The Impact of Flying Qualities on Helicopter Operational Agility

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Abstract

Flying Qualities standards are formally set to ensure safe flight and therefore reflect minimum, rather than optimum, requirements. Agility is a flying quality but relates to operations at high, if not maximum, performance. While the quality metrics and test procedures for flying, as covered for example in ADS33C, may provide an adequate **structure** to encompass agility, they do not currently address flight at high performance. This is also true in the fixed-wing world and a current concern in both communities is the absence of sustantiated agility criteria and possible conflicts between flying qualities and high performance. AGARD is sponsoring a working group (WG19) titled 'Operational Agility' that deals with these and a range of related issues. This paper is condensed from contributions by the three authors to WG19, relating to flying qualities. Novel perspectives on the subject are presented including the agility factor, that quantifies performance margins in flying qualities terms; a new parameter, based on manoeuvre acceleration is introduced as a potential candidate for defining upper limits to flying qualities. Finally, a probabalistic analysis of pilot handling qualities ratings is presented that suggests a powerful relationship between inherent airframe flying qualities and operational agility.

Introduction

Good flying qualities are conferred to ensure that safe flight is guaranteed throughout the Operational Flight Envelope (OFE). Goodness, or quality, in flying can be measured on a scale spanning three Levels (Ref 1). Aircraft are normally required to be Level 1 throughout the OFE (Ref 2); Level 2 is acceptable in failed and emergency situations but Level 3 is considered unacceptable. Level 1 quality signifies that a minimum required standard has been met or exceeded in design and can be expected to be achieved regularly in operational use, measured in terms of task performance and pilot workload. Compliance flight testing involves both clinical open loop measurements and closed loop mission task elements (MTE). The emphasis on minimum requirements is important and is made to ensure that manufacturers are not unduly constrained when conducting their design trade studies.

Two issues arise out of this quality scale and assessment. First, the minimum requirements reflect and exercise only moderate levels of the dynamic OFE, rather than high or extreme levels. Second, the assessments are usually made in 'clean' conditions, uncluttered by secondary tasks or the stress of real combat. Beyond the minimum quality levels there remains the question of the value of good flying qualities to the overall mission effectiveness. For example, how much more effective is an aircraft that has, say, double the minimum required (Level 1) roll control power? More generally, how much more mission effective is a Level 1 than a Level 2 aircraft when the pilot is stressed? The answers to these questions cannot be found in flying qualities criteria. At higher performance levels, very little data are available on helicopter flying qualities and, consequently, there are no defined upper limits on handling parameters. Regular and safe (carefree) use of high levels of transient performance has come to be synonymous with the attribute **agility**. The relationship between flying qualities and agility is important because it potentially quantifies the value of flying qualities to effectiveness. This is the subject of the paper.

The issues that this paper addresses then, concern the flying qualities that are important for agility, in both an enabling and limiting context, and how far existing flying qualities requirements go, or can be extended to embrace agility itself. The answers are developed within a framework of deterministic flying qualities criteria coupled with the probabilistic analysis of success and failure. The definition of flying qualities by Cooper & Harper (Ref 1) provides a convenient starting point,

'those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role'.

The pilot subjective rating scale and associated flying qualities Levels introduced by Cooper & Harper (Fig 1) will be used in this paper in the familiar context of quality discernment and will be developed to make the link with agility and mission effectiveness.

Flying 'Quality' can be further interpretted as the **synergy** between the **internal attributes** of the air vehicle and the **external environment** in which it operates (Fig 2). The internals consist typically of the air vehicle (airframe, powerplant and flight control system) response characteristics to pilot inputs (handling qualities) and disturbances (ride qualities) and the key elements at the pilot/vehicle interface eg cockpit controls and displays. The key factors in the external environment which influence the flying qualities requirements are;

i) the mission, including individual mission task elements (MTE) and the required levels of task urgency and

