for the pilot, especially in a right sidestep at the roll reversal stage when the power was reduced and right pedal was required to control the heading. Full pedal was frequently needed here and although control of the aircraft was never in question, the encroachment of the control margin established a definite performance limit.

The control strategy required for the quickhop was very similar for both aircraft. Referring to Fig 10b, the time histories show typical examples of the control inputs. Again, the manoeuvre was initiated with a cyclic input with accompanying collective and pedal inputs. At this point, because of the large change in pitch attitude, height control became a problem, as evidenced by the cyclic and collective activity following the initial input. Once again, the deceleration was the most difficult part of the manoeuvre to accomplish for much the same reasons given for the sidestep, eg transient rotorspeed droop for the Puma and yaw control for the Lynx.

A more complete account of the contributory factors which limited the performance is given in the following section, together with the numerical results recorded. For convenience, the two subject pilots are referred to hereafter as P1 and P2 respectively. Unfortunately pilot involvement in the trials was limited by availability of the aircraft which meant that the Puma was flown by only P1. The main results for the quickhops and sidesteps are summarised in Figs 11-15. The variables shown represent the task time, agility factor, peak roll/pitch rate and the ratio of peak rate to the roll/pitch attitude change for each test point. In order to demonstrate the effect of task aggression, the data are shown plotted against the initial peak attitude applied to start the manoeuvre. For clarification, the task time was measured from the time of the initial cyclic control input to the point at which the control activity had subsided to the level observed at the initial hover condition. Task performance was checked for compliance with required standards.

4.2 Agility and piloting aspects

Agility

The results illustrated in Fig 11 show how the agility factor and roll kinematics vary with task aggression and sidestep size for pilot P1 flying the Lynx. Fig 12 compares the Puma and Lynx agility flying the 200 ft sidestep and Fig 13 presents the HQRs for both P1 and P2, again as a function of initial bank angles. Fig 14 and 15 illustrate corresponding results for the quickhop manoeuvre over the range 150-600 ft. A number of important observations can be made from these results.

i As expected, the agility factors increase with increase in initial acceleration (bank and pitch angle), but characteristically level off at the higher bank angles as the pilot experiences difficulties in reducing the task time further while maintaining task performance. The decrease in agility factor with reducing sidestep and quickhop size reflects the greater proportion of task time spent during entry transients and the final settling phase.

ii Higher values of agility factors were achieved by pilots flying the Lynx than the Puma reflecting the different design roles of the aircraft and reduced task times of the order of 1-2 s depending on manoeuvre size. The price paid for using this increased agility was increased workload and degraded pilot ratings (see 'Piloting aspects').

iii Roll rates used in the Lynx rose to over 60°/s for the most aggressive cases (see Fig 11, 100 ft sidestep) where the $P/\Delta\Phi$ ratios also increased with initial bank angles. This result was somewhat of an exception as with most runs the $P/\Delta\Phi$ ratio decreased with initial bank. The 100 ft sidestep results do indicate the kind of agility that could be usable by pilots more confident in their aircraft's handling qualities.

iv Maximum pitch rates greater than 40°/s were measured on the Lynx during the initial and reversal phases of the quickhop manoeuvre.

v Roll and pitch rates used in the Lynx were typically 50% higher than used in the Puma.

vi The format for roll and pitch response characteristics proposed in the revision to Mil Spec 8501 has already been discussed in section 2 of this Paper and summarised in Fig 7. A selection of test points are superimposed on the Ref 4 requirements in Fig 16. The HQR boundaries represent a requirement minimum for roll and pitch 'bandwidth' for moderate amplitude tasks. The upper limit of 2 rad/s corresponds to the requirement on open loop response bandwidth for small amplitude tracking tasks (Ref 4). Included on the pitch diagram is the control power line that requires at least 30°/s pitch rate for large amplitude menoeuvres. The HQRs derived from the RAE tests correspond to pilot ratings for the roll (pitch) axis alone and a multi-axis rating, ie roll axis rating/multi-axis rating. When secondary axis compensation become very demanding it is doubtful whether such a distinction is really valid; the Level 2/3 boundary is probably an upper limit on the validity of the sub-axes ratings. The roll and pitch axes ratings on Fig 16 highlight an important feature that the Mil Spec boundaries disguise, ie the sensitivity of task performance and HQRs to task aggression or time loading effects in the parlance of Ref 2. On both roll and pitch diagrams, Level 1 ratings are located in the Level 2 region and Level 2 ratings in the Level 1 region. Two issues are raised in response to these observations. Firstly, the location of the Level 1/2 boundaries on Fig 16 does not accord with the RAE measurements. Secondly, the sensitivity to task aggression is so strong that it must be taken into account in compliance testing of new configurations to format standards like Fig 16.

Piloting aspects

To introduce this section, the following excerpts, gleaned from the wealth of pilot comment recorded, are given in order to bring into focus the key handling problems encountered in the tests:

Puma

"The fuselage response to lateral cyclic inputs was noticeably lagged behind the rotor and was manifested to the pilot as an almost pendulous sensation."

"In all conditions tested, judgement of the point at which to start the deceleration was a critical factor. If the point was too late, large angles of bank were required and the handling deficiencies became apparent. The manoeuvre became uncoordinated, making it difficult to achieve the task performance."

"Large transient rotorspeed droops were observed as power was applied when the aircraft rolled wings level, particularly following a left sidestep. Rotorspeed recovered rapidly giving rise to rotor overspeed and the accompanying torque reactions required large and frequent pedal inputs to maintain heading. Control margins were encroached and the yaw pedal dampers prevented sufficient application of pedals to prevent large heading perturbations."

"Following a right sidestep, a large aft cyclic input was required in order to prevent the aircraft pitching nose down. Again control margins were reached as indicated by aft cyclic movement being restricted by the pilots legs and the seat."

Lynx

"The roll response characteristics were excellent for the task and improved task performance and pilot confidence when compared with the Puma. The size of lateral stick inputs was surprisingly large but reflected pilot confidence in the aircraft. Engine and rotorspeed governing was good but did affect performance during more aggressive runs. However, the yaw control was not as good, and problems were exacerbated by the strong collective cross-coupling which made precise and aggressive yaw control difficult, these problems were more apparent when translating to the left. Further yaw problems were a negative stability gradient when moving left and poor control margins when moving to the right."

"The effects of the roll to pitch cross-coupling were predictable and controllable but they increased pilot workload particularly in the deceleration phase when they caused occasional over-controlling."

"The top window frame descended into the FOV (field of view) during the acceleration and obscured the end marker. During the deceleration the FOV over the nose totally obscured all ground references. Height control was poor on many of the tests because the pilot had to use visual cues only and poor FOV only compounded the problem."

The associated handling qualities ratings for the sidestep results are given in Fig 13. In all cases, the same general trend can be seen: as task aggression increases viz Φ_{start} , the ratings deteriorate, in some cases attaining the Level 3 régime. For the Lynx, in right sidesteps, the ratings for P1 and P2 are in broad agreement, although there are significant differences for the left sidesteps. In almost all cases, P1 returned poorer ratings for the left sidestep because of the problems noted above. In comparison, for low values of Φ_{start} (approximately 5-15°), P2 rated the left sidestep as the worse case because of the same problems mentioned above, whereas for larger values of Φ_{start} (approximately 15-30°), he awarded poorer ratings for the right sidestep because of the difficulty in maintaining yaw control in the deceleration. Pilot comment reveals a further point here: P1 tended to pursue heading control more aggressively than P2, and was working to a tighter error margin than the one given in the task definition (±15°). Hence, overall he tended to be more critical of the yaw control problems in left sidesteps for the effect on task performance, especially in the translational phase of the manoeuvre. In contrast, while P2 noted the adverse yaw control handling effects, he tolerated a wider margin of error, and 'flew through' the problems encountered.

Interestingly, sidestep ratings for the Puma were generally ½-1 rating point better than those given for the unaugmented Lynx, across the range of test points. This may be attributed to the difference in task times, see Fig 12; Fig 1 shows the strong relationship between task time and handling qualities rating. Thus, since the Lynx returned times of some 2 s faster than for the Puma, the ratings reflect the greater 'time loading' effect on the aircraft performance and pilot workload. However, preliminary results for the augmented Lynx show similar ratings as those given for the Puma, although increased task times infer that some price is paid in terms of the agility performance. Although ratings for the Puma were largely influenced by the poor engine and rotorspeed governing, weak control sensitivity in lateral and longitudinal cyclic were contributory factors.

For both aircraft, ratings for pilot workload were generally within one rating of the handling qualities ratings in each case. To a degree, this is a reflection of the pilot compensation required for the aircraft's handling deficiencies, although other factors regarding, for example, task cues and aircraft limitations obviously exert an influence. In the main, outside visual cues were used for all aspects of the task performance, ie track, height and for holding attitude and heading. Where there was a need to look into the cockpit, say for example to monitor torque limits, then workload increased and task performance was inhibited. The main problem in terms of the task performance was the over/undershoot criteria. As described above, the point at which the deceleration commenced was critical in determining the success of the control strategy. Heading hold was the next most critical element of the task performance, followed by height and track. Height control was generally good, especially for the Lynx, although a price was paid for aggressive height tracking because of handling problems caused by collective to yaw, roll and pitch cross-coupling.

