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Controlling Tension between Performance and Safety in Helicopter Operations

A Perspective on Flying Qualities

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ABSTRACT

As twin goals in the design and operation of aircraft, performance and safety often struggle together for prominence. This struggle creates a tension that runs throughout the design, development and qualification processes and on into utilisation. The tension is felt most when missions are stressed, in the sense of being at the extremes of the requirements; for example, operations into degraded visual conditions in poor weather, or when the degree of urgency increases, in emergency manoeuvres or when the pilot is required to divide attention between flying and other mission duties. The pilot plays a key role in controlling this tension but safety margins reduce when the pilot's ability to react fast enough and with the correct strategy are impaired. The pilot is prone to failure, often described as human error, in these situations. Two important contributions assist the pilot in managing this tension. First, designs which confer the aircraft with sufficiently good handling characteristics, such that even in emergency conditions, the attentional demands of control workload are acceptable. Second, providing sufficient spatial awareness relative to the surrounding airspace and surface/obstacle layout that the pilot is able to maintain an adequate safety margin. These two attributes combine together into flying qualities. Flying qualities are a product of the four elements - the aircraft, the pilot, the task and the environment. In this paper, mission-oriented flying qualities engineering is described within the systems framework of Aeronautical Design Standard - 33 (ADS-33), utilising concepts like the mission task element, usable cue environment, response type and dynamic response criteria. The paper argues that the requirements for what constitute safe and easy, Level 1, flying qualities now exist and are well substantiated. New aircraft can now be designed to these performance and safety standards and existing aircraft can be upgraded with integrated flight management systems featuring advanced control/flying qualities technologies. Good flying qualities provide critical support to the pilot in the management of the performance-safety tension. The paper will examine this tension in more detail, drawing on results of a probabilistic analysis of the impact of flying qualities on flight safety. This analysis highlights the point that handling deficiencies can increase the risk of accident in helicopters, particularly in degraded visual conditions or in emergencies where excursions beyond the operational flight envelope can lead to piloting difficulties. The author considers the development of criteria for situations where handling degrades into Level 2, 3 or worse as the new challenge for flying qualities engineers, and in the paper two areas are discussed in some detail. First, flight in severely degraded visual conditions where the author highlights the importance of understanding the fundamentals of human visual perception in the development of integrated control and display augmentation. Second, handling qualities following tail rotor failures are discussed and results from current research to develop new advice for aircrew are presented. The author takes the view that much more can, and needs to be done to assist the pilot in the management of the tension between performance and safety in helicopter operations, through the provision of improved flying qualities. The pilot's vulnerability to failure in stressed situations is considered to be too high in current helicopter operations. The paper will develop the argument that flight system automation to improve handling and spatial awareness can reduce this vulnerability and increase the safety of helicopter operations without compromising operational efficiency.

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NOTATION

p, q, r	roll, pitch, yaw rates (deg/sec)
p_{pk}	peak roll rate used in quickness computation (deg/sec)
$r(t), v(t)$	optical expansion of image of object on retina (m, m/sec)
$X(t), V(t)$	distance and velocity of object from pilot (m, m/sec)
x,z	location of points on surface ahead of aircraft in eqn 1 (m)
$\Delta\phi$	change in roll attitude used in quickness computation (deg)
$\theta(t)$	elevation angle of points on surface ahead of aircraft in eqn 1(deg)
$\tau(t)$	optical τ; instantaneous time to contact (sec)
τ_p	phase delay parameter (secs)
$\omega_{bw\theta}$	pitch attitude bandwidth (rad/sec)
ω_n	natural frequency (rad/sec)
ζ	relative damping

1 INTRODUCTION

As a technical discipline, 'Flying Qualities' embraces those functions and technologies required to support the piloting task. As pilot-centred operational attributes, Flying Qualities are the product of a continual tension between performance and safety. These two descriptions and the interplay between them will feature as different viewpoints on the subject throughout this paper. The most obvious contributor to flying qualities are the air vehicle dynamics - the stability and control characteristics - but flying qualities are much more; they are a product of the four elements - the aircraft, the pilot, the task and the environment, and it is this broader, holistic view of the technical discipline and operational attribute that emphasises the contribution of good flying qualities to flight safety and operational effectiveness. The performance-safety tension is strongest when flying a helicopter close to the ground. A first priority for the pilot is to maintain a sufficient margin of 'spatial awareness' to guarantee safe flight. This spatial awareness has a temporal dimension; the pilot is actually trying to predict and control the future. We can imagine a pilot flying to maintain a safe time margin, avoiding obstacles and the ground, with a relaxed control strategy. The pilot may try to maintain a 10 second 'time to encounter' between his/her aircraft and any potential hazard, giving him time to manoeuvre around, climb over, or even stop if required. But external pressures can make things more difficult for the pilot, increasing workload. Imagine that the task is to transit, within tight time constraints, to deliver an underslung load to a confined forest clearing at night, with the threat of enemy action. Under relentless time pressures, the pilot has some scope for trading off performance and workload, depending on the requirements of the moment. He will be forced to fly low to avoid detection by the enemy. Increasing the tempo at low level reduces the safety margin; more precision or more agility requires higher levels of concentration on flight path guidance and attitude stabilisation. The more the pilot concentrates on flight management, the more that global situation awareness is compromised with increased risk of getting lost or becoming disconnected with the military situation. Flying qualities affect and are powerfully affected by these demands and nowadays can only be sensibly discussed in terms of mission - oriented requirements and criteria. Section 2 of the paper provides a summary of the latest military helicopter standard, Aeronautical Design Standard - 33 (ADS-33) (Ref 1).