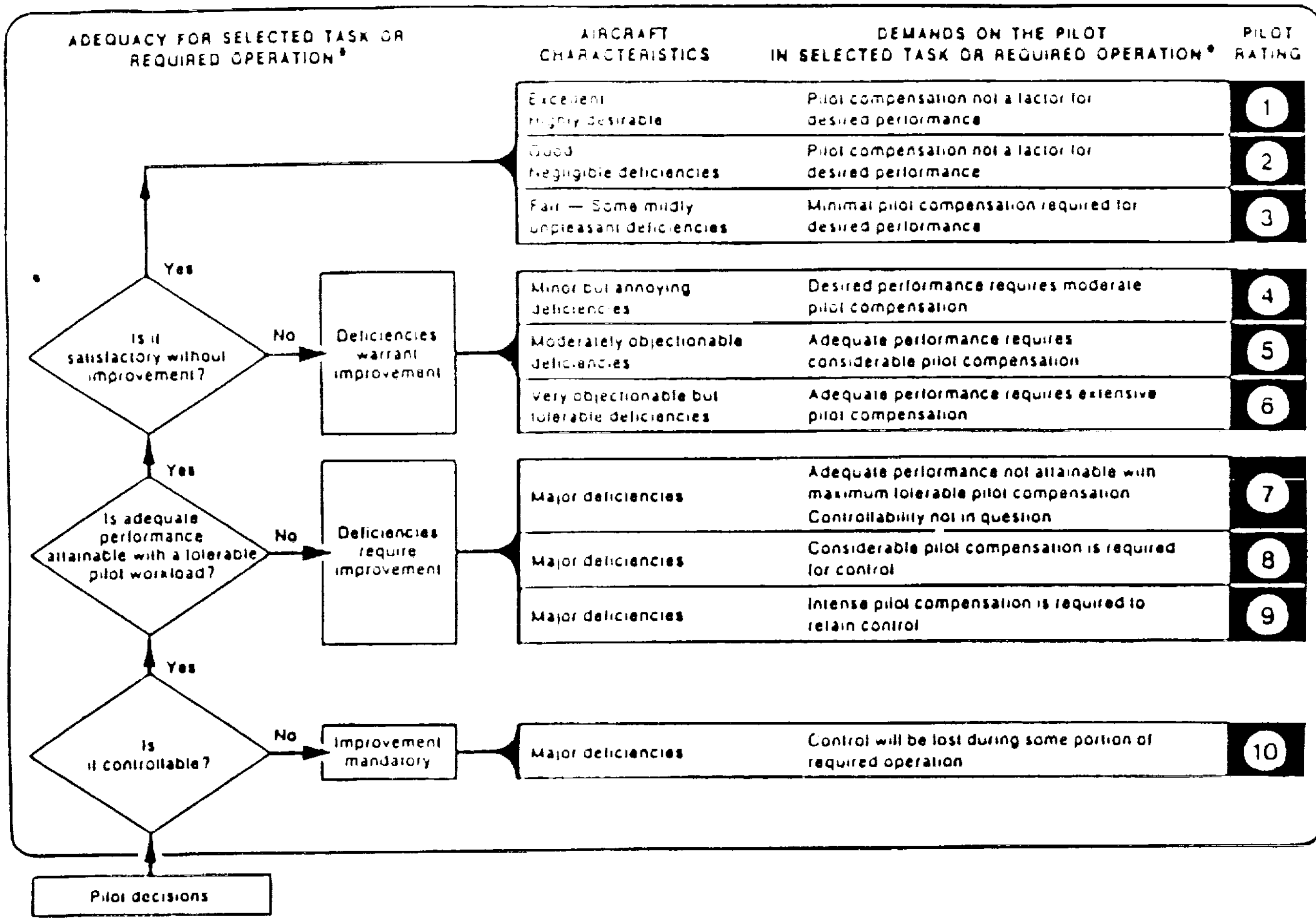

Fig 1 The Cooper-Harper Handling Qualities Rating Scale

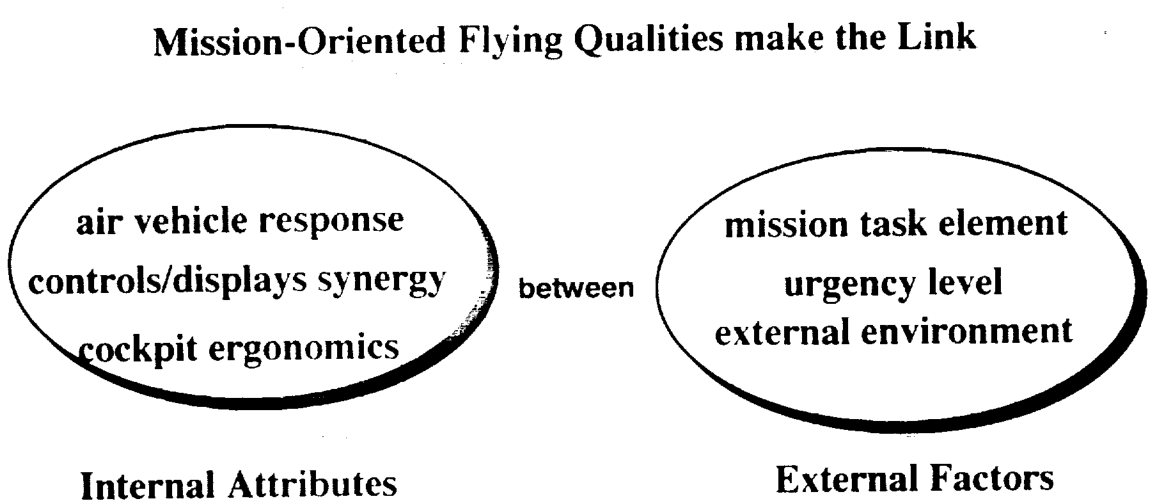

Fig 2 The Synergy of Flying Qualities

divided attention dictated by the circumstances governing individual situations, eg threat level.

ii) the external environment, including the usable cue environment (UCE) and level of atmospheric disturbance.

Flying qualities, as seen by the pilot who is ultimately the judge of quality, therefore change as the external world changes, for example, with weather conditions and flight path constraints and other task demands. Mission oriented flying qualities requirements, like those for fixed-wing aircraft, MIL STD 1797 (Ref 3), and, more particularly, helicopters, ADS33C (Ref 2), try to set quality standards by addressing the synergy of these internal attributes and external factors. ADS33C defines the response types required to achieve Level 1 and 2 handling qualities for a wide variety of different mission task elements, in different usable cue environments for normal and failed states, with full and divided pilot attention. At a deeper level, the response characteristics are broken down in terms of amplitude and frequency range, from the small amplitude, higher frequency requirements set by criteria like equivalent low order system response or bandwidth, to the large amplitude manoeuvre requirements set by control power. With these developments now mature, one would expect that any 'special' flying characteristics, like agility, could be embraced by the flying qualities requirements, or at least that the flying qualities criteria should be an appropriate format for quantifying agility.

The Flight Mechanics Panel of AGARD (Adviary Group for Aeronautical Research and Development) is currently sponsoring a working group (WG19) under the title 'Operational Agility', tasked with reporting the status of requirements and design capabilities for operational agility for aeroplanes and rotorcraft. The authors of this paper are members of WG19 and the work reported here is developed from their contribution to this group; the association and debate with fixed wing engineers and pilots has provided much fruitful discussion and comparison with the rotary wing world and some of this is embodied in the paper. While speed and manoeuvre envelopes and associated limits for aeroplanes and rotorcraft are quite different, often paradoxically so, they share the essence of agility and operational effectiveness. Agility requirements for the two vehicle types have traditionally stemmed from two quite different drivers; close combat of air-superiority fighters in the open skies contrasting with stealth of anti-armour helicopters in the nap-of-the-earth. While both still feature large in the two worlds, it is now recognised that agility is relevent to a wider range of roles including aircraft recovering to ships, transport refuelling, support helicopters delivering loads into restricted areas and, more recently, helicopter air-to-air combat.

AGARD WG19 is considering operational agility in the broader context of the total weapon system, encompassing sensors, mission systems, pilot, airframe/engine, flight control system and weapon; the concept is that the total system can only be as agile as the slowest element and that all elements need to work concurrently to be effective. AGARD will report on this activity in 1993. This paper focusses on the vehicle and the pilot centred agility requirements of the airframe, engine and flight control system elements. The next Section discusses the nature of operational agility, outlining some of the WG19 background and motivation and setting the scene for the following Section which addresses the relationship between flying qualities and agility. The principal innovations of this paper are contained here where the agility factor is introduced and related to quantitative handling criteria; the subjective quality scale (Cooper Harper) for pilot-perceived handling qualities is interprettted in a probabilistic fashion to indicate the likelihood of mission success or failure with a given level of flying qualities. Techniques for including flying qualities attributes in combat models are also discussed.

The Nature of Operational Agility

Operational agility is a primary attribute for effectiveness. Within the broader context of the total weapon system, the Mission Task naturally extends to include the actions of the different cooperating (and non-cooperating) sub-systems, each having its own associated time delay (Ref 4). We can imagine the sequence of actions for an air-to-air engagement - threat detection, engagement, combat and disengagement; the pilot initiates the action and stays in command throughout, but a key to operational agility is to automate the integration of the subsystems - the sensors, mission systems, airframe/engine/control system and weapon, to maximise the concurrency in the process. Concurrency is one of the keys to Operational Agility. Another key relates to minimising the time delays of the subsystems to reach full operational capability and hence effectiveness in the MTE. Extensions to the MTE concept are required that encompass the functions and operations of the subsystems, providing an approach to assessing system operational agility. WG19 is addressing this issue. Minimising time delays is crucial for the airframe, but flying qualities can suffer if the accelerations are too high or time constants too short, leading to jerky motion.

Later in this paper we examine how well existing flying qualities requirements address agility; to set the scene for this, we first consider a generalised definition of agility;

"the ability to adapt and respond rapidly and precisely with safety and with poise, to maximise mission effectiveness"

Agility requirements for helicopters falls into four areas - stealthy flying to avoid detection, threat avoidance once detected, the primary mission engagement (eg threat engagement) and recovery and launch from confined area; MTEs can be defined within each category. The key attributes of airframe agility, as contained in the above definition are,

i) rapid - emphasising speed of response, including any transient or steady state phases in the manoeuvre change; the pilot is concerned to complete the manoeuvre change in the **shortest possible time;** what is possible will be bounded by a number of different aspects.

ii) precise - accuracy is the driver here, with the motivation that the greater task precision eg pointing, flight path achievable, the greater the chance of a successful outcome.

iii) safety - this reflects the need to reduce piloting workload, making the flying easy and to free the pilot from unnecessary concerns relating to safety of flight, eg respecting flight envelope limits.

iv) poise - this relates to the ability of the pilot to establish new steady state conditions quickly and to be free to attend to the next task; it relates to precision in the last moments of the manoeuvre change but is also a key driver for ride qualities that enhance steadyness in the presence of disturbances.

v) adapt - the special emphasis here relates to the requirements on the pilot and aircraft systems to be continuously updating awareness of the operational situation; the possibility of rapid changes in the external factors discussed above (eg threats, UCE, wind shear/vortex wakes) or the internals, through failed or damaged systems, make it important that agility is considered, not just in relation to set piece manoeuvres and classical engagements, but also for initial conditions of low energy and/or high vulnerability or uncertainty.

Flying qualities requirements address some of the agility attributes implicitly, through the use of the handling qualities ratings (HQR), that relate the pilot workload to task performance achieved, and explicitly through criteria on response performance, eg control power, bandwidth, stability etc. The relationship has been fairly tenuous however, and the rotorcraft community can learn from fixed-wing experience in this context.

Flying Qualities - the Relationship with Agility

Fixed-Wing Perspectives

The original concern sprang from the notion that flying qualities specifications, as guardians of transient response, should embrace agility, since it too resides by definition in the transient domain. Initial thoughts on this theme appeared in Refs 5 and 6. Reference 5 indicated the interactions between agility, operational capability and flying qualities and listed some of the flying qualities requirements that, because of their treatment of the transient response, clearly crossed into the realm of agility. At that time, it was hypothesized that simply increasing the available agility, in terms of accelerations, rates etc, would lead to diminishing operational returns, since an over-responsive vehicle would not be controllable. That point was considered worth making because some combat analyses were being performed using computer tools that approximated the transient response only in a gross fashion. These models resulted in aircraft which had unquestionably high agility but did not account for the interaction of the vehicle with the pilot and, in fact, due to the approximations made in the interests of computational tractability, did not obey the laws of motion in their transient responses. In Ref 6, the Control Anticipation Parameter, CAP from the USAF Flying Qualities requirements (Ref 3), was quoted as an example of a criterion defining over-responsiveness, since an upper limit is specified for it. Artificially high pitch agility could, according to CAP, correspond to excessive pitch acceleration relative to the normal load factor capability of the aircraft. Performance constraints are also suggested by the tentative upper limits set on pitch bandwidth in Reference 3, although it is suspected that this is a reflection of the adverse acceleration effects associated with high bandwidth/control power combinations.