Performance limits for the Lynx tended to be linked to the size of the sidestep. For the two shorter distances, 50 ft and 100 ft, as Φ_{start} increased, the speed increased and the performance was limited by the difficulty experienced in avoiding overshooting the end marker, although at 100 ft transient over-torques were also a problem. High levels of workload (ratings of 6-7), were also quoted as a limiting factor. For the two longer distances, the performance was limited by a combination of factors including high levels of workload (ratings of up to 7-8), transient over-torques, yaw and cyclic control margins and the perceived encroachment of the aircraft's sideways velocity limit. The over-torque problems were generally experienced during the deceleration, where roll attitudes in excess of 30° were recorded, in particular for test points at the higher values of Φ_{start} .

Many of the handling problems experienced in the sidestep tests were also common to the quickhop tests. Again the problems were more apparent during the deceleration, although increased pilot workload and handling difficulties were noted at the start of the quickhop, largely because of the difficulties in controlling height. Regarding the Puma, large variations in power demand caused the problems associated with the engine and rotorspeed governing. Poor yaw control was still a problem with the Lynx, although not as intrusive as in the sidestep tests.

Pilot ratings for handling qualities are shown in Fig 15, and as for the sidesteps, the most notable feature is the deterioration of the ratings across the range of test points. Looking at the Lynx results, there is close agreement in the ratings for the two pilots, perhaps a reflection on the reduced level of interference from the yaw control. For comparable values of Θ_{start}, ratings for both aircraft were similar for 150 ft test points, although for the longer distances the Puma was consistently awarded ratings of at least 2 scale points poorer. It is worth noting here that the 300 ft and 600 ft test points were flown following a sortie where severe handling difficulties had been experienced in the sidesteps, due to the Puma's engine and rotorspeed governing problems, and it may be that in consequence, the pilot ratings were influenced by the effect. In contrast, ratings for the 150 ft case are much better, ie HQR 3-4 as opposed to HQR 6-7, because the forward speeds achieved were relatively slow and the deceleration phase correspondingly less harsh.

Workload ratings for both aircraft were within 1 point of the handling qualities ratings. As a general point it is worth noting that for the Lynx, the workload ratings were at least 1 scale point better for the quickhops when compared to sidestep results, for values of Θ_{start} of up to 30°, mainly because of the reduced yaw control problems. Overall, levels of workload were significantly affected by the demands of the height task performance and restrictions on the pilots field of view. In all cases the height keeping task performance deteriorated with increased pitch attitude and for attitudes above 20°, a task performance limit of ±8 ft would be more realistic. The task difficulty was increased by the fact that the pilot lost sight of the end markers for nose down attitudes greater than 20-25° and nose up attitudes greater than 5-10°! Other factors contributing to workload were the high fore/aft cyclic stick forces experienced during the translational stage of the manoeuvre and of course the need to monitor the instruments.

In terms of the aircraft performance achieved, for the Lynx the pilot was able to make use of attitudes of up to 35°, for all three test distances, before the onset of over-torque problems. For the Puma, the performance was limited by the pitch attitude used in the deceleration phase; the pilot was reluctant to exceed 20° nose up pitch attitude, thus effectively reducing the braking force available, because of engine/rorotspeed governing problems.

The sensitivity of handling and workload ratings to the level of task aggression contrasts sharply with the relative insensitivity of the agility factor at the higher values of performance used. These two effects tell the whole story but it is interesting to view the situation from the third perspective. Fig 17 illustrates the variation of pilot HQRs with agility factor for both tasks and both aircraft; this form of viewing the data was conceptualised in Fig 5. The higher agility factors achieved with the Lynx at the expense of a degradation in pilot rating are clearly illustrated, particularly for the quickhop. Both manoeuvre sizes are typical of a repositioning in NOE flight. Desirable levels of agility factor are difficult to extrapolate from the results of this Paper; values of 0.7 should certainly be achievable for the moderate duration manoeuvres and perhaps even as high as 0.8. Firm recommendations cannot be made until results from ground and in-flight experiments with 'fully Level 1' configurations are available. A desirable objective for future combat rotorcraft designs is that maximum agility should be achievable with Level 1 pilot ratings. Without the potential improvements offered by high authority active control augmentation and carefree manoeuvring this does not appear possible. Optimisation of this technology for application to helicopters is considered to be essential to realising the exploitation of full aircraft performance at low workload. Future research should be directed towards the realisation of this objective.

5 CONCLUSIONS

A series of flight trials has been conducted to explore the factors influencing helicopter agility in low speed manoeuvres. This Paper has presented results for two stylised NOE manoeuvres, the sidestep and quickhop flown by two subject pilots in two test aircraft - the RAE research Puma and Lynx. For the tests the aircraft were operated at relatively high levels of hover thrust margin (⩾20%) to allow corresponding high values of initial translational acceleration (~0.6 g). A primary objective of the tests was to determine the constraints on the use of full aircraft performance; pilots were required to increase initial attitude (acceleration) incrementally until the task was completed successfully in minimum time. The analysis of flight recordings and pilot comments and ratings presented allow a number of important conclusions to be drawn.

1 Pilot ratings for handling qualities and workload reveal the profound effect of task aggression; with few exceptions the ratings deteriorate from marginal Level 1, through Level 2 to Level 3 as the initial attitudes increase from 10-30°. Although primarily roll and pitch tasks respectively, the sidestep and quickhop are multi-axis in reality, requiring the pilot to apply large compensatory inputs on all controls. These had to be carefully coordinated, otherwise the resulting flight path excursions could seriously distract the pilot and impede task performance. In most cases the deterioration to Level 3 arose through problems in other axes - engine and rotorspeed response impeded thrust and hence height control on the Puma and tail rotor limits affected yaw control on the Lynx.

2 Pilots strongly preferred and used the higher pitch and roll agility on the Lynx conferred by the hingeless rotor. Pilots demanded roll rates up to 60°/s and pitch rates up to 40°/s in this aircraft (50% higher than with the Puma) when flying most aggressively to achieve minimum times. Manoeuvre times were therefore better with the Lynx by about 1-2 s, across the step and hop sizes.

3 The agility factor introduced in this Paper has provided a useful measure of the extent to which the full aircraft performance is used by the pilot. Rarely were values greater than about 0.7 achieved except for the longer hops where the time penalties associated with achieving maximum acceleration and deceleration were less significant. Without comparative data on highly augmented types it is difficult to make firm recommendations for the levels to be achieved by future types. However, it would seem highly desirable that pilots operating current fleet replacements should be able to achieve values of 0.7 with Level 1 ratings rather than the Level 2/3 ratings awarded in the current tests.

4 Pilot ratings overlaid on the proposed Mil Spec 8501 criteria for pitch and roll handling qualities in moderate amplitude manoeuvres, indicate that the Level 1/2 boundaries do not reflect pilot opinion in tests conducted at full aircraft performance and task aggression (see also conclusion 5).

5 The sensitivity of pilot rating to task aggression reported in this Paper has highlighted the need for this aspect to be taken into account during compliance testing of a new type. Moreover the conclusion of Ref 2 that tasks defined without terminal position and time loading constraints are inappropriate for the discrimination of handling qualities in the NOE, is endorsed.

From the range of pilot comments collected during the tests a number of important issues relating to the design of future combat helicopters have been raised. These are listed below following the above numbering sequence.

6 A wide and clear field of view is required to maintain accurate flight path control close to the ground. The side-by-side seating arrangement on both Puma and Lynx restricted the FOV and inhibited agility particularly in left sidesteps and deceleration phases of both manoeuvres.

7 The requirement to monitor flight envelope limits through cockpit instruments significantly increased workload and hence inhibited agility. Pilots would prefer carefree manoeuvring at the edges of the flight envelope with any essential information displayed head-up, and helmet mounted. A carefree power demand control is highly desirable and would significantly reduce workload.

8 Cockpit design, including seating, controllers and displays needs to be even more pilot centred and radical improvements are likely to be required to enable the future combat helicopter pilot to function most effectively.

In the twenty years since the results of Reference 1 were published several new types have successfully entered combat service; higher performance and the ability to operate in a wider range of conditions have led the design requirements on the whole. Yet today, demanding NOE mission task elements can still require intolerably high piloting workload for operations at the limits of aircraft performance. The application of active control to combat helicopters offers the opportunity to enable the full exploitation of agility at low pilot workload.