Good stability is vital for flight in poor weather and/or low visibility. The traditional approach for flight well clear of the ground and obstacles is to refer to visual or instrument flight conditions (VMC or IMC); aircraft required to operate in IMC need to have sufficiently good stability that the pilot workload is tolerable, for example when flying on instruments in gusty conditions. For helicopters operating close to terrain in degraded visual conditions, the concept of IMC becomes rather meaningless. The pilot needs sufficient cues to guide the aircraft safely over and around features, but we might hypothesise that the level of aircraft stability required is also related to the quality of these visual cues as it is in the extreme case of IMC. The adequacy of visual cues and the relationship with aircraft stability are captured in the flying qualities standard, ADS-33 by the Usable Cue Environment (UCE) concept. Qualitatively, the worse the UCE (UCE degrades from 1 to 3), the better needs to be the stability to confer satisfactory handling qualities, and we shall expand on this later in the paper. In the case of UCE 3, the stability needs to be provided, not only for attitude changes, but also translational movement, through the so-called translational rate command response type. But a foggy moon-less night is actually much worse than UCE 3, and no amount of stability augmentation is sufficient to make manual flight safe in such conditions. Visual cue augmentation is required to transform to at least UCE 3. One way of providing this kind of augmentation is through the medium of helmet-mounted displays (HMD). HMD design requirements need to take account of both technical and human factors, the latter underpinned by the psychology and physiology of the human visual perception process. One of the current challenges within the flying qualities discipline is the integration the engineering and human science approaches to flight control. This topic will be explored further in Section 3 of this paper.

While stability is a critical flying quality for divided attention or degraded visibility operations, when flying in active, fully attentive mode, the pilot needs different flying qualities; he/she needs the aircraft to respond smoothly and precisely to commands and, in emergencies, to be able to command full dynamic performance rapidly without risk of exceeding limits. This particular form of flying quality has been described as agility (Ref 2), defined as '*the ability to adapt and respond, rapidly and precisely, with safety and poise, to maximise mission effectiveness*'. Research conducted to understand the limits to agility has highlighted deficiencies that inhibit pilots from commanding full performance in a carefree manner. In a series of flight and simulation trials at DERA (then RAE), pilots were asked to fly manoeuvres with increasing tempo until either a performance or safety limit was reached. In all cases the safety limit came first, which raised the question as to how much of the inherent performance of the aircraft was safely usable and how much reserve margin was, in effect, being wasted because it was unsafe to use ? In Refs 3 and 4 the Agility Factor was introduced as the ratio of used to usable performance, actually expressed in terms of manoeuvre time ratio. To establish the kinds of agility factors that could be achieved in flight test, pilots were required to fly current operational types with various levels of aggressiveness or manoeuvre tempo, defined by the maximum attitude angles used and rate of control application. The flight tests revealed that handling qualities rapidly deteriorate as the pilot attempts to exploit the full performance. Maximum agility factors of 0.7 were achieved with borderline Level 2/3 handling qualities, making the top 30% of dynamic performance virtually unusable, and emphasising the 'cliff edge' nature of the effects of handling deficiencies. At high agility, these deficiencies include degraded response characteristics, exacerbated by the unpredictability of the control nonlinearities, strong cross couplings, poor stability and the lack of carefree handling features, increasing the need for pilot attention to respecting airframe and engine/transmission limits an hence avoid exceedances of the operational flight envelope. Good flying qualities are sometimes thought to be merely "nice to have", but with this interpretation they actually delineate a vehicle's achievable performance. This lends a much greater urgency to defining where flying qualities boundaries should be.

Dramatic and sudden changes in flying qualities can occur following the failure of flight critical components in the powertrain or flight control system, with the ensuing risk of excursions outside the operational or even safe flight envelope. Design requirements state that all such components should have sufficient reliability or fail-safe characteristics that the chance of losing a flight critical function is extremely remote (unlikely to occur when considering the total operational life of the rotorcraft type). Nevertheless, critical components do fail (and often result in accidents), sometimes because they are not well enough maintained, or because they are subject to operational damage, or simply because the design does not meet the required level of system reliability. Flying qualities requirements in failed conditions are, on the whole, fairly generic in existing military or civil standards, except for special failure cases. Certainly, the basic performance required to be able to recover from, or land safety following engine failure, along with associated operational restrictions, are emphasised in civil standards (Refs 5, 6). The UK Defence Standard for military aircraft provides fairly stringent requirements on failure and post-failure characteristics associated with automatic flight control systems (Ref 7). ADS-33 also refers to handling criteria relating to engine and flight control system failures. A flight critical component that has received much less attention is the tail rotor. Tail rotor failures occur at an alarmingly high rate in both military and civil operations and a study conducted by DERA (Ref 8) has highlighted the absence of design guidelines and handling qualities criteria to protect against the effects of tail rotor failures, and a dearth of validated advice for aircrew on how to cope in such situations. Aspects of this work will be described in Section 3 of the paper.

Loss of control following failures, during agile manoeuvring or in degraded visual conditions represents the extreme of poor flying qualities. We can consider the same aircraft to have benign behaviour during peace-time operations in good weather during the day, the pilot regularly able to perform to desired performance standards with minimal workload at low to moderate levels of aggressiveness. Flying qualities are what the pilot experiences at the interface between the aircraft as a system and its operating environment and mission. This line of argument leads us to consider the integrated pilot-vehicle system as having flying qualities across the whole spectrum of the HQR range, depending on the situation. If we follow this concept through, the notion of average handling qualities can be postulated with a statistical distribution about this average (Ref 9). The better the average HQR, then the less chance of losing an aircraft to system or pilot failure. The designers challenge is then how to make helicopters with the best possible mean and with distributions skewed towards goodness. We shall return to this line of reasoning later in Section 4, to present results from a probabilistic analysis of handling qualities.