About that time, Riley et al at McAIR began a series of experiments on fighter agility. In Ref 7 it was emphasised that the definition of the categories in the Cooper-Harper pilot rating scale precluded the idea of an operationally useful vehicle with a rating worse than Level 2, using the US Military Specifications and Standard for flying qualities. In Level 3, the operational effectiveness of the vehicle is compromised, so increasing performance would add little as the pilot could not use it safely. In Refs 7, 8 and 9, Riley and Drajeske describe a fixed-base simulation in which the maximum available roll rate and roll mode time constant were independently varied and the pilot's time to bank 90 degrees and stop was measured. Care was taken in the experiment to allow sufficient time for learning and to generate large numbers (10 to 15) of captures for analysis. The start of the maneuver was when the stick deflection began, and the end was defined as when the roll rate was arrested to less than 5 degrees/second, or 5% of the maximum rate used, whichever was greater. Therefore a realistic element of precision was introduced into the protocol. The results from that experiment, in which the aircraft banked from -45 degrees to +45 degrees, are shown in Figure 3. The lower curved surface summarizes calculated time responses for a step lateral input and shows the expected steady increase in agility, ie a decrease in the time to bank with increasing roll rate. The upper surface in the plot summarizes the bank - to - bank and stop data obtained in the piloted cases. The references to controllability on that surface are from the pilot ratings and comments that were collected. The time to complete the maneuver actually increases for the higher available roll rates because the pilot could not adequately control the maneuver. The data therefore show that flying qualities considerations do limit agility. Though the data are from fixed-base simulation, we can speculate that in - flight results might show still more dramatic results. In Ref 9 the authors suggest that the effects of motion would in fact change the shape of Figure 3 to look like Figure 4.

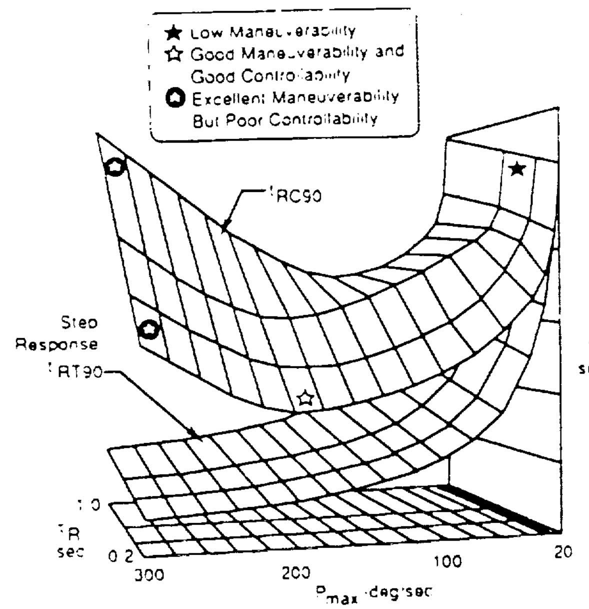

Fig 3 Agility in a Roll Manoeuvre (Ref 7)

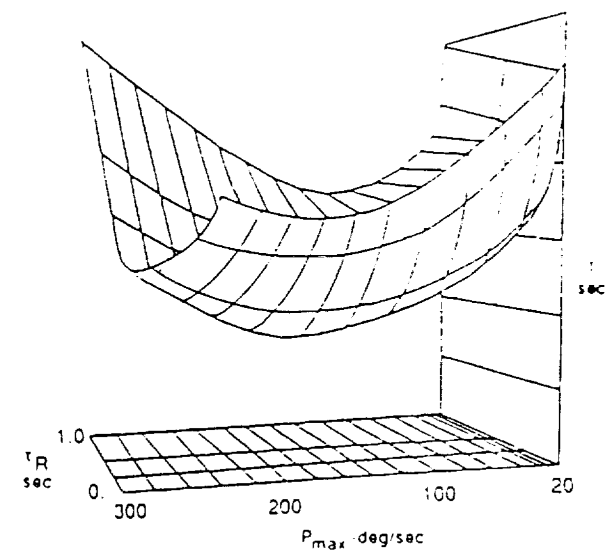

Fig 4 Effects of Motion on Agility

In MIL STD 1797, upper limits on lateral flying qualities are almost exclusively set by tolerable levels of acceleration at the pilot station, in the form of lateral g per control power; the Level 1 boundary at about 2g for a typical fighter seems extraordinarily high, but Reference 3 does state that "in order to achieve the needed roll performance it may be necessary to accept some uncomfortable lateral accelerations". There is considerable discussion on lateral control sensitivity in Reference 3, but as with helicopters, the criteria are strongly dependent on controller type and only guidance is given. Clearly there will always be upper limits to sensitivity but it seems a desirable goal to design the pilot/vehicle interface so that agility is not inhibited by this parameter.

The Agility Factor

One of the most common causes of dispersion in pilot HQRs stems from poor or imprecise definition of the performance requirements in a mission task element, leading to variations in interpretation and hence perception of achieved task performance and associated workload. In operational situations this translates into the variability and uncertainty of task drivers, commonly expressed in terms of precision but the temporal demands are equally important. The effects of task time constraints on perceived handling have been well documented (Refs 10, 11, 12), and represent one of the key external factors that impact pilot workload. Flight results gathered on Puma and Lynx test aircraft at DRA (Refs 12, 13) showed that a critical parameter was the ratio of the task performance achieved to the maximum available from the aircraft; this ratio gives an indirect measure of the spare capacity or performance margin and was consequently named the agility factor. The notion developed that if a pilot could use the full performance safely, while achieving desired task precision requirements, then the aircraft could be described as agile. If not, then no matter how much performance margin was built into the helicopter, it could not be described as agile. The Bedford agility trials were conducted with Lynx and Puma operating at light weights to simulate the higher levels of performance margin expected in future types (eg up to 20-30% hover thrust margin). A convenient method of computing the agility factor was developed as the ratio of ideal task time to actual task time. The task was deemed to commence at the first pilot control input and complete when the aircraft motion decayed to within prescribed limits (eg position within a prescribed cube, rates < 5 deg/s) for re-positioning tasks or the accuracy/time requirements met for tracking or pursuit tasks. The ideal task time is calculated by assuming that the maximum acceleration is achieved instantaneously, in much the same way that aircraft models work in combat games. So, for example, in a sidestep re-positioning manoeuvre the ideal task time is derived with the assumption that the maximum ***translational*** acceleration (hence aircraft roll angle) is achieved instantaneously and sustained for half the manoeuvre, when it is reversed and sustained until the velocity is again zero.

The ideal task time is then simply given by

$$T_i = \sqrt{(4S/a_{max})} \qquad 1$$

where S is the sidestep length and a_{max} is the maximum translational acceleration. With a 15% hover thrust margin, the corresponding maximum bank angle is about 30deg, with a_{max} equal to 0.58g. For a 100ft sidestep, T_i

then equals 4.6 seconds. Factors that increase the achieved task time beyond the ideal include,

i) delays in achieving the maximum acceleration (eg due to low roll attitude bandwidth/control power)

ii) pilot reluctance to use the max performance (eg no carefree handling capability, fear of hitting ground)

iii) inability to sustain the maximum acceleration due to drag effects and sideways velocity limits

iv) pilot errors of judgement leading to terminal re-positioning problems (eg caused by poor task cues, strong cross coupling)