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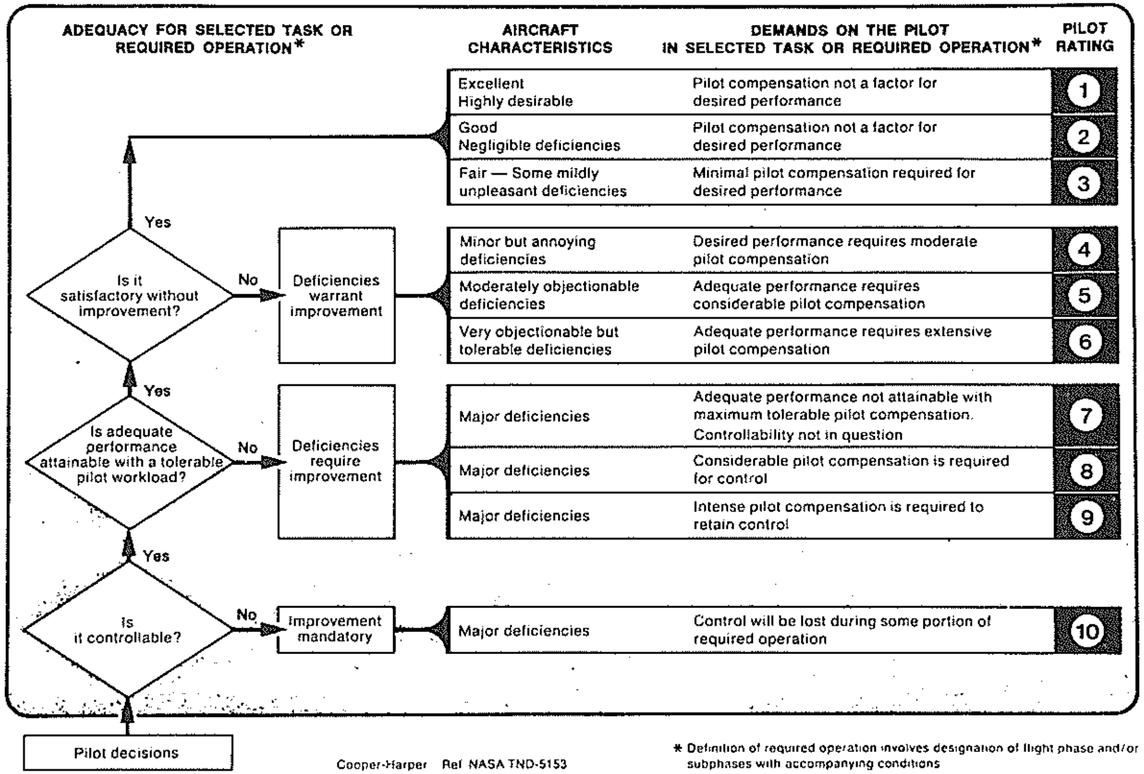
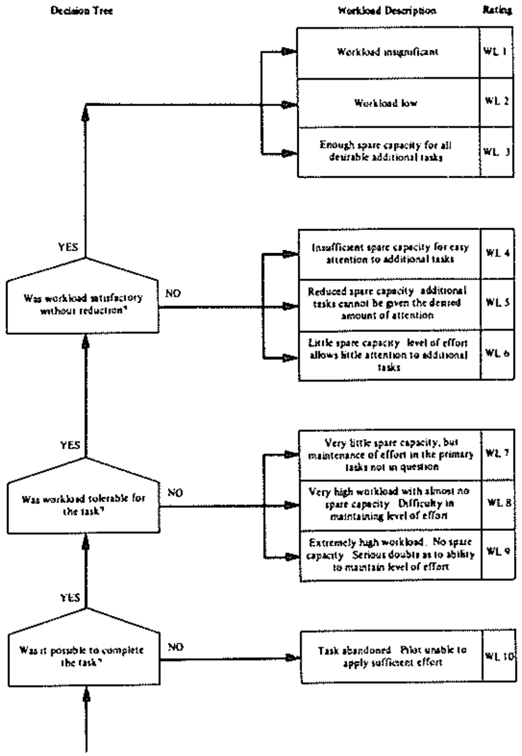


AIRCRAFT CHARACTERISTICS	DEMANDS ON THE PILOT IN SELECTED TASK OR REQUIRED OPERATION*	PILOT RATING
Excellent Highly desirable	Pilot compensation not a factor for desired performance	1
Good Negligible deficiencies	Pilot compensation not a factor for desired performance	2
Fair — Some mildly unpleasant deficiencies	Minimal pilot compensation required for desired performance	3
Minor but annoying deficiencies	Desired performance requires moderate pilot compensation	4
Moderately objectionable deficiencies	Adequate performance requires considerable pilot compensation	5
Very objectionable but tolerable deficiencies	Adequate performance requires extensive pilot compensation	6
Major deficiencies	Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question	7
Major deficiencies	Considerable pilot compensation is required for control	8
Major deficiencies	Intense pilot compensation is required to retain control	9
Major deficiencies	Control will be lost during some portion of required operation	10

Cooper-Harper Ref NASA TND-5153

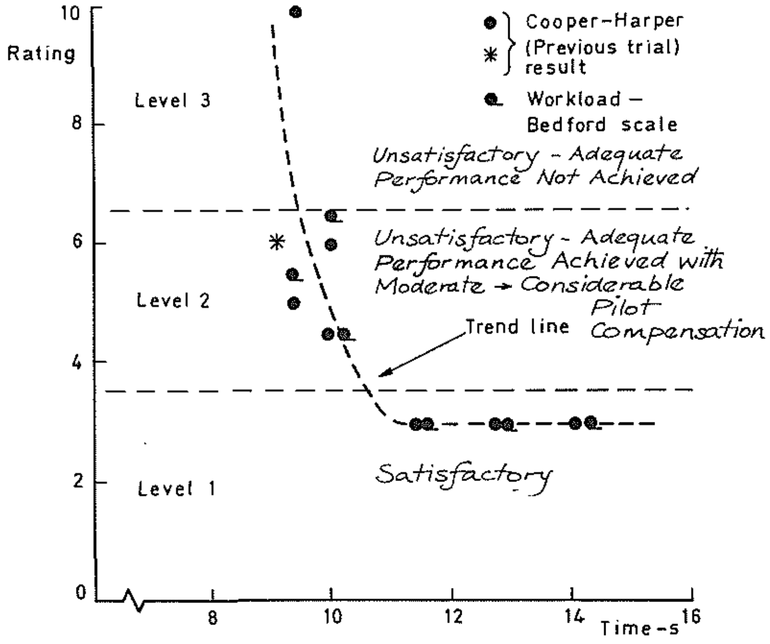
* Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions

Table 1 COOPER-HARPER HANDLING QUALITIES RATING SCALE



Workload Description	Rating
Workload insignificant	WL 1
Workload low	WL 2
Enough spare capacity for all desirable additional tasks	WL 3
Insufficient spare capacity for easy attention to additional tasks	WL 4
Reduced spare capacity additional tasks cannot be given the desired amount of attention	WL 5
Little spare capacity level of effort allows little attention to additional tasks	WL 6
Very little spare capacity, but maintenance of effort in the primary tasks not in question	WL 7
Very high workload with almost no spare capacity Difficulty in maintaining level of effort	WL 8
Extremely high workload. No spare capacity Serious doubts as to ability to maintain level of effort	WL 9
Task abandoned Pilot unable to apply sufficient effort	WL 10