The paper stresses the author's conviction that greater emphasis paid to flying qualities by users when writing requirements, and manufacturers when designing and building, will reap significant rewards in terms of flight safety. Moreover, advanced 'flying qualities technologies' are maturing rapidly to the point where users and designers will no longer need to struggle quite so hard with the safety-performance compromise, which so often in current designs leaves the pilot with the difficult task of managing this nebulous tension. A premise of this paper is that providing the pilot the greatest possible assistance in the control of this tension should be a priority for the rotorcraft community.

Some readers may already have noticed the author's tendency to interchange flying and handling qualities with a degree of impunity in this Introduction. This is deliberate. While there may be good arguments for making one distinct from the other, there is no widespread agreement on this and the author chooses to elevate both to a common level where any attempt to distinguish between them would distract from the breadth and depth of the technical volume encompassed by the discipline. In this paper they mean the same.

2 FLYING QUALITIES REQUIREMENTS - THE BASICS

Fig 1 serves as the framework and guide for this general discussion on flying qualities engineering. The process begins with the user defining the required missions and environments. In the transformation from operational to technical requirements, a number of concepts are introduced. First is the concept of flying qualities Levels and the associated pilot handling qualities rating (HQR) scale developed by Cooper and Harper (Ref 10); we shall draw on relevant material developed by the author in Ref 11 in this presentation. Second, much of the structure in the new approach to flying qualities was conceived during the development of ADS-33 and a brief summary of the key elements - the mission task element, the response type and usable cue environment - will be given.

2.1 Flying Qualities Levels;

The acceptability of rotorcraft flying qualities for mission tasks is quantified in three levels;

Level 1 corresponds to good flying qualities that enable the pilot to achieve a desired level of performance, well within the margins of error for the mission task, and acceptable workload, corresponding to minimal control compensation.

Level 2 corresponds to flying qualities with tolerable deficiencies that enable the pilot to achieve an adequate performance standard, within the margins of mission task error, but possibly requiring extensive pilot compensation, hence high workload.

Level 3 corresponds to flying qualities with major deficiencies that intrude significantly on the

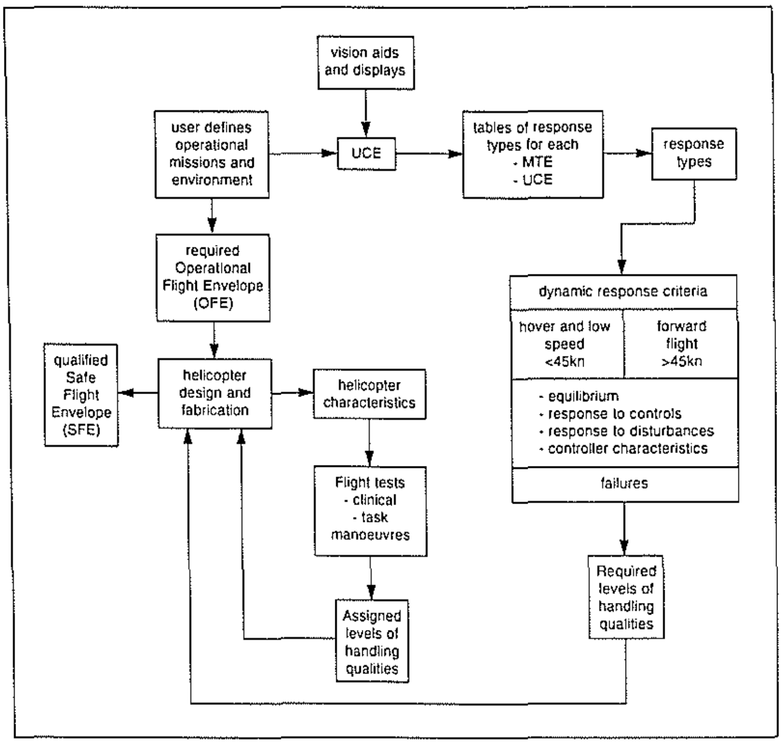

Fig 1 A Systems Approach to Flying Qualities Engineering

pilot's ability to achieve even the adequate performance standards in a mission task, with maximum tolerable control compensation. It is not possible to perform missions with an aircraft that possesses Level 3 qualities.

These levels are linked to the Cooper-Harper handling qualities rating scale as shown in Fig 2.