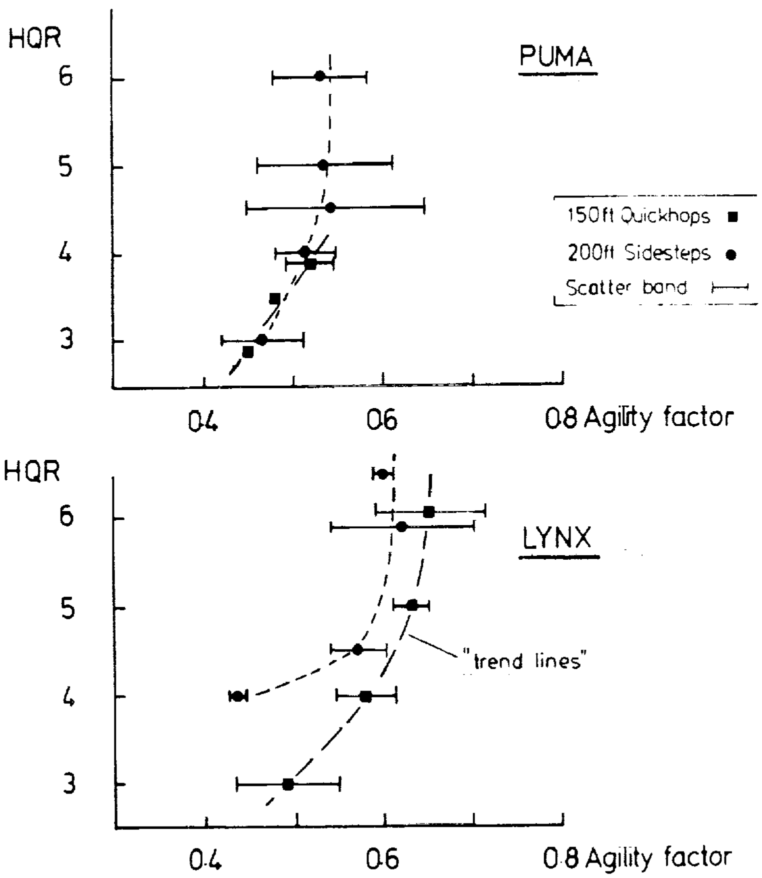

Fig 5 Variation of HQR with A_f showing the Cliff-Edge of Handling Deficiencies

To establish the kinds of agility factors that could be achieved in flight test, pilots were required to fly the Lynx and Puma with various levels of aggression, defined by the maximum attitude angles used and rate of control application. For the low speed re-positioning Sidestep and Quickhop MTEs, data were gathered at roll and pitch angles of 10, 20 and 30 degs corresponding to low, moderate and high levels of aggression respectively. Fig 5 illustrates the variation of HQRs with agility factor.

The higher agility factors achieved with Lynx are principally attributed to the hingeless rotor system and faster engine/governor response. Even so, maximum values of only 0.6 to 0.7 were recorded compared with 0.5 to 0.6 for the Puma. For both aircraft, the highest agility factors were achieved at marginal Level 2/3 handling; in these conditions, the pilot is either working with little or no spare capacity or not able to achieve the flight path precision requirements. According to Fig 5, the situation rapidly deteriorates from Level 1 to Level 3 as the pilot attempts to exploit the full performance, emphasising the 'cliff edge' nature of the effects of handling deficiences. The Lynx and Puma are typical of current operational types with low authority stability and control augmentation; while they may be adequate for their current roles, flying qualities deficiencies emerge when simulating the higher performance required in future combat helicopters.

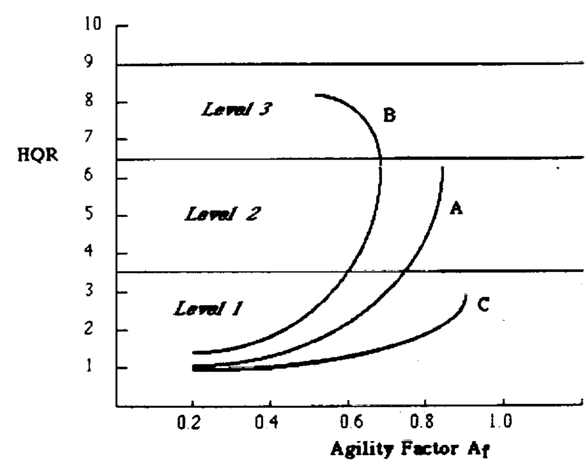

Fig 6 Variation of HQR with A_f for Different Notional Configurations

The different possibilities are illustrated in Fig 6. All three configurations are assumed to have the same performance margin and hence ideal task time. Configuration A can achieve the task performance requirements at high agility factors but only at the expense of maximum pilot effort (poor level 2 HQR); the aircraft cannot be described as agile. Configuration B cannot achieve the task performance when the pilot increases his aggression and Level 3 ratings are returned; in addition, the attempts to improve task performance by increasing aggression have led to a decrease in agility factor, hence a waste of performance. This situation can arise when an aircraft is PIO prone, is difficult to re-trim or when control or airframe limits are easily exceeded in the transient response. Configuration B is certainly not agile and the proverb 'more haste, less speed' sums the situation up. With configuration C, the pilot is able to exploit the full performance at low workload; he has spare capacity for situation awareness and being prepared for the unexpected.

Configuration C can be described as truly agile. The inclusion of such attributes as safeness and poise within the concept of agility emphasises its nature as a flying quality and suggests a correspondance with the quality Levels. These conceptual findings are significant because the flying qualities boundaries, that separate different quality levels, now become boundaries of available agility. Although good flying qualities are sometimes thought to be merely "nice to have", with this interpretation they can actually delineate a vehicle's agility. This lends a much greater urgency to defining where those boundaries should be. Put simply, if high performance is dangerous to use, then most pilots will avoid using it.

Conferring operational agility on future helicopters, emulating configuration C above, requires significant improvements in handling, but research into criteria at high performance levels and innovations in active control are needed to lead the way. There are two remaining links to be connected to assist in this process. First, between the agility factor and the operational agility or mission effectiveness and second between the agility factor and the flying qualities metrics themselves. If these links can be coherently established, then the way is open for combat analysts to incorporate prescribed flying qualities into their pseudo-physical models through a performance scaling effect using the agility factor. These links will now be developed.

Quality - Objective Measurement

Figure 7 provides a framework for discussing the influence of an aircraft's clinical flying qualities on agility.

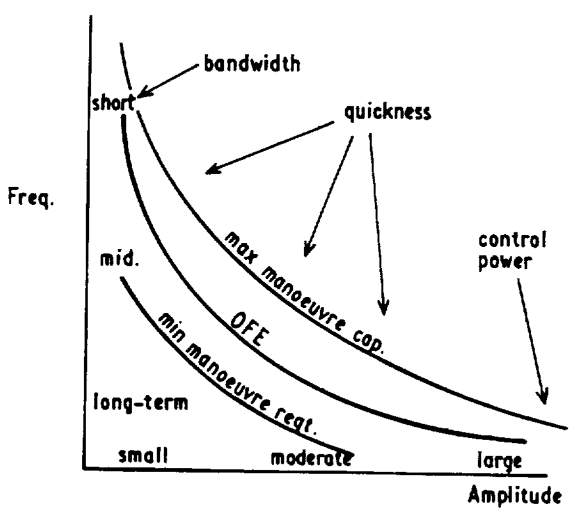

Fig 7 Response Characteristics on the Frequency-Amplitude Plane

The concept is that an aircraft's response characteristics can be described in terms of frequency and amplitude. The three lines refer to the minimum manoeuvre requirements, the normal OFE requirements and some notional upper boundary reflecting a maximum capability. Response criteria are required for the different areas on this plane - from high frequency/small amplitude characterised by bandwidth to low frequency/large amplitude motions characterised by control power. The region between is catered for by an ADS33 innovation, the Quickness parameter (Ref 2), and is particularly germane to agility. For a given manoeuvre amplitude change (eg bank angle, speed change), the pilot can exercise more of the aircraft's inherent agility by increasing the speed of the manoeuvre change, and hence the frequency content of his control input and the manoeuvre quickness. Likewise, the pilot can increase the manoeuvre size for a given level of attack or aggression. Increasing the manoeuvre quickness will theoretically lead to an increase in agility factor. But the maximum manoeuvre quickness is a strong function of bandwidth and control power. In ADS33C the quickness parameter is only defined for attitude response (ϕ, θ, ψ) and is given by the ratio of peak attitude rate (p_{pk}, q_{pk}, r_{pk}) to attitude change,

$$p_{pk}/\Delta\phi, \qquad q_{pk}/\Delta\theta, \qquad r_{pk}/\Delta\psi$$

Figure 8 shows derived quickness parameters for a sidestep MTE gathered on the DRA Lynx (Ref 13) and configuration T509 flown on the DRA Advanced Flight Simulator (AFS) (Ref 14).