Table 2 PILOT WORKLOAD RATING SCALE



200ft sidesteps ~ Puma results

Fig 1 Variations of pilot handling quality rating with task time

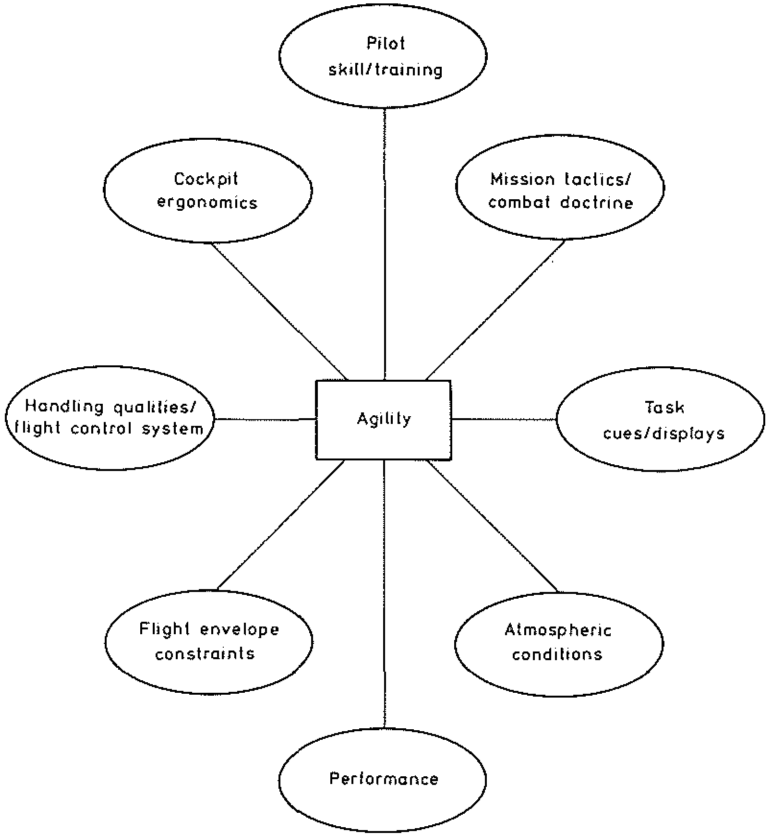


Fig 2 Factors influencing helicopter agility

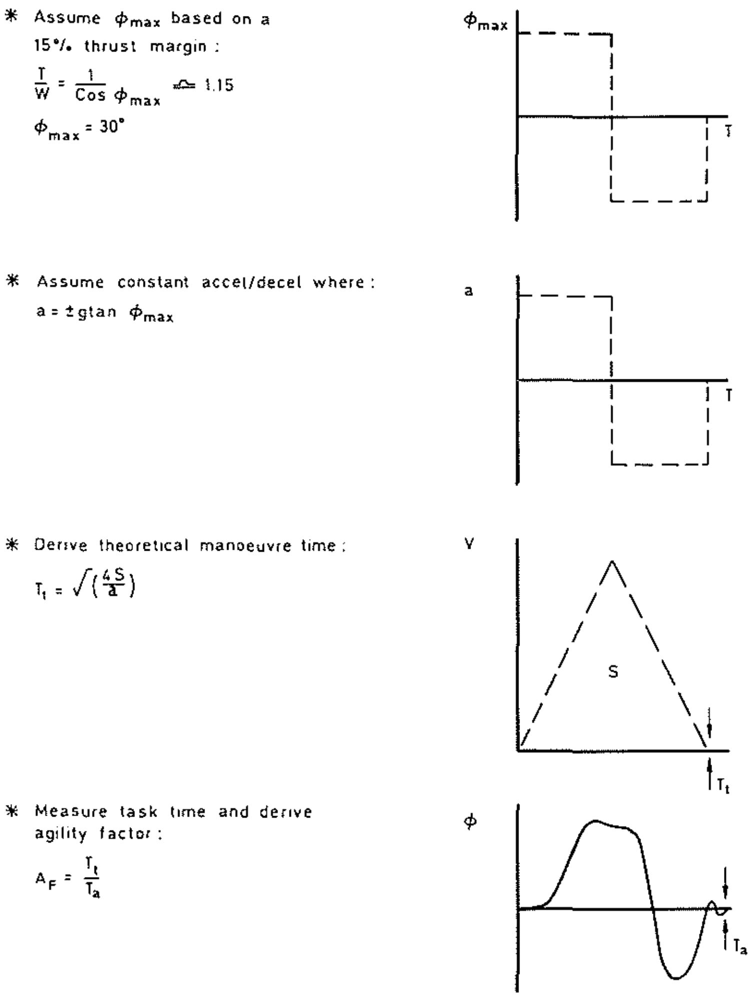


Fig 3 Agility factor derivation

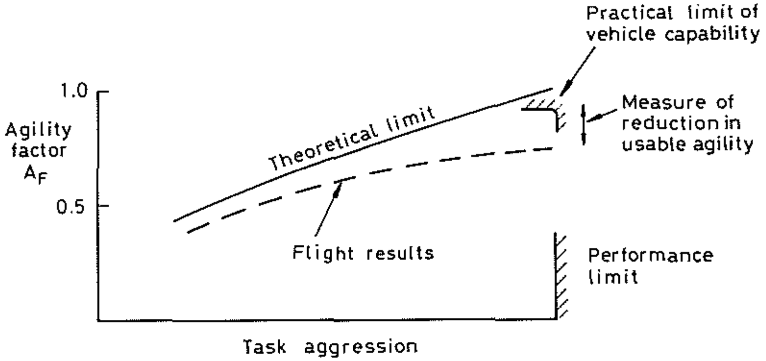


Fig 4 Variation of agility factor with level of task aggression

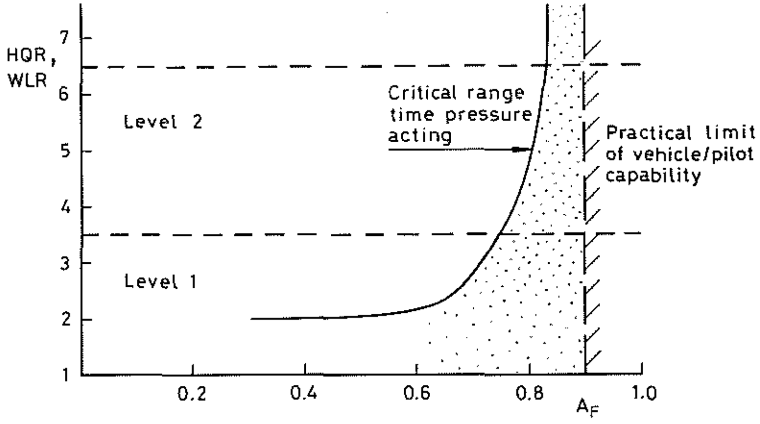


Fig 5 HQR degradation with agility factor

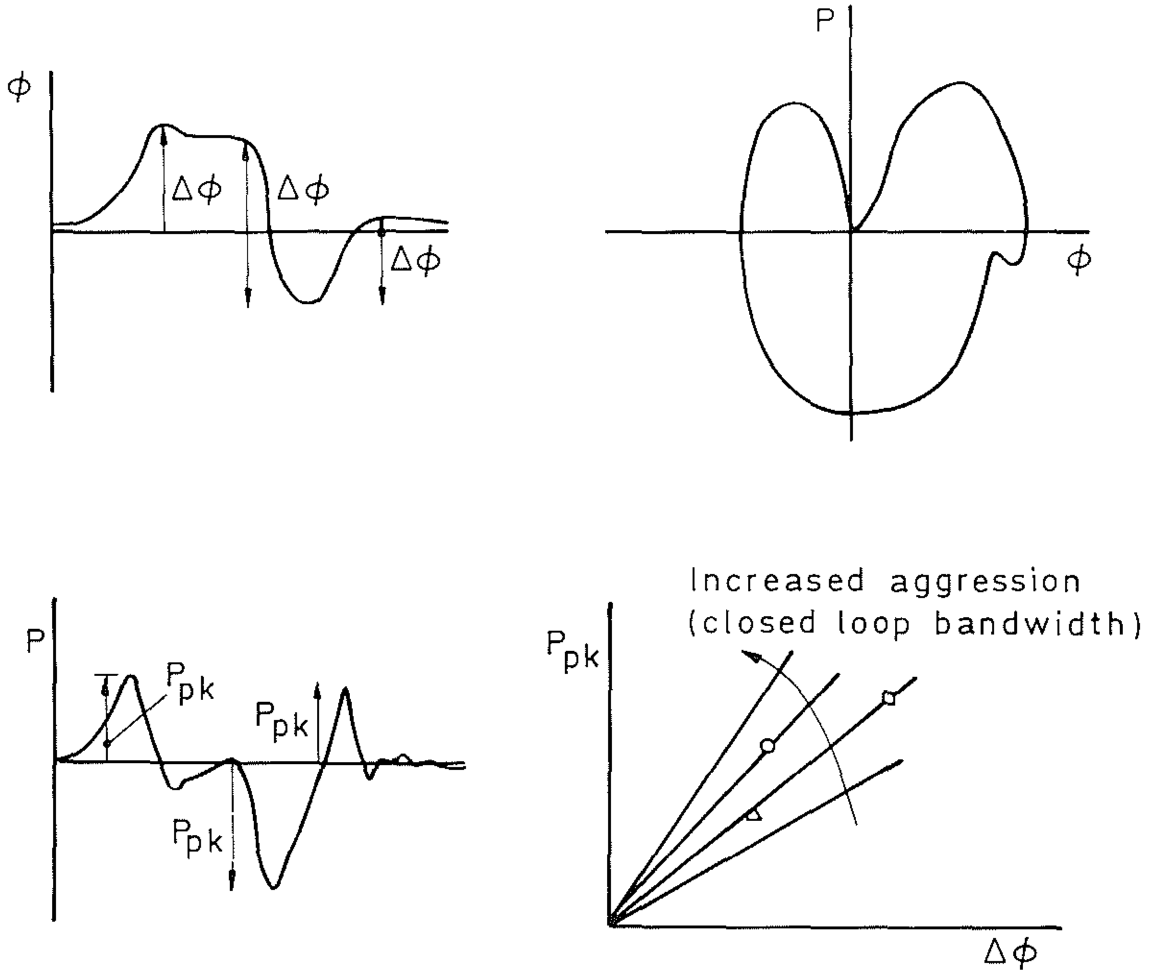


Fig 6 Task signature for sidestep roll-control

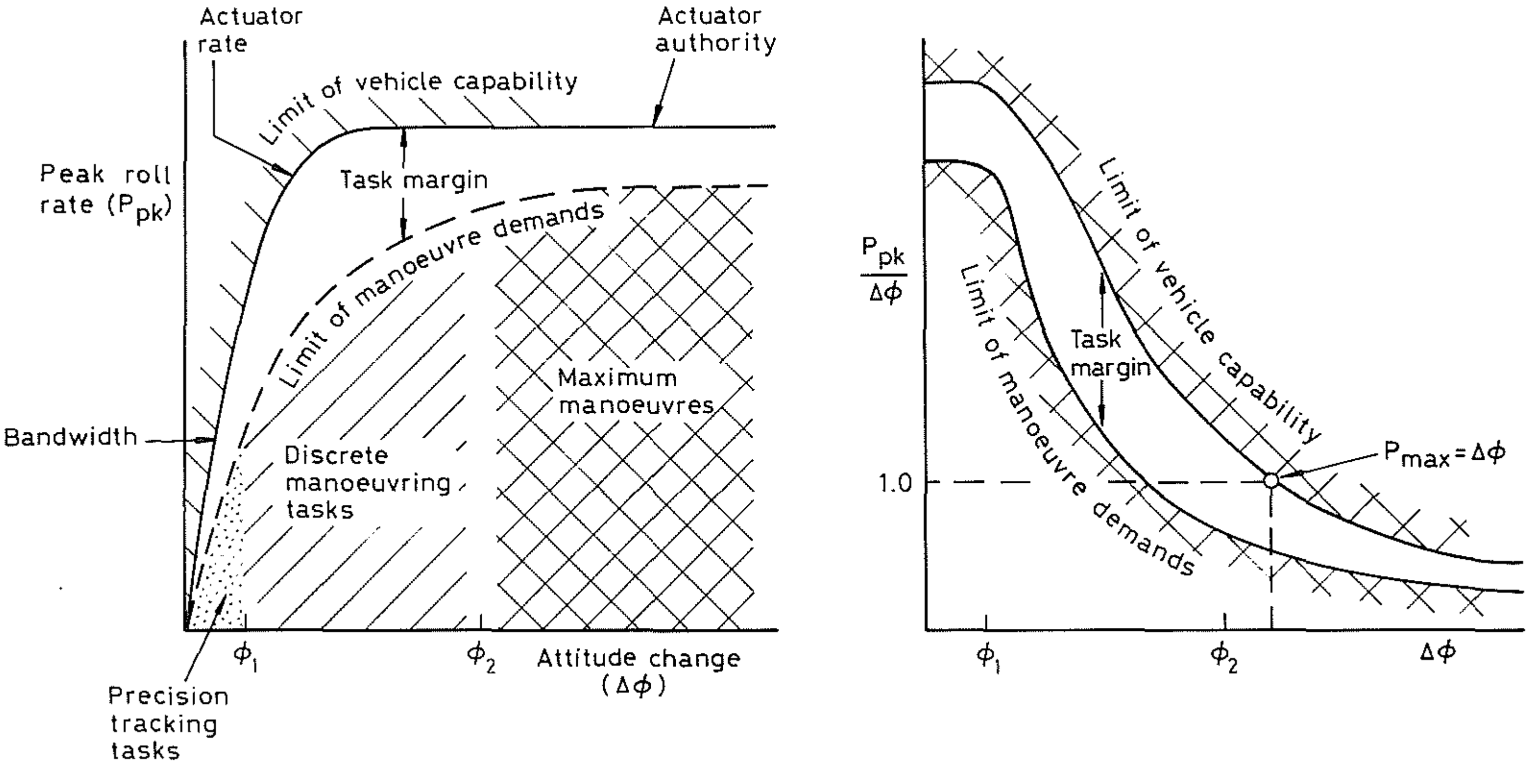
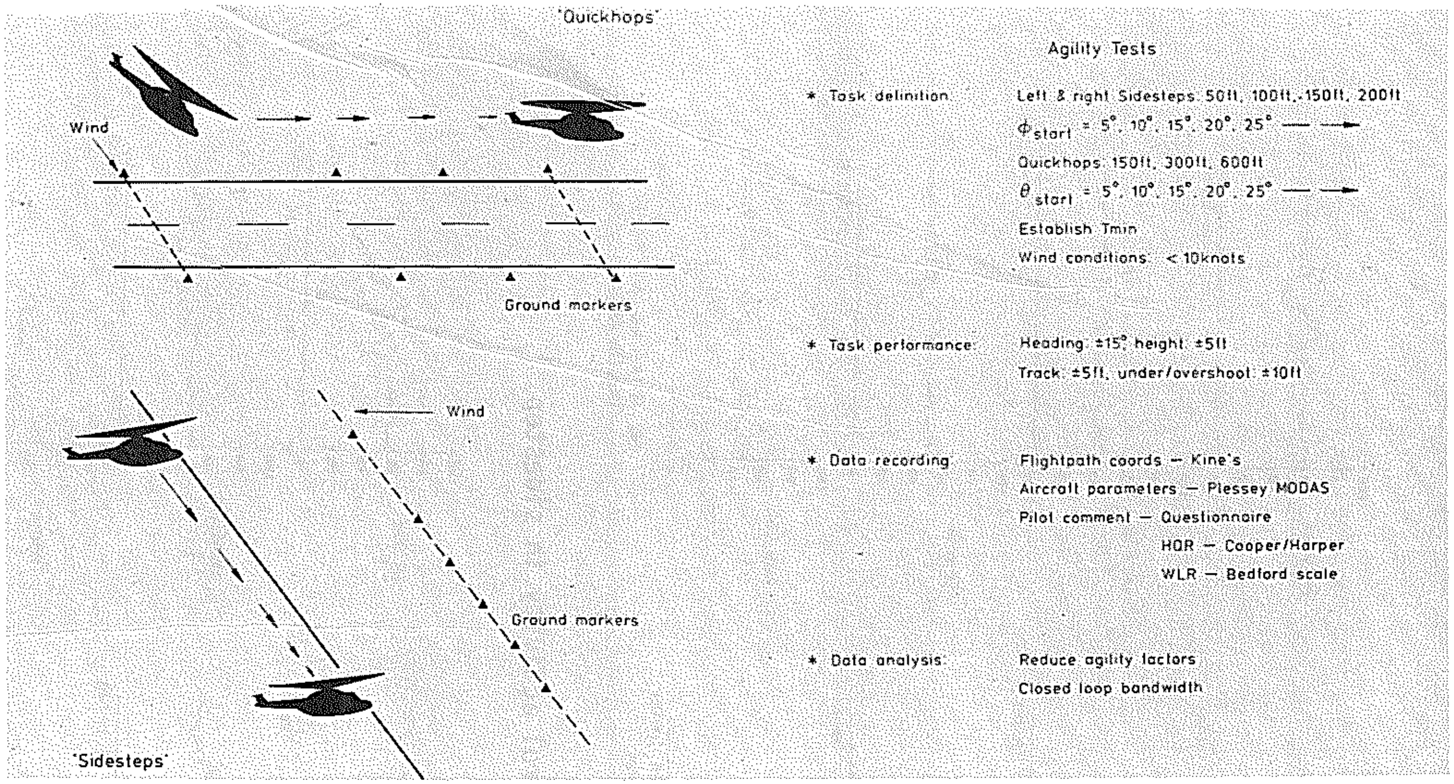