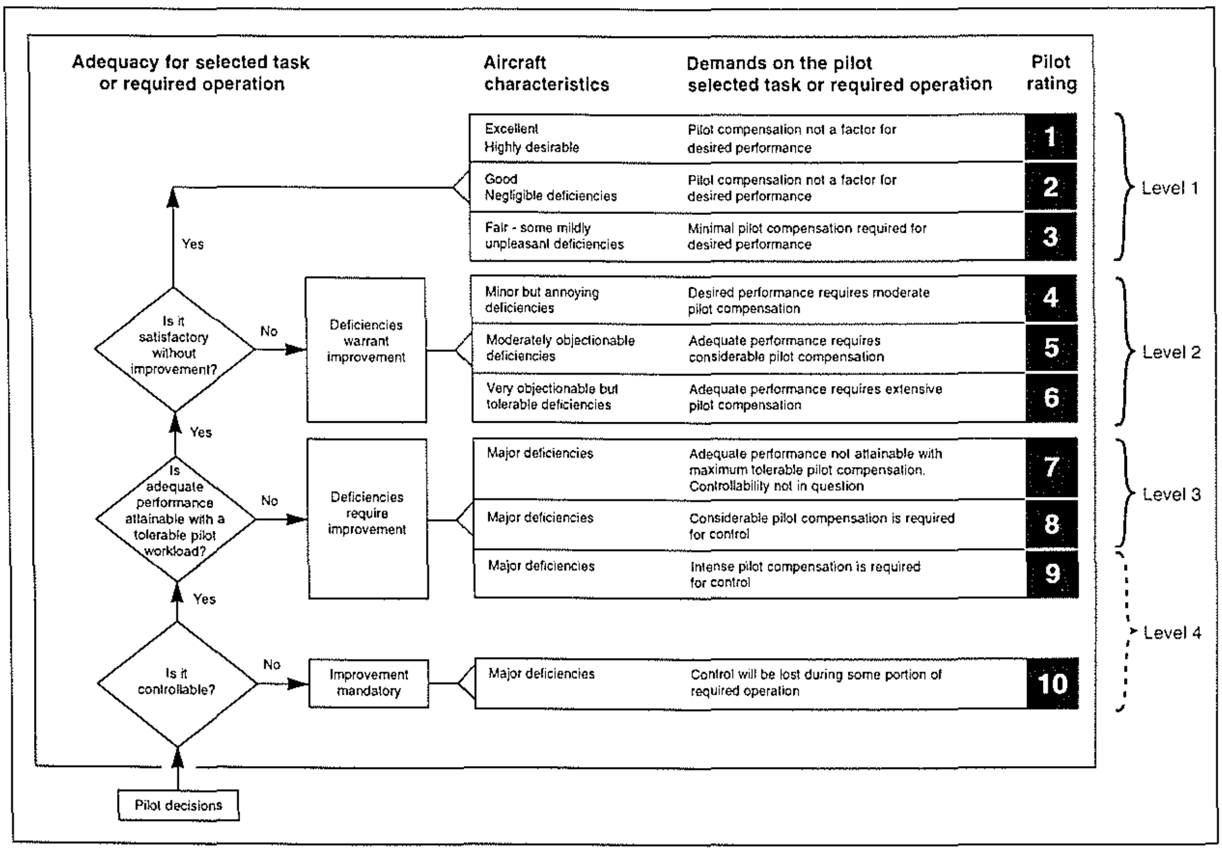

Fig 2. The Cooper-Harper Handling Qualities Rating Scale

Fig 2 actually shows 4 levels, the 4th referring to flying qualities with such major deficiencies that the pilot is likely to lose control. Such flying qualities should not feature of course, but incidents and accidents continue to occur in development programmes associated with the pilot losing control, or in operational service when critical functions fail. The HQR is a numerical summary of pilot opinion, and the HQ methodology emphasises the importance of training in the use of the HQR scale by pilots and engineers, to guard against mis-use which, unfortunately, is all too common. In Ref 11, the author attempts to encapsulate this methodology in a set of HQR application rules.

2.2 Elements of Aeronautical Design Standard-33:

The most comprehensive set of flying qualities design criteria are provided by the US Army's Aeronautical Design Standard for handling qualities - ADS-33, developed with the focused purpose that - *"The requirements of this specification shall be applied in order to assure that no limitations on flight safety or on the capability to perform intended missions will result from deficiencies in flying qualities"*. Three important innovations of ADS-33 - the Mission Task Elements (MTE), Usable Cue Environment (UCE) and Response Types - form the starting point in the constructive development of flying qualities requirements. They are closely coupled, with the MTE/UCE combinations defining the required response types and hence on through the details of the dynamic response criteria, failure criteria and so forth.

2.2.1 Mission Task Elements: For the purposes of handling qualities testing, missions can be considered to be constructed of a sequence of mission task elements (MTEs), each with defined goals in terms of flight and mission performance. A mission task element is "*an element of a mission that can be treated as a handling qualities task*" (Ref 1). Flight performance standards are defined for the test manoeuvres based on mission task constraints in terms of effectiveness (e.g. targeting accuracy) or survivability (e.g. exposure or distance from terrain/obstacles). For example, the recovery phase of a maritime helicopter mission completes with the helicopter approaching the ship, manoeuvring over the deck and touching down on the landing spot, finally to be secured to the deck. The aircraft is decelerated and brought to the hover on the port side of the ship. The pilot will then manoeuvre sideways over the deck, wait for a quiescent period in the ship motion, descend, land and engage a harpoon in the deck lock grid. Two important MTEs can be distinguished in the final phase - the approach and hover alongside, and the sidestep and landing (Ref 12), with the latter by far the most demanding on flying qualities. High sea states can result in the landing spot moving vertically and horizontally with amplitudes of several metres and frequencies as high as 1 rad/sec. The disturbed air flow over the flight deck can contain vertical and horizontal shear flows that present significant demands on power management and yaw control. In flying qualities terms there is a need for good agility during the station keeping hover in the airwake over the deck lock grid (to reduce airborne scatter), good stability during the precision landing (to reduce landing scatter) and good enough visual cues in both good and degraded visual conditions that the pilot can manoeuvre with confidence.

MTEs are the basis of stylised flight test manoeuvres (FTMs) which can, in turn, be used to develop task-oriented flying qualities criteria and also in the design and evaluations of the acceptability of new aircraft or flight systems. ADS-33 contains a list of more than 20 MTEs and a description of the associated FTMs for battlefield helicopter operations, addressing course layout, performance standards and test conduct including the capture of handling qualities ratings.