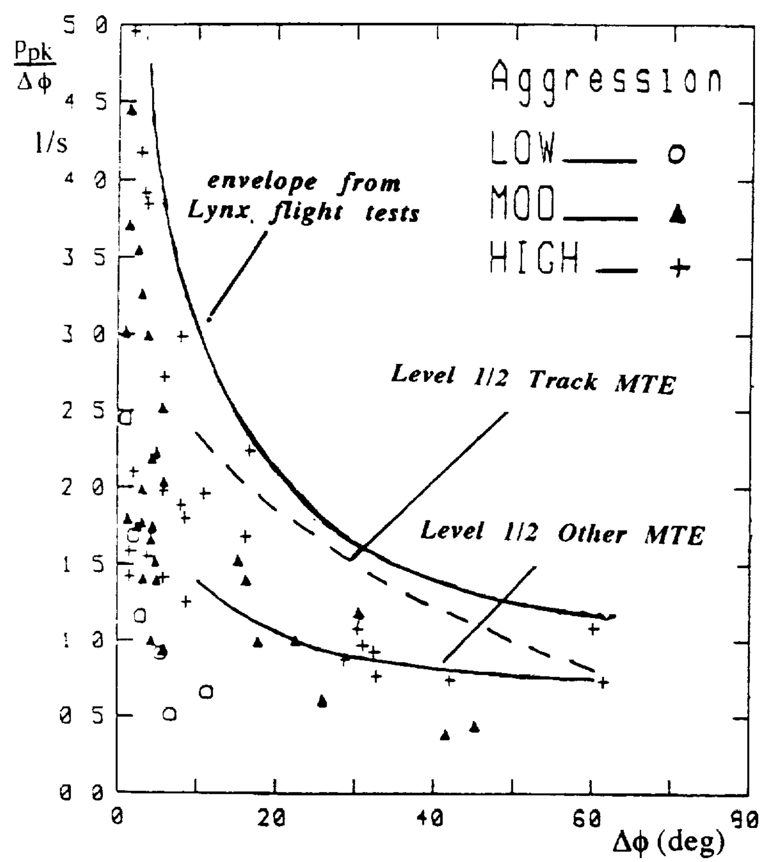

Fig 8 Roll Attitude Quickness from Sidestep Test Data in Flight (Lynx) and Ground-Based Simulation (AFS)

A quickness is calculated for every rate peak in the attitude time histories. The Lynx line on Fig 8 represents the upper boundary of all data gathered for a range of aggressiveness and sidestep sizes. The data includes the cases plotted in Figure 5 showing that at the highest agility factors/quickness, poor Level 2 ratings were awarded. The AFS data corresponds to a 150ft sidestep flown at the three levels of aggression shown; although the roll bandwidth of the AFS configuration T509 was less than the Lynx (~ 3 rad/s compared with ~ 5rad/s for the Lynx), the control power was similar (~ 100deg/s) and similar levels of quickness were achieved by the pilots across the full amplitude range. Also shown on Figure 8 are the Level 1/2 boundaries for tracking and other MTEs from ADS33C. There are several points worth making about this data that impact on agility.

1) the shape of the quickness boundaries reflect the shape of the response capability limits on Fig 7. The quickness has generic value and forms the link between the bandwidth and control power but is not, in general, uniquely determined by them.

2) the result of increased aggressiveness is to increase the achieved quickness across the amplitude range.

3) the cluster of quickness at small amplitude correspond with the pilot applying closed loop control in the terminal re-positioning phase and attitude corrections during the accel/decel phases.

4) at low amplitude, the quickness corresponds to the open loop bandwidth except when a pure time delay is present (as with the AFS configuration) when the bandwidth is lower than the quickness.

5) the lower ADS33C quickness boundaries at high amplitude correspond to the lower minimum control power requirements (50deg/s) of Ref 2.

From considerations of control power, quickness and bandwidth alone, Lynx and T509 are Level 1 aircraft. In practice, at the higher aggressiveness when the highest quickness is recorded, both are Level 2. Some of this degradation can be accounted for by simulated visual cue deficienies with T509 and severe cross couplings with the unaugmented Lynx. The data in Figure 8 is a useful benchmark for the kind of quickness required to achieve high agility factors in low speed MTEs, but it does not provide strong evidence for an upper boundary on quickness (or bandwidth and control power). The AFS rate response configuration T509 was implemented in the DRA's Conceptual Simulation Model (Ref 15) as a simple low order equivalent system of the form;

$$\frac{p}{\eta_{1c}} = K \frac{e^{-\tau s}}{(\frac{s}{\omega_m} - 1)(\frac{s}{\omega_a} - 1)} \qquad 2$$

where p is the body axis roll rate (rad/s), and η_{1c} is the pilot's lateral cyclic stick displacement($\pm$1), ω_m is the fundamental first-order break frequency or roll damping (rad/s) and ω_a is a psuedo-actuator break frequency (rad/s). K is the steady state gain or control power (rad/s. unit η_{1c}) and τ is a pure time delay.

Figure 9 illustrates the effects of the various parameters in the CSM on the maximum achievable quickness. In particular the actuator bandwidth has a powerful effect on quickness in the low to moderate amplitude range. Maximising the actuation bandwidth and minimising delays in the achievement of maximum acceleration is in accordance with maximising the agility factor.

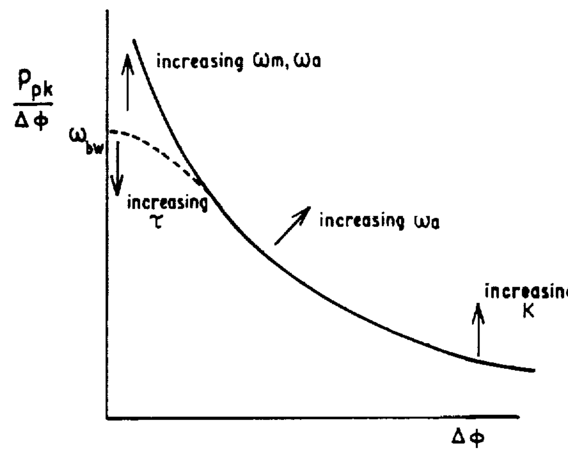

Fig 9 Effect of CSM Parameters on Roll Quickness

The sensitivity of agility factor with the parameters of the CSM is relatively easy to establish. If we consider the same bank and stop MTE discussed in the fixed-wing context earlier, some useful insight can be gained. A pulse type control input will be assumed, although in practice pilots would adopt a more complex strategy to increase the agility factor. To illustrate the primary effect we consider the case where the 'secondary' time delays are set to zero (ie $\tau = 0$, $\omega_a = \infty$). For a roll angle change of $\Delta\phi$, the ideal time is then given by assuming the time to achieve maximum rate is zero,

$$T_i = \Delta\phi / K = \Delta t \qquad 3$$

where Δt is the control pulse duration.

The time to reduce the bank angle to within 5% of the peak value achieved is given by,

$$T_a = \Delta t - \ln(0.05) / \omega_m \qquad 4$$

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The agility factor is then given by,

$$A_f = T_i / T_a = \frac{\omega_m \Delta t}{\omega_m \Delta t - \ln(0.05)} \qquad 5$$

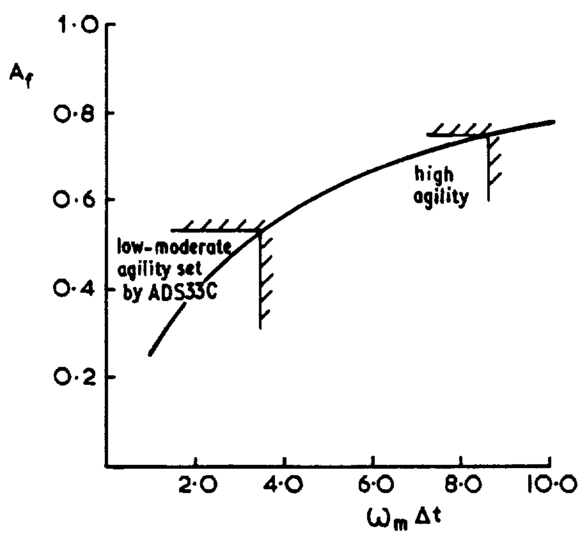

Fig 10 Variation of A_f with Normalised Bandwidth

Figure 10 illustrates the variation of A_f with $\omega_m \Delta t$. The bandwidth ω_m is the maximum achievable value of quickness for this simple case and hence the function shows the sensitivity of A_f with both bandwidth and quickness. The normalised bandwidth is a useful parameter as it represents the ratio of aircraft to control input bandwidth, albeit rather crudely. For short, sharp control inputs, typical in tracking corrections, high aircraft bandwidths are required to achieve reasonable agility factors. For example, at the ADS33C minimum required value of 3.5 rad/s and with 1 second pulses, the pilot can expect to achieve agility factors of 0.5 using simple control strategies in the bank and stop manoeuvre. To achieve the same agility factor with a half second pulse would require double the bandwidth. This is entirely consistent with the argument that the ADS33C boundaries are set for low to moderate levels of aggression. If values of agility factor up to 0.75 are to be achieved, Fig 10 suggests that bandwidths up to 8 rad/sec will be required; whether this is worth the 30% reduction in task time can only be judged in an overall operational context.