Fig 7 Manoeuvre demands and task margin for attitude dynamics



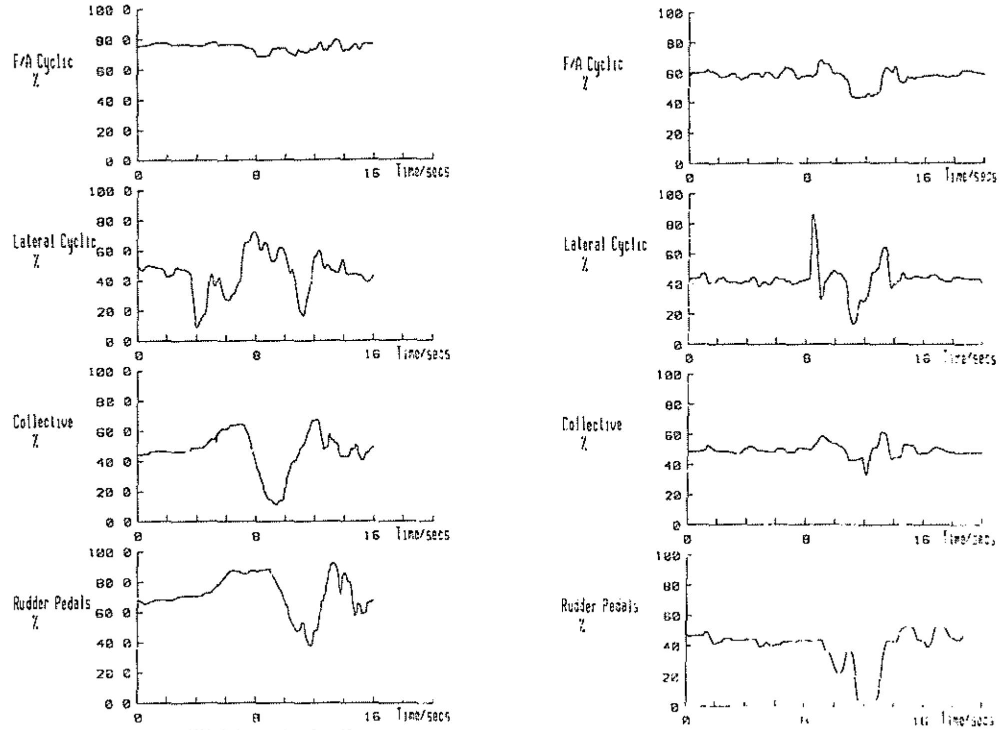
Agility Tests

* Task definition:	Left & right Sidesteps: 50ft, 100ft, 150ft, 200ft ϕ_{start} = 5°, 10°, 15°, 20°, 25° —— ⟶ Quickhops: 150ft, 300ft, 600ft θ_{start} = 5°, 10°, 15°, 20°, 25° —— ⟶ Establish Tmin Wind conditions: < 10knots
* Task performance:	Heading: ±15°, height: ±5ft Track: ±5ft, under/overshoot: ±10ft
* Data recording:	Flightpath coords — Kine's Aircraft parameters — Plessey MODAS Pilot comment — Questionnaire HQR — Cooper/Harper WLR — Bedford scale
* Data analysis:	Reduce agility factors Closed loop bandwidth