2.2.2 The UCE and Aircraft Response Type: The Usable Cue Environment concept was developed to aid the specification of the level of control augmentation required when a pilot can no longer make aggressive and precise manoeuvres due to inadequacies in visual cueing (Ref 13). The UCE is a measure of the degraded visual environment (DVE) when flying close to obstacles and surfaces, and encompasses all of the visual cues available to the pilot, both inside and outside the cockpit, both natural and synthetic. Recognition of the interaction between the sufficiency of piloting cues and rotorcraft response characteristics is a cornerstone of the systems approach to flying qualities. In ADS-33, the UCE is employed to define the required control response type to provide acceptable handling qualities for different MTEs in a DVE. For example, flying a precision vertical landing in UCE1, Level 1 handling can be achieved with a rate command (RC) response type. If the UCE degrades to 2, attitude command with attitude hold (ACAH) is required for Level 1 handling. The highly augmented translational rate command with position hold (TRCPH) is required in UCE3. In a nutshell, high levels of stability augmentation allow the pilot to concentrate on the guidance task, and with firm TR stability, workload in re-positioning tasks is greatly reduced.

As shown in Fig 3, the UCE is divided into three ranges where 1 is good, 2 is fair and 3 is poor.

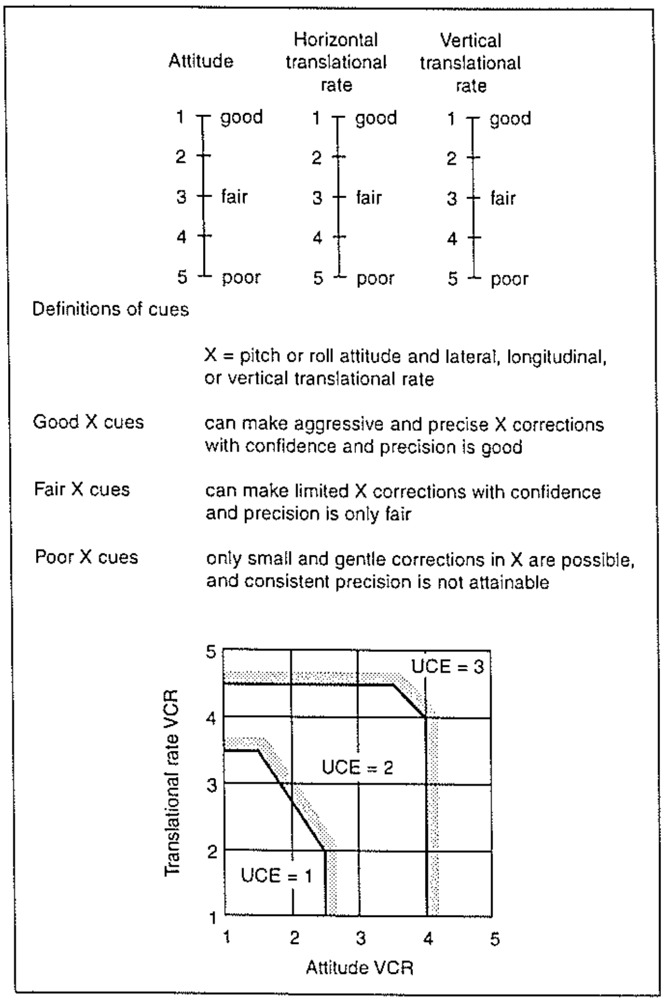

Fig 3. The Useable Cue Environment Chart

The UCE is determined for a given MTE in the DVE from a subjective evaluation of the cueing environment in terms of the pilot's ability to accomplish aggressive and precise manoeuvres. An important assumption in the UCE methodology is that the aircraft possesses Level 1 flying qualities in the good visual environment (GVE). This should not be a surprise, and points to the need to ensure that the design first matches the GVE handling requirements. The process by which the UCE is determined involves obtaining Visual Cue Ratings (VCRs) from pilots for particular MTE/DVE combinations. The VCR scale is designed to calibrate the usability of all available visual cues on a scale of 1 to 5, where 1 is good, 3 is fair and 5 is poor as indicated on Fig 3. To determine the UCE, VCRs are recorded for attitude, horizontal translational rate and vertical translational rate. Individual worst ratings for each 'axis' are sorted and averaged across a group of test pilots, to be applied to the chart in Fig 3.

Determining the UCE for the user-defined missions and environments is important for establishing the level of control augmentation and hence the required Response Types. Fig 4 summarises the ADS-33 response type table for the shipborne landing task, and although these requirements were determined from a read-across from battlefield mission task elements, more recent research into handling qualities for maritime helicopters has so far validated this read-across . They show that TRCPH is required in a UCE 3, but that the designer could reduce the level of augmentation to ACAH if Level 2 standards were acceptable for these conditions (e.g. if they were considered to occur sufficiently infrequently that designing for this worst case was not warranted) or if only UCE 2 was expected with the required operating conditions and technology assumptions. The response type drives the flight control system architecture and hardware/software, including the sensor suite requirements. The maritime helicopter recovery MTEs bring out the point that handling qualities improvements can be achieved by either providing greater vision augmentation, hence upgrading the UCE, or providing enhanced control augmentation at the degraded UCE.