This simple example has many questionable assumptions but the underlying point, that increasing key flying qualities parameters above the ADS33C boundaries has a first order effect on task performance, still holds. But it provides no clues to possible upper performance boundaries set by flying qualities considerations. As stated earlier, ADS33C does not address upper limits directly. Also, practically all the upper boundaries in Mil Stan 1797 are related to the acceleration capability of the aircraft. As noted earlier, there are tentative upper limits on pitch attitude bandwidth, but it is suspected that these are actually a reflection of the high control sensitivity required to maintain the minimum level of control power required, rather than the high values of bandwidth per se. Control sensitivity itself (rad/s2.inch) is a fundamental flying qualities parameter and is closely related to the pilot's controller type; while some data exists for helicopter centre and side sticks, more research is required to establish the optimum characteristics including shaping functions. Mil Stan 1797 provides a comprehesive coverage of this topic for fixed-wing aircraft, rather more as guidance than firm requirements.

Another fruitful avenue appears to lie in the extension of the quickness parameter to the acceleration phase of an MTE. The fixed wing CAP already suggests this as the ratio of pitch acceleration to achieved normal 'g' (effectively, pitch rate). The DRA CSM used in the AFS trials offers a good example to explore and develop the concept of rate quickness. Setting the pure delay term in the CSM to zero for this study, the magnitude and time constant of the peak roll acceleration, for a step control input, can be written in the form;

$$\dot{p}_{pk} = \frac{K\omega_m}{\gamma} e^{-\omega_a t} \eta_{1c} \qquad 6$$

$$\omega_a t = \frac{\log\gamma}{1-\gamma}, \qquad \gamma = \omega_m/\omega_a \qquad 7$$

The rate quickness can then be written in the form,

$$\frac{\dot{p}_{pk}}{\Delta p} = \frac{\omega_m}{\gamma} e^{\frac{\log\gamma}{1-\gamma}} \qquad 8$$

and this is plotted in normalised form in Figure 11. During the AFS handling qualities trial described in Ref 14, the lag bandwidth ω_a was set at 20 rad/s to satisfy the pilot's criticism of jerky motion. This gave a γ of 0.5 at the highest bandwidth flown (T509). Corresponding values of rate quickness and time to peak acceleration were 0.5 and 0.7, both relative to the damping ω_m. Intuitively there will be upper and lower flying qualities bounds on both of these parameters. Hard and fast may be as unacceptable as soft and slow, both leading to low agility factors; the opposite extremes may be equally acceptable when referred to the maximum quickness. This suggests closed boundaries delineating the quality levels on the Figure 11 format. More systematic research is required to test and develop this hypothesis further.

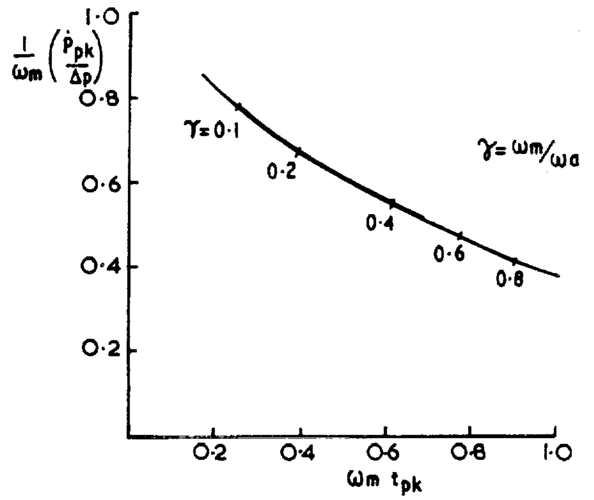

Fig 11 Variation of Rate Quickness with Acceleration Time Constant

Quality - Subjective Measurement

Flying quality is ultimately determined by pilot subjective opinion. The 'measurement scale' and understanding for this continue to stimulate vigorous debate but the Cooper-Harper handling qualities rating (HQR or CHR) provides the most widely accepted standard. The operational benefit of good flying qualities has never really been properly quantified using the CHR approach, however. The benefits to safety have been addressed in References 16 and 17, using the Cooper-Harper pilot rating scale as a metric (Fig 1). These references consider the pilot as a vital system component who can fail (be stressed to failure) in an operational context. The authors point out that if a normal distribution of ratings is assumed, then the probability of control loss, P_{loc}, can be calculated for various mean ratings and dispersions (Fig 12). P_{loc} is the probability of obtaining a rating greater/worse than 9.5, which in turn is simply proportional to the area under the distribution to the right of the 9.5 rating. Thus the probability of **flight**, and hence mission failure, due to flying qualities can be estimated. For the case studied in Ref 16 and depicted in Fig 12, operating a Level 1 aircraft can be seen to reduce the probability of a crash by an order of magnitude relative to a Level 2 aircraft. This result immediately raises the question - what is the probability of **mission** success or failure and can the same comparisons be made between aircraft with different mean flying qualities?

Figure 13 shows a notional distribution of ratings, with the regions of desired, adequate and inadequate performance clearly identified. The desired and adequate levels can be considered as reflecting varying degrees of mission (task element) success while the inadequate level corresponds to mission (task element) failure. Effectively the mission is composed of a number of contiguous MTEs, each having a virtual HQR assigned on the basis of performance and workload that the situation demands and allows respectively. If a particular MTE was assigned a Level 3 rating, then the pilot would either have to try again or give up on the particular MTE. Loss of control has obvious ramifications on mission success. The probability of obtaining a rating in one of the regions is proportional to the area under the distribution in that region. Note that, as discussed in Refs 16 an 17, we include ratings greater than 10 and less than 1 in the analysis. The rationale is that there are especially good and bad aircraft or situations, whose qualities correspond to ratings like 13 or minus 2. However, the scale enforces recording them as 10 or 1.

Note too, that the scatter produces, even with a good mean rating, a large probability of merely adequate performance and even a finite probability of total loss of control and crash. We have said in the Introduction to this paper that flying qualities are determined by the synergy between internal attributes and external influences. It follows then that sources of scatter originate both internally and externally. Internals include divided attention, stress and fatigue, pilot skill and experience. Externals include atmospheric disturbances, changing operational requirements and timelines, threats etc. The flying qualities community has done much to minimise scatter by careful attention to experimental protocol (Ref 18) but, in operational environments, the effective pilot rating scatter is omnipresent .

Fig 14 shows the probability of obtaining ratings in the various regions when the standard deviation of the ratings is unity. This curve, which we have labelled as preliminary, has some interesting characteristics. First, the intersections of the lines fall close to, or exactly at, the ratings 4.5, 6.5 and 9.5, as expected. Also it turns out that for a mean rating of 7, the probability of achieving inadequate performance is, of course, high, and we can also see that the probability of achieving desired performance is about the same as that for loss of control - about one in a hundred. Improving that rating to 2, lowers the probability of loss to 10^{-13} (for our purposes zero) and ensures that performance is mostly at desired levels. Degrading the mean rating from 2 to 5 will increase the chances of mission failure by three orders of magnitude.

We describe these results as preliminary because we assume that there is a rational continuum between desired performance, adequate performance and control loss. For example, desired and adequate performance may be represented by discrete touchdown zones/velocities on the back of a ship and loss of control might be represented by, say, the edge of the ship or hanger door. On a smaller ship (or bigger helicopter), the desired and adequate zones may be the same size, which puts the deck-edge closer to the adequate boundary, or represent a similar fraction of the deck size, hence tightening up the whole continuum. This raises some fundamental questions about the underlying linearity of the scale.