Fig 8 Low speed manoeuvre test techniques

Fig 9a RAE (Bedford) research Lynx

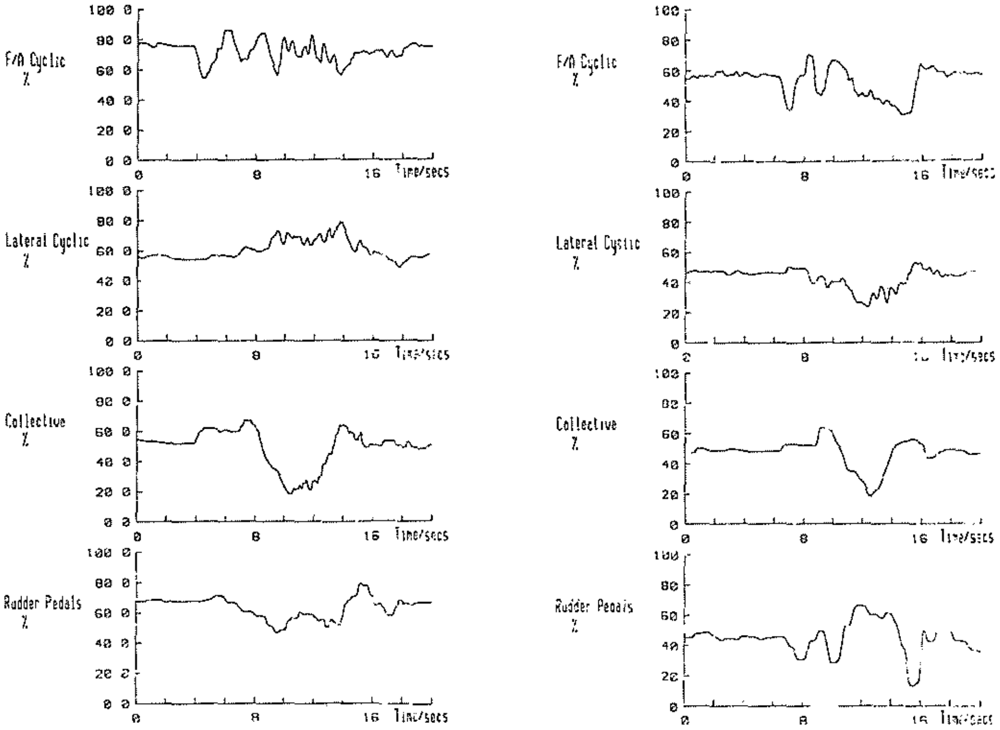
Fig 9b RAE (Bedford) research Puma



PUMA - 200ft Left Sidesteps/Phi=26Degrees
Flight 690, Run 40

LYNX - 100ft Right Sidesteps/Phi 20 Degrees
Flight 130a, Run 53

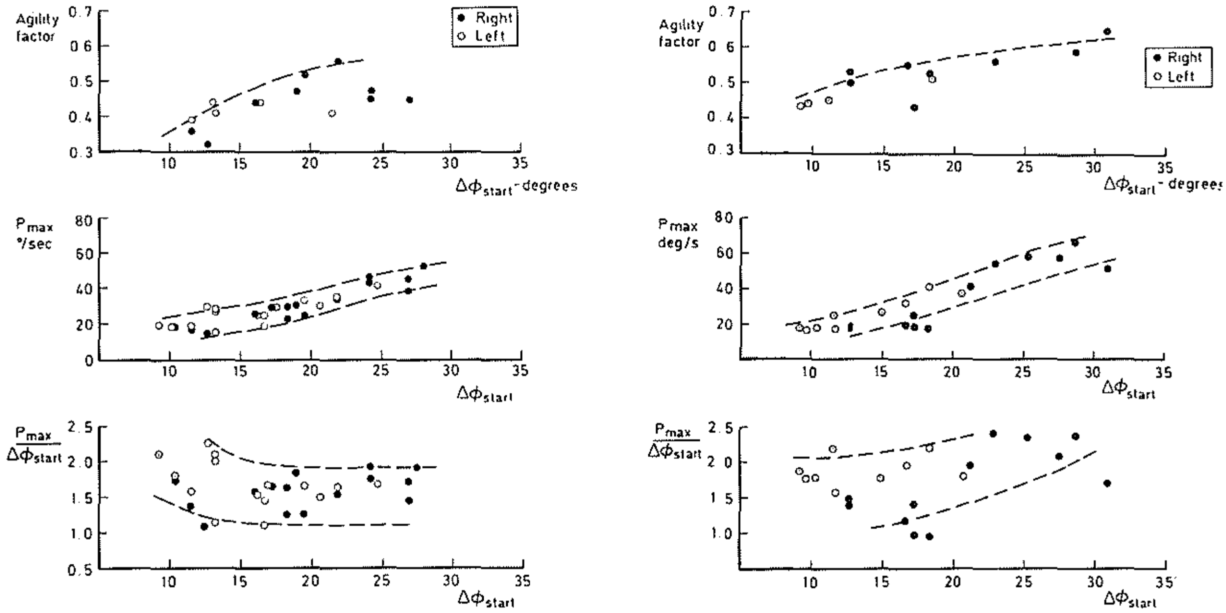
Fig 10a Control activity in sidestep



PUMA - 300ft Quickhop/Theta=30 Degrees
Flight 729, Run 18

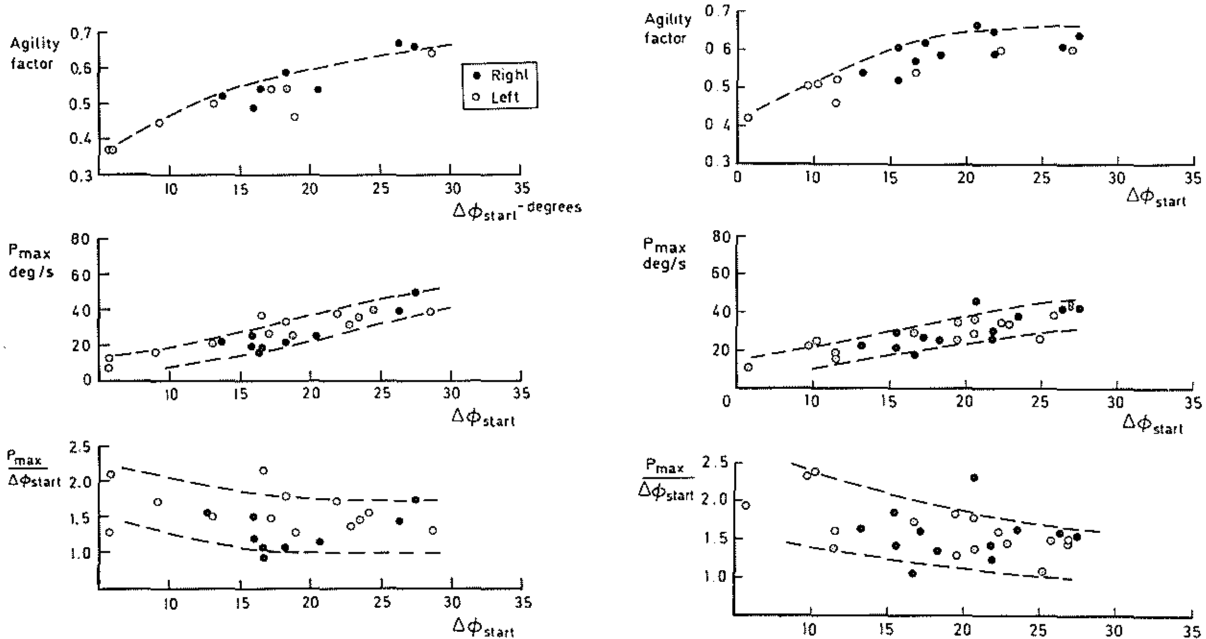
LYNX - 300ft Quickhop/Theta=35 Degrees
Flight 131, Run 23

Fig 10b Control activity in quickhop



LYNX — 50ft Sidesteps; CAC & AFCS disengaged
Pilot — P1; Flights 138 & 139A

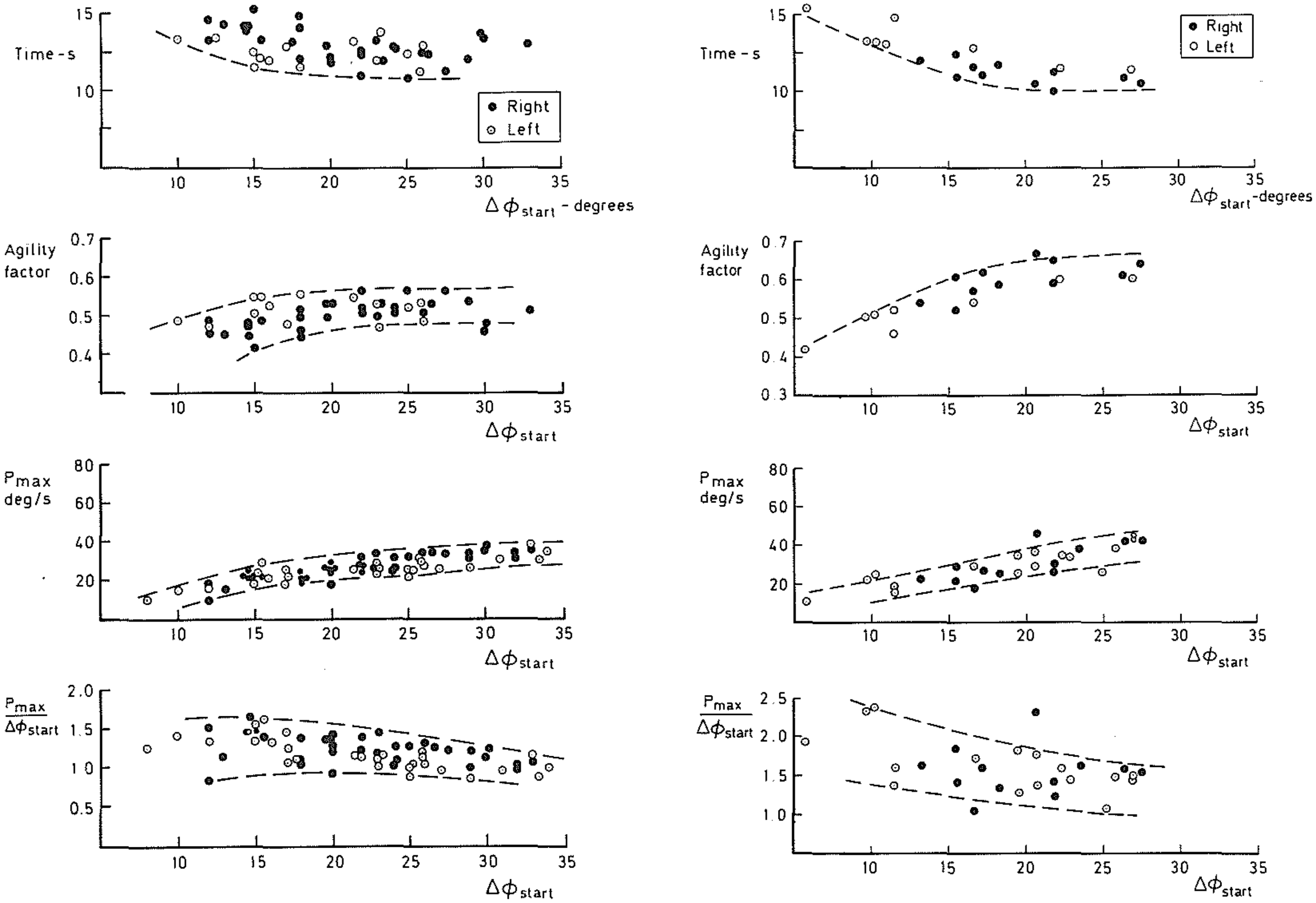
LYNX — 100ft Sidesteps; CAC & AFCS disengaged
Pilot — P1; Flight 139A