	Control Axis	UCE 1	UCE 2	UCE 3
Level 1 HQ	Pitch	RC	ACAH	TRCPH
	Roll	RC	ACAH	TRCPH
	Yaw	RC	RCDH	RCDH
	Heave	RC	RCHH	RCHH
Level 2 HQ	Pitch	RC	RC	ACAH
	Roll	RC	RC	ACAH
	Yaw	RC	RCDH	RCDH
	Heave	RC	RC	RCHH

RC - Rate Command Response Type
ACAH - Attitude Command Attitude Hold Response Type
RCDH - Rate Command Direction (Heading) Hold
RCHH - Rate Command Height Hold
TRCPH - Translational Rate Command (Horizontal) Position Hold

Fig 4. Response Type Requirements in Different UCEs for the Deck Landing Task according to ADS-33

The UCE and Response Type form a framework for higher level requirements on flying qualities. They can drive the technology of pilotage systems. They also open the door to developing requirements at the most detailed level for dynamic response criteria.

<u>2.2.3 Dynamic Response Criteria:</u> Dynamic Response Criteria (DRC) define flying qualities of the aircraft responses to controls and disturbances, both on-axis and off-axis cross coupling, as well as trim characteristics, typically in the form of two-parameter diagrams divided into Level 1, 2 and 3 regions. For the purposes of defining DRC, ADS-33 treats the helicopter operational flight envelope in two regions - the low speed/hover region up to 45kn ground speed (particularly nap-of-the-Earth and flight close to obstacles), and forward flight, at speeds in excess of 45kn ground speed. Aircraft dynamic response can be divided into areas on a frequency-amplitude chart as shown by the central diagram in Fig 5.

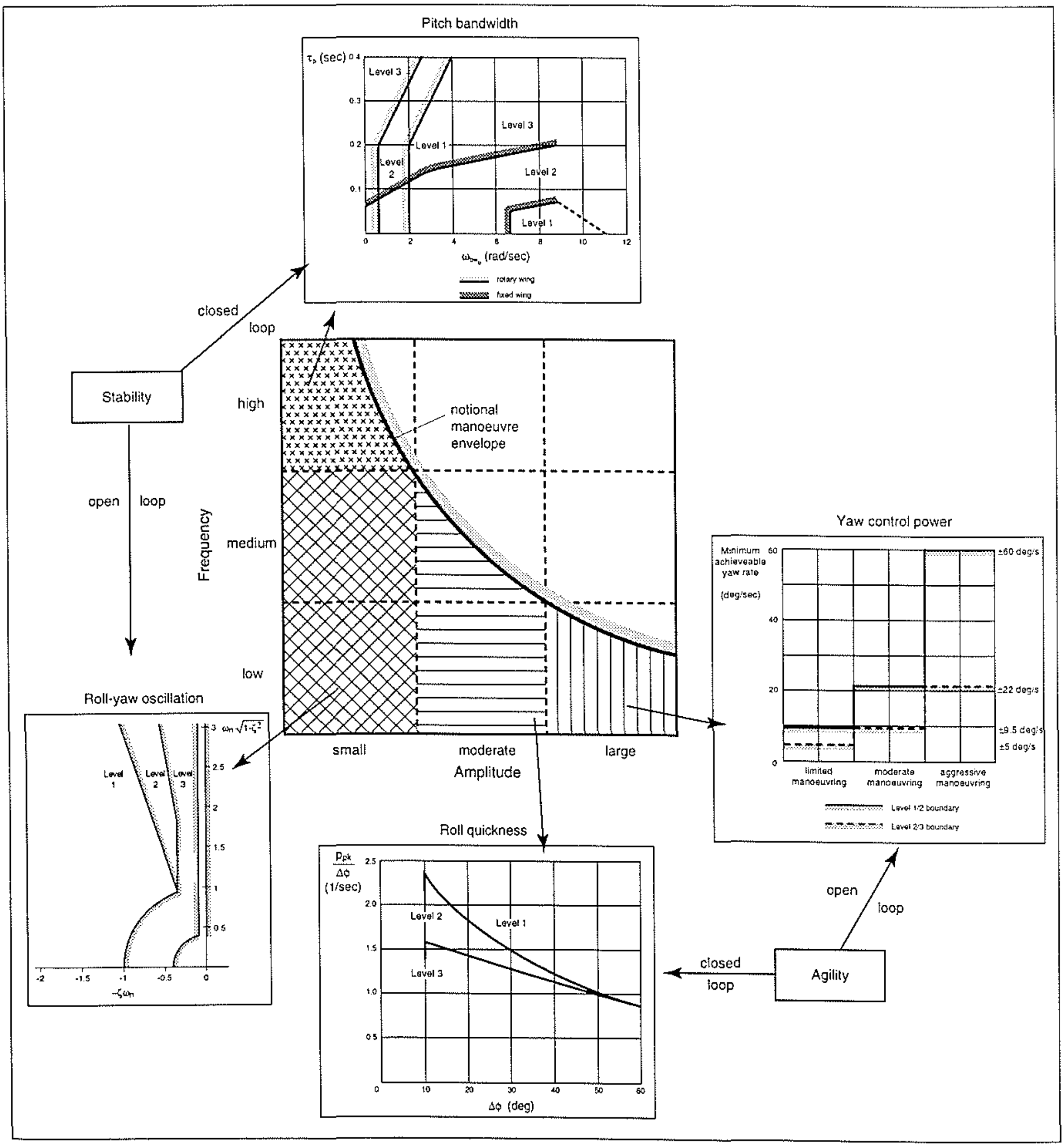

Fig 5. Dynamic Response Criteria on the Frequency-Amplitude Manoeuvre Chart

The manoeuvre envelope line is drawn to limit criteria to practical manoeuvres, whereby the achievable amplitude reduces as frequency increases. Within this envelope, 4 areas can be distinguished - 2 dealing with stability criteria and 2 dealing with agility criteria as shown. The outer diagrams on Fig 5 give examples of 2-parameter handling qualities charts, themselves divided into quality levels.