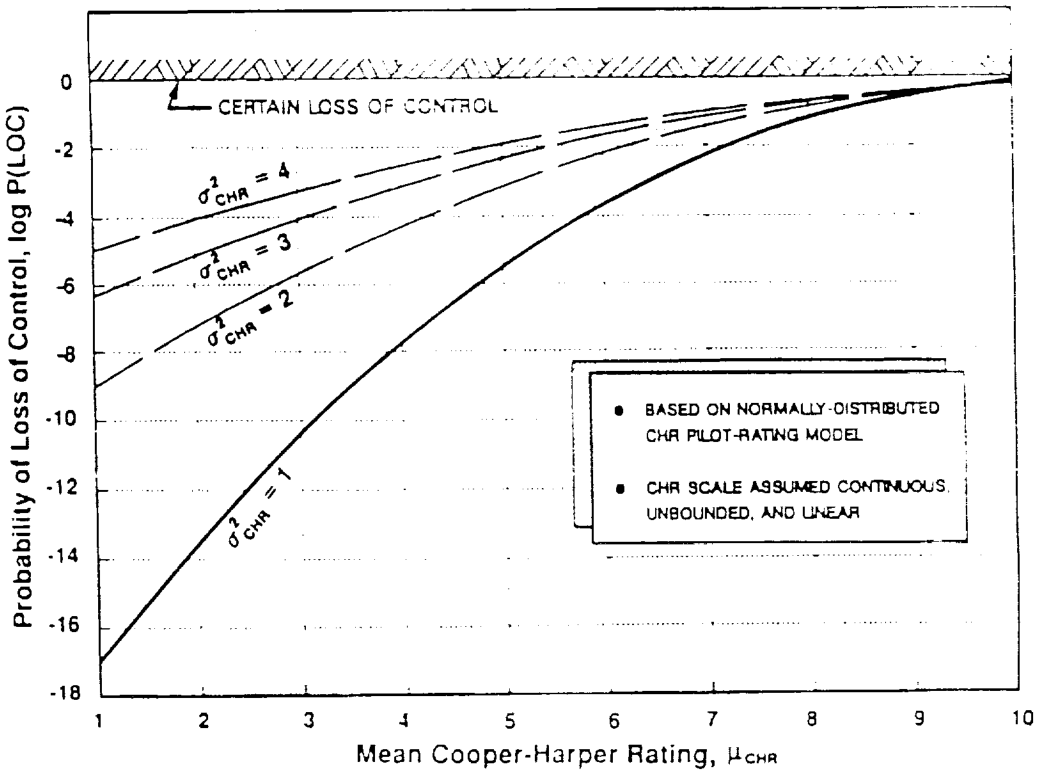

Fig 12 Relationship Between Mean CHR (HQR) and P_{loc}

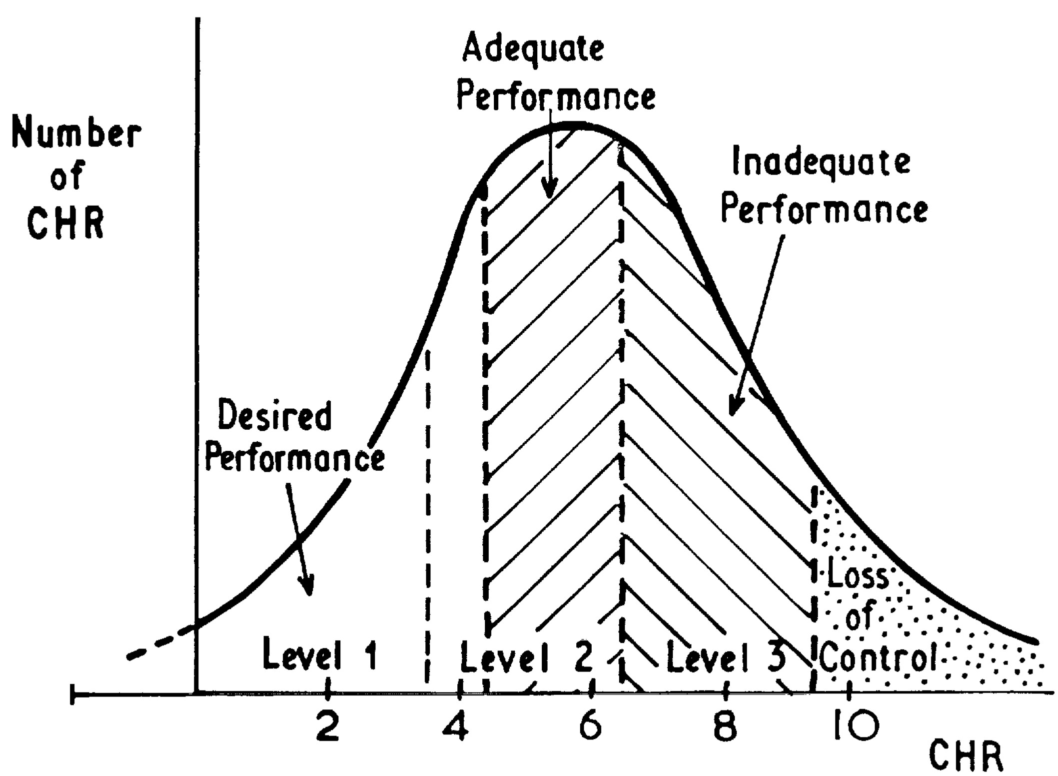

Fig 13 Notional Distribution of Pilot Handling Qualities Ratings for a Given Aircraft

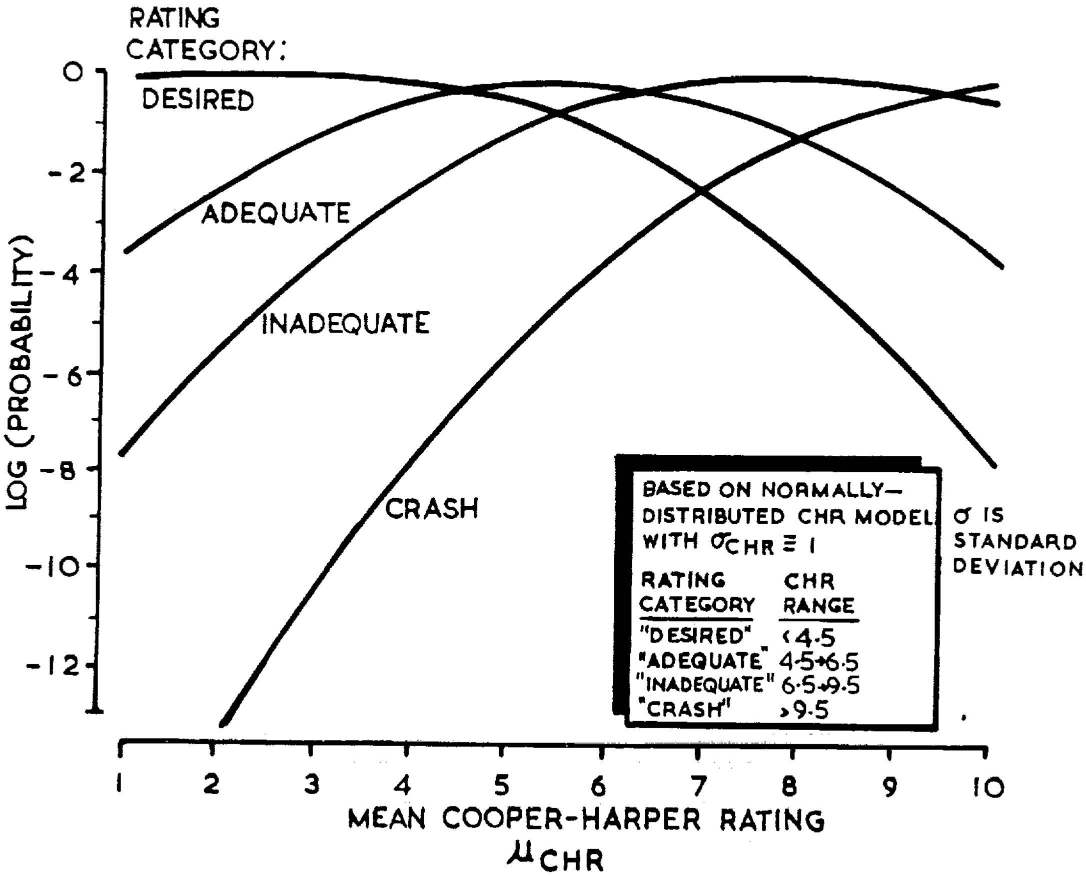

Fig 14 Relationship Between Mean CHR (HQR) and Probability of Mission Success, Failure or Crash - Preliminary Results

With the servo-model of piloting behaviour, for example, we can always define a desired level of flight path task performance so demanding that, whatever the aircraft attitude bandwidth, pilot induced oscillations will result.