LYNX — 150ft Sidesteps; CAC & AFCS disengaged
Pilot — P1; Flight 162

LYNX — 200ft Sidesteps; CAC & AFCS disengaged
Pilot — P1; Flights 139A & 162

Fig 11 Agility diagrams for Lynx in sidestep manoeuvre



PUMA — 200ft Left & Right Sidesteps; AFCS engaged
Pilot — P1; Flights 690 & 715

LYNX — 200ft Sidesteps; CAC & AFCS disengaged
Pilot — P1; Flights 139A & 162

Fig 12 Comparison of Puma and Lynx agility for 200 ft sidestep

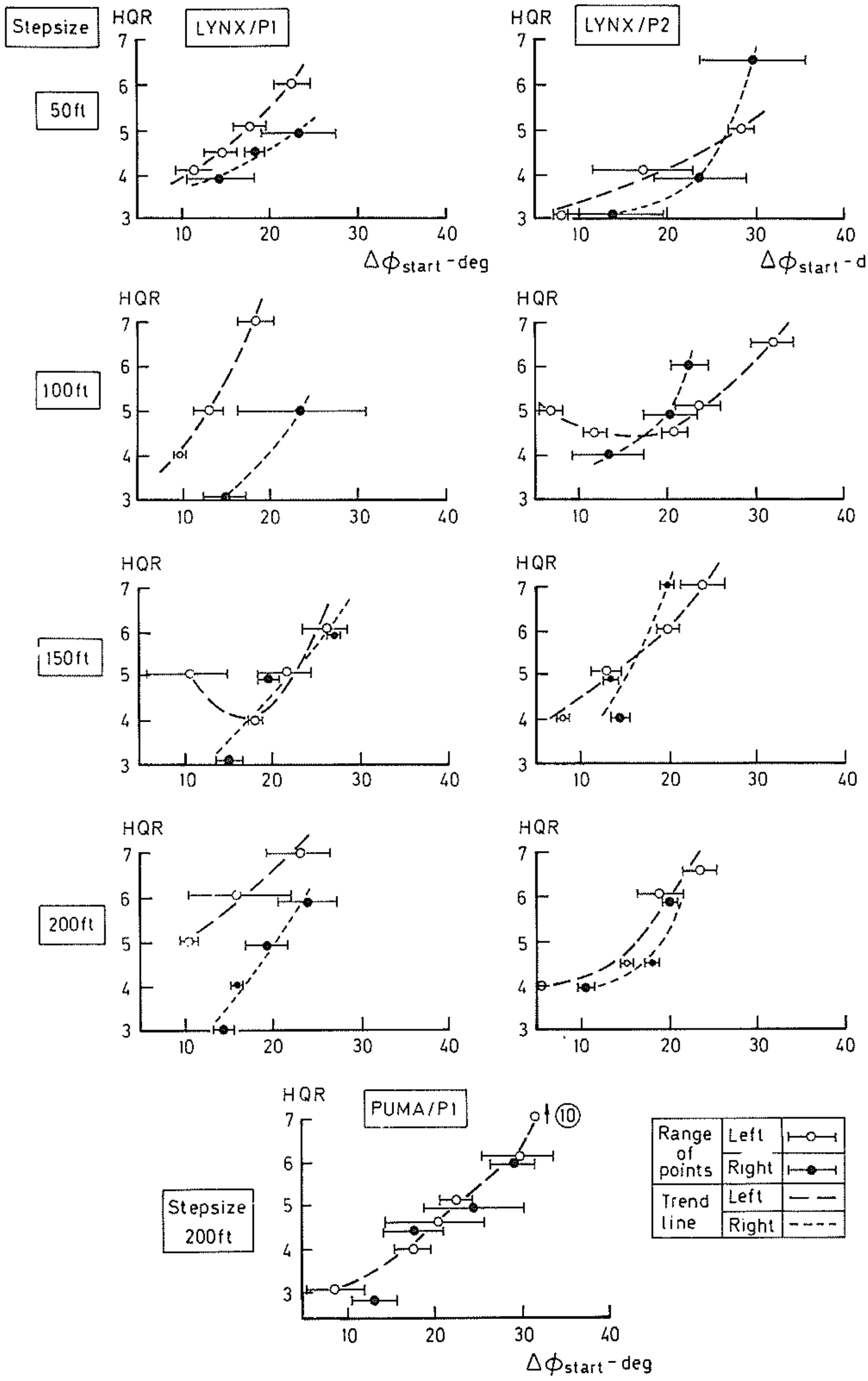
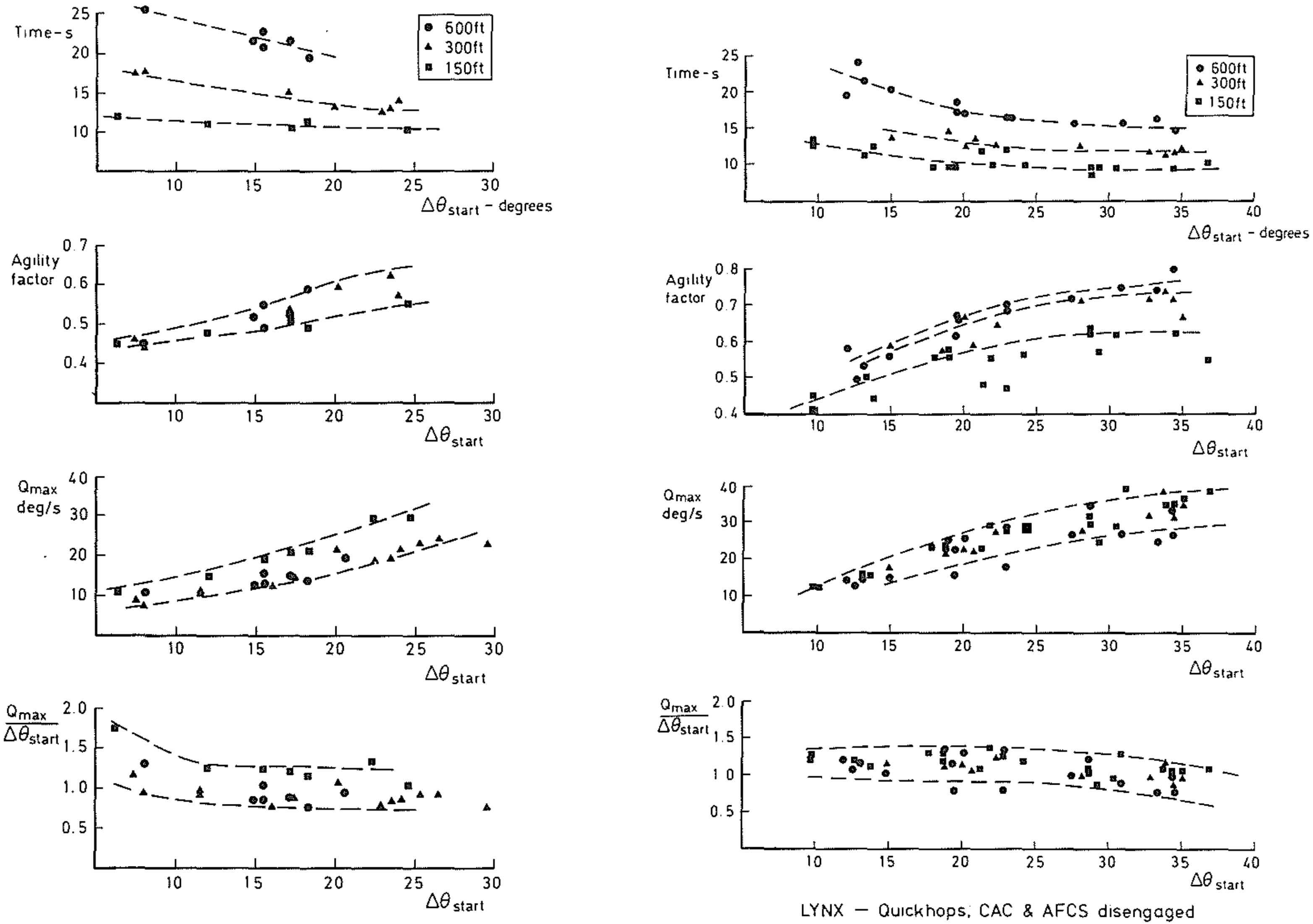