Response Power; Large amplitude manoeuvring is characterised by control power and the example shown on the right side of Fig 5 relates to the low speed/hover yaw control power requirements for a rate command response type. For example, if the mission requirements demand an aggressive yaw manoeuvre capability, then the aircraft must be capable of at least +/- 60 deg/sec yaw rate.

Response Quickness; One of the innovations of the rotorcraft flying qualities research that fed into ADS-33, the attitude quickness parameter, shown on the lower-middle chart in Fig 5, defines moderate amplitude handling requirements. Defined as the ratio of peak attitude rate (p_{pk}) to attitude change ($\Delta\phi$) achieved during a sharp attitude-change manoeuvre (e.g. in response to a pulse control input with a rate response type), quickness is a measure of short-term agility. The roll quickness boundaries for target acquisition and tracking tasks illustrated, are defined across the moderate amplitude range; the boundaries are lowered for more general manoeuvres (Ref 1). In the small amplitude response range (e.g. roll angles < 10deg), flying qualities are determined more by stability than agility and, to maintain continuity, we first discuss requirements on closed-loop stability, and refer to the top chart on Fig 5.

Response Bandwidth; Quickness is actually a hybrid time/frequency domain parameter, having units of frequency but extracted from time responses. It links the pure, time domain, control power with the frequency domain 'bandwidth' parameter. Response bandwidth (ω_{bw}) defines the upper end of the frequency range where the pilot can close the loop on a particular motion without having to apply significant lead to avoid closed-loop instability. In this context, helicopters are particularly susceptible to so-called pilot-induced oscillations (PIO) in high gain tracking tasks, because of the dynamic coupling between the fuselage and the rotor system. Another important effect is the shape of the response phase above the bandwidth frequency; if this is too steep then the aircraft will be even more PIO prone; phase delay (τ_p) is the complementary parameter on the pitch attitude bandwidth chart in Fig 5. Bandwidth and phase delay parameters therefore define flying qualities in terms of closed-loop stability. Discussion on the development of the bandwidth parameter for ADS-33 is given in Ref 11. On Fig 5, boundaries for bandwidth and phase delay are shown for pitch axis tasks in the target acquisition and tracking category. Also shown are corresponding boundaries for fixed-wing aircraft in category A flight phases including air combat (Ref 14, alternate criteria for non-classical response types). The differences in the requirements are striking. The fixed-wing Level 1/2 boundaries are typically set at bandwidths two to four times those for helicopters and the phase delay boundaries are set much lower for fixed-wing aircraft. Both of these differences reflect the different character of the rotary and fixed-wing aircraft dynamics and MTEs, the latter also a reflection of the different speed ranges over which the aircraft operate. It is no coincidence that fixed-wing air combat typically takes place at speeds three to four times those envisaged for rotary-wing aircraft with similar differences in target closure ranges and rates. Not only is the higher bandwidth required to enable the pilot to track effectively, but the higher speeds in fixed wing combat provide the aerodynamic forces to achieve the higher bandwidth. It would be very difficult, if not impossible, to engineer the 6 rad/sec capability for rotorcraft manoeuvring at 100kn !

Mid-Long Term Stability; The lower left chart on Fig 5 shows the frequency/damping requirements for roll-yaw oscillations in forward flight. Fairly strong relative damping is required in all axes, particularly for flight in a degraded visual environment or when the pilot's attention is divided between flight and other functions. Achieving 35% critical damping requires artificial stabilisation with moderate feedback gains, particularly for flight through turbulence or strong wind shear. The requirements are again drivers on the flight control augmentation system, and call for careful design of the interface between any autopilot functions designed to confer automatic guidance, and the stability augmentation system, to minimise any negative flying qualities arising from actuator saturation. Careful aerodynamic design of the fuselage and empennage can also ameliorate adverse effects on natural stability in forward flight.

2.3 The Basics Re-emphasised;

Getting the basics right is the most important step in the control of the performance-safety tension. For the first time in the history of helicopter development, comprehensive and substantiated criteria for how helicopters should fly to exhibit Level 1 qualities are available. Recent efforts have been directed at providing guidance on tailoring ADS-33 for specfic applications (Ref 15). New projects and type upgrades can benefit from this by integrating the criteria into the design process. However, getting the basics right, while necessary, is not sufficient to ensure that the tension does not become too strong for the pilot to control; criteria for degraded flying qualities are also required.

3 DEGRADED FLYING QUALITIES REQUIREMENTS

Level 1 flying qualities should enable a pilot to achieve desired performance with ample safety margin in normal operations. But the performance-safety tension can get stronger and the intimate link between pilot and safe operations/machine can weaken and ultimately break in the presence of degraded flying qualities. We shall consider two areas where degraded flying qualities can threaten flight safety - loss of spatial awareness in degraded visual conditions and failures of flight systems.