Though these questions remain, pilot rating and mission success or failure are powerfully related through the preliminary data in Fig 14. Flying qualities alone can determine whether operational agility is flawless or whether control is lost.

Flying Qualities Effects in Combat Models

The results highlighted in this paper suggest ways by which the effects of flying qualities can be incorporated into unmanned combat mission simulations. Such models are regularly used to establish the effectiveness of different weapon system attributes or tactics, but the human element is usually absent for obvious reasons. The aircraft are therefore assumed to have perfect flying qualities and the models are often configured to ignore the transient responses, effectively assigning an agility factor of unity to each manoeuvre change or MTE. The impact of these assumptions is twofold; first, that there is no way that flying qualities or their enabling technologies can be included in the trade studies conducted with such models. Second, the implied perfect flying qualities may give a false impression of the importance or the value of mission performance enhancements. The key steps to embodying the key flying qualities effects are suggested as follows;

1) through objective design and assessment establish the level of flying quality and hence the effective mean HQR

2) describe the mission in terms a series of contiguous MTEs, selectable in the same way that set manoeuvres are in combat models

3) establish a MTE hazard weighting on the basis of threat, divided attention and other internal/external factors, that will define the effective HQR for the MTE. This will vary as the mission develops.

4) establish a time scaling for each MTE, on the basis of the maximum achievable agility factor

5) overlay the time scaling on the mission profile; there will be an option for each MTE to fly at reduced agility factor with level 1 HQR or to fly at the higher agility factor at a poorer HQR.

Improvements or degradations in flying qualities can then explored through variations in the achievable agility factors and mean HQR for the aircraft and can be linked directly to the enabling control technologies. There are, of course, some fundamental questions associated with this approach. How can we assign the mean rating and the standard deviation? How do we classify the hazards resulting from the various degrading influences? How are the maximum agility factors derived? These and others will need to be addressed if this approach is to be taken further; the benefits are potentially high however, both in terms of clarifying the value of active control to effectiveness and, conversely, establishing the cost of flying qualities limitations to operational agility.

Conclusions and Recommendations

Operational agility is a key attribute of any weapon system and its subsystems from sensors, through the airframe elements, to the primary mission element, eg weapon. The total system can only be as agile as its slowest element and maximising the concurrency within the subsystems is a key method for enhancing agility. AGARD Working Group 19 is currently examining this topic and will report in 1993; the present paper is assembled from material reviewed and developed within this activity. The focus of the paper is the airframe and its primary enabling attribute - its flying qualities. The adequacy of existing flying qualities criteria for providing agility is addressed along with the benefits to agility of good flying qualities and the penalties of poor flying qualities. The following principal conclusions can be drawn.

1) Existing flying qualities criteria provide a useful framework for describing and quantifying agility; however, the quality boundaries are only minimum standards and do not reflect or quantify the desirable characteristics at high performance levels. Indeed, there are no boundaries defined that set upper limits on usable performance.

2) The agility factor provides a measure of usable performance and can be used to quantify the effects of flying qualities on agility; agility factors up to 0.7 can be achieved with current aircraft types operated with high performance margins, but handling deficiencies typically lead to HQRs in the poor level 2/level 3 region. Moreover, the degradation from Level 1 to 3 is rapid. High agility factors achievable with Level 1 flying qualities should be a goal for future operational types.

3) Extensions of the ADS33C innovation, the quickness, into the acceleration response is suggested as a potentially useful parameter for setting flying qualities limits on performance. Flight and simulation data needs to be gathered and analysed systematically to test this hypothesis.

4) It is argued that even a Level 1 aircraft will degrade to level 2 and 3 in unfavourable situations. In this context, a probabalistic analysis can be used to highlight the benefits of improved flying qualities on operational agility and mission effectiveness. Operating a Level 2 aircraft is shown to increase the chances of mission failure by three orders of magnitude, compared with a Level 1 aircraft. The results are preliminary and dependent on a number of underlying assumptions, but indicate a powerful relationship. Experimental results are needed to substantiate the results; these could include learning runs and trials with varying degrees of external influences.

5) Considering the mission as a series of contiguous mission task elements enables the agility factor and probability of success/failure to be overlayed on non-piloted combat mission simulations. This should allow flying qualities to be included in such exercises and flight control technologies to be integrated into mission effectiveness trade studies.

6) The key to ensuring that future projects are not susceptable to performance shortcomings from flying quality deficiencies would appear to be in the development of a unified specification for flying qualities and performance, with a clear mission orientation in the style of ADS33C.

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References

1 Cooper, G.E., Harper, R.P.Jr.; "The Use of Pilot Ratings in the Evaluation of Aircraft Handling Qualities", NASA TM D-5133 (1969)

2 AVSCOM; Aeronautical Design Standard (ADS) 33C - Handling Qualities for Military Helicopters, US Army AVSCOM (1989)

3 USAF; Flying Qualities of Piloted Vehicles; Mil Std - 1797 (USAF) (1987)

4 Skow, A.M.; "Agility as a Contribution to Design Balance", AIAA 90-1305, 5th bi-annual Flight Test Conference, Ontario Ca., May 1990

5 Hodgkinson, J. and Hodgkinson, R.K.; "Fighter Transient Agility and Flying Qualities", AIAA Conference on Atmospheric Flight Mechanics, Flying Qualities Workshop, Monterey, California, August 1987

6 Hodgkinson, J. et al; "Relationships Between Flying Qualities, Transient Agility, and Operational Effectiveness of Fighter Aircraft", AIAA Paper 88-4329, AIAA Conference on Atmospheric Flight Mechanics, Minneapolis, Minn., August 1988.

7 Riley, D.R., and Drajeske, M.H.; "An Experimental Investigation of Torsional Agility in Air-to-Air Combat" AIAA Paper 89-3388, Conference on Atmospheric Flight Mechanics, Boston, Mass, August 1989

8 Riley, D.R, and Drajeske, M.H.; "Status of Agility Research at McDonnell Aircraft Company and Major Findings and Conclusions to Date". ICAS Paper 90-5.9.4, 1990a.

9 Riley, D.R. and Drajeske, M.H.; "Relationships Between Agility Metrics and Flying Qualities" Paper 901003, SAE Aerospace Atlantic, April 1990b

10 Brotherhood, P., Charlton, M. T.; "An assessment of helicopter turning performance during NOE flight"; RAE TM FS(B) 534, January 1984

11 Heffley, Robert E.; "Study of Helicopter Roll Control Effectiveness", NASA CR 177404, April 1986

12 Padfield, G. D., Charlton, M. T.; "Aspects of RAE flight research into helicopter agility and pilot control strategy"; paper presented at a Handling Qualities (Mil Spec 8501) specialists meeting, NASA Ames June 1986

13 Charlton, M. T., Padfield, G. D., Horton, R. I.; "Helicopter Agility in Low Speed Manoeuvres"; Proceedings of the 13th European Rotorcraft Forum, Arles, France, Sept 1987 (also RAE TM FM 22, April 1989)

14 Padfield, G. D., et al; "Helicopter Flying Qualities in Critical Mission Task Elements"; Paper F2, 18th European Rotorcraft Forum, Avignon, Sept 1992

15 Buckingham, S. L., Padfield, G. D., "Piloted Simulations to Explore Helicopter Advanced Control Systems"; RAE Tech Report 86022, April 1986

16 Hodgkinson, J., Page, M., Preston, J., Gillette, D.; "Continuous flying quality improvement - the measure and the payoff"; AIAA Paper 92-4327, 1992 Guidance, Navigation and Control Conference, Hilton Head Island, S. Carolina, August 1992

17 Page, M., Gillette, D., Hodgkinson, J., Preston, J.; "Quantifying the pilot's contribution to flight safety"; International Air Safety Seminar, Flight Safety Foundation, Long Beach, California, November 1992, MDC Paper 92K0377

18 Wilson, D., Riley, D.; "Cooper-Harper pilot rating variability"; AIAA Paper 89-3358, Atmospheric Flight Mechanics Conference, Boston, Massachusetts, August 1989