Fig 13 Handling quality ratings for sidestep manoeuvre



PUMA — Quickhops / AFCS engaged
Pilot — P1; Flight 729

LYNX — Quickhops; CAC & AFCS disengaged
Pilot — P1; Flights 131 & 132

Fig 14 Comparison of Puma and Lynx agility for quickhop manoeuvre

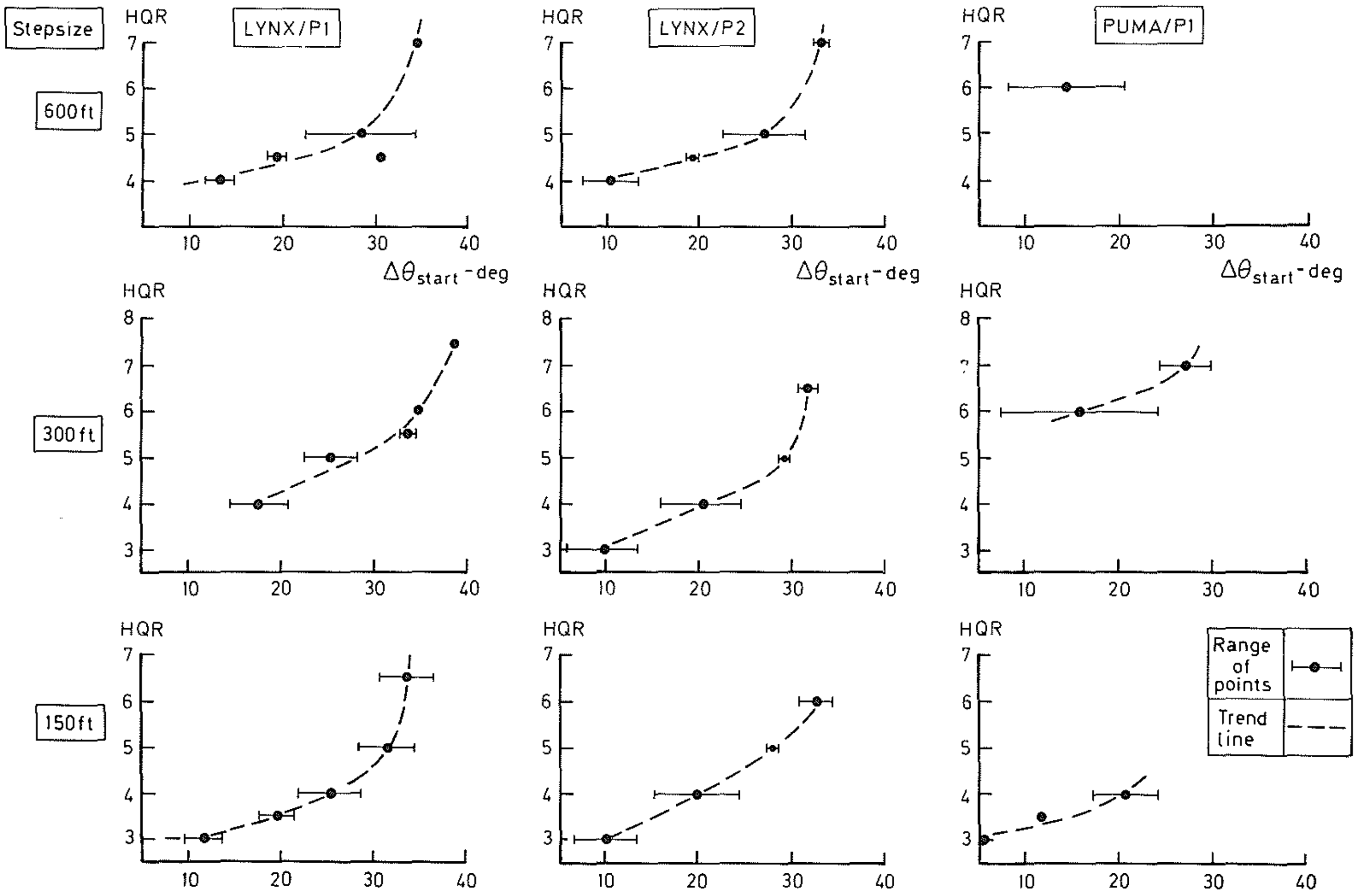


Fig 15 Handling quality ratings for quickhop manoeuvre

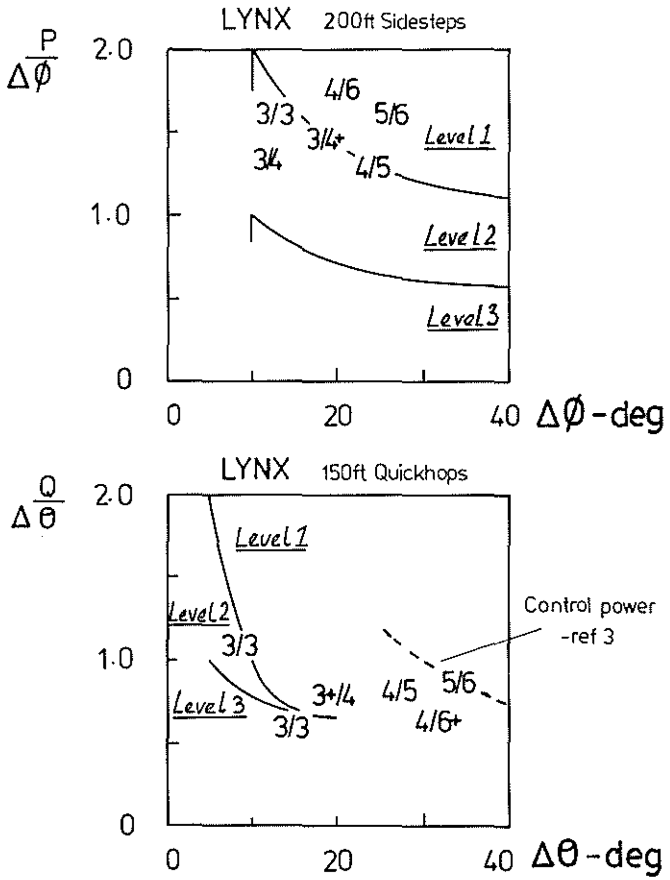


Fig 16 Lynx handling ratings on proposed Mil-Spec 8501 criteria (Ref 4)

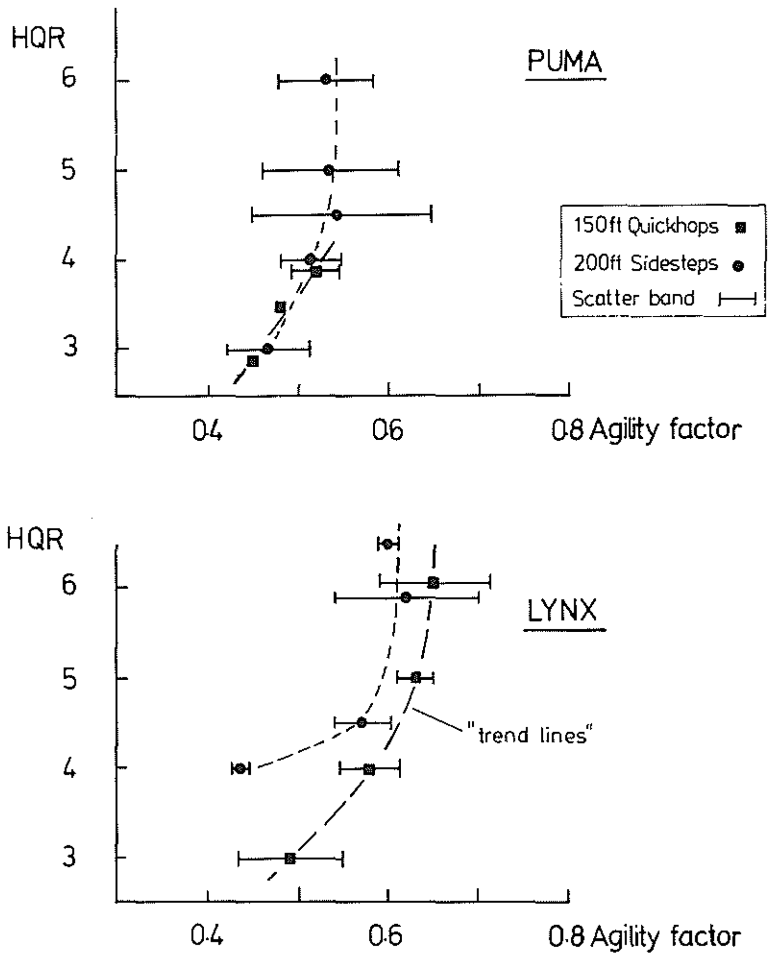


Fig 17 Variation of HQR with agility factor