3.1 Flying Qualities in Degraded Visual Environments (DVE)

In the drive to 'weather-proof' flight operations, future rotorcraft will be required to perform roles in more severely degraded visual conditions than is currently possible with safety. This Section makes the point that improving flying qualities for flight in a DVE is about the integration of vision and control augmentation. The UCE was introduced earlier as a concept for describing the utility and adequacy of visual cues for guidance and stabilisation. The pilot rates the visual cues based on how aggressively and precisely corrections to attitude and velocity can be made. An assumption in this approach is that the aircraft has Level 1 RC handling qualities in a good visual environment. In a DVE, the handling qualities of the aircraft degrades because of the impoverishment of the visual cues; handling qualities in the conventional sense remain good, but there is now a risk that the pilot may fail to maintain the conditions for safe flight. According to the UCE methodology of ADS-33, provided the DVE is no worse than UCE 3, then Level 1 handling qualities can be 'recovered' by control augmentation. The augmentation process therefore appears straightforward, at least in principle, as illustrated in Fig 6 - recover to UCE 3 or better via vision augmentation, then use an appropriate and harmonised mix of control and display augmentation to recover to Level 1 flying qualities.

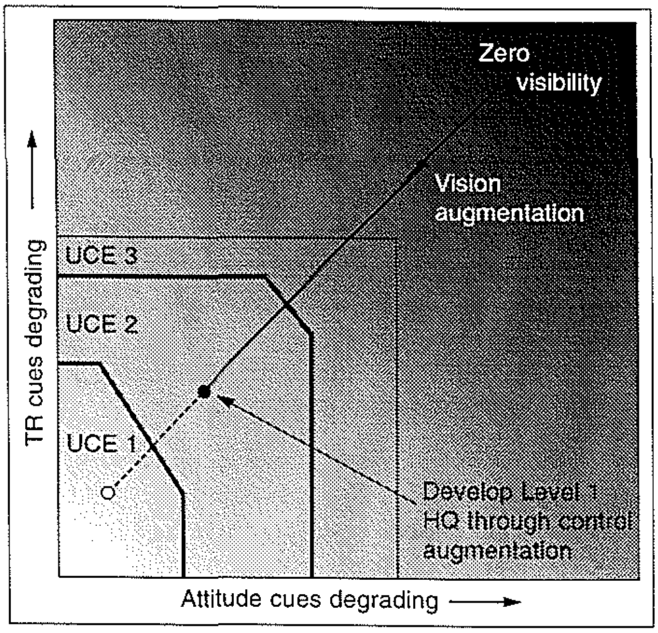

Fig 6. Conceptualised Requirements for Integrated Vision-Control Augmentation

The requirements for control augmentation were discussed in Section 2. Recovering the UCE through vision augmentation is about improving spatial awareness for the pilot. Research on this topic is required to establish relationships between the pilot's visual cue ratings, features in the visual scene and the pilot's control strategy. The two components of a pilot's VCR reflect the adequacy of cues for flight guidance (translational rate) and flight stabilisation (attitude), which can also be thought of as the two dimensions of spatial awareness. While our previous discussions on response types and dynamic response criteria have centred around the vehicle and its input and output characteristics, when addressing spatial awareness, we have to face the most uncertain and adaptable element of the system and the whole flying qualities subject - the pilot and his/her visual system. To understand more about what makes up the UCE/VCR and how the pilot organises visual information, we need to understand the human science of visual perception in flight control.

One of the earliest published works on visual perception in flight control presented a mathematical analysis of 'motion perspective' as used by pilots when landing aircraft (Ref 16). The first author of this work, James Gibson, introduced the concept of the optical flow and the centre of expansion when considering locomotion relative to, and particularly approaching, a surface. Gibson suggested that the *"psychology of aircraft landing does not consist of the classical problems of space perception and the cues to depth."*. In making this suggestion, Gibson was challenging conventional wisdom that piloting ability was determined by the sufficiency of linear/aerial perspective and parallax cues. Gibson had already introduced the concept of motion perspective in Ref 17, but in applying it to flight control he laid the foundation for a new understanding of spatial awareness. To quote from Ref 16, *"Speaking in terms of visual sensations, there might be said to exist two distinct characteristics of flow in the visual field, one being the gradients of 'amount' of flow and the other being the radial patterns of 'directions' of flow. The former may be considered a cue for the perception of distance and the latter a cue for the perception of direction of locomotion relative to the surface."*

The flight variables of interest when flying nap-of-the-Earth or close to obstacles are encapsulated in the definition of performance requirements in the ADS-33 flight manoeuvres - speed, heading, height above surface, flight path accuracies etc. In visual perception parlance these have been described as ego-motion attributes (Ref 18) and key questions concern the relationship between these and the direct optical variables, like Gibson's motion perspective. If the relationships are not one-to-one then there is a risk of uncertainty when controlling the ego-motion attribute. Also, are the relationships consistent and hence predictable ? In the following discussion, we draw on selected research results within the framework of a set of three optical variables considered critical to recovering a safe UCE for helicopter NoE flight - optical flow, time to contact and differential motion parallax.

<u>3.1.1 Gibson's Optical Flow Streaming:</u> Fig 7, from Ref 19, illustrates the optical flowfield when flying over a surface at 3 eyeheights per second (corresponds to fast NoE flight - about 50kn at 30 feet height - or a running person). The eye-height scale has been used in human sciences because of its value to deriving body-scaled information about the environment during motion. Each flow vector represents the angular change of a point on the ground during a 0.25 sec snapshot. Inter-point distance is one eyeheight. The scene is shown for a limited field-of-view window, typical of current helmet-mounted-displays. A 360deg perspective would show flow vectors curving around the sides and to the rear of the aircraft (see Gibson, Ref 17). The centre of optical expansion is on the horizon. If the pilot were to descend, the centre of optical expansion would move closer to the aircraft, in theory giving the pilot a cue that his/her flight trajectory has changed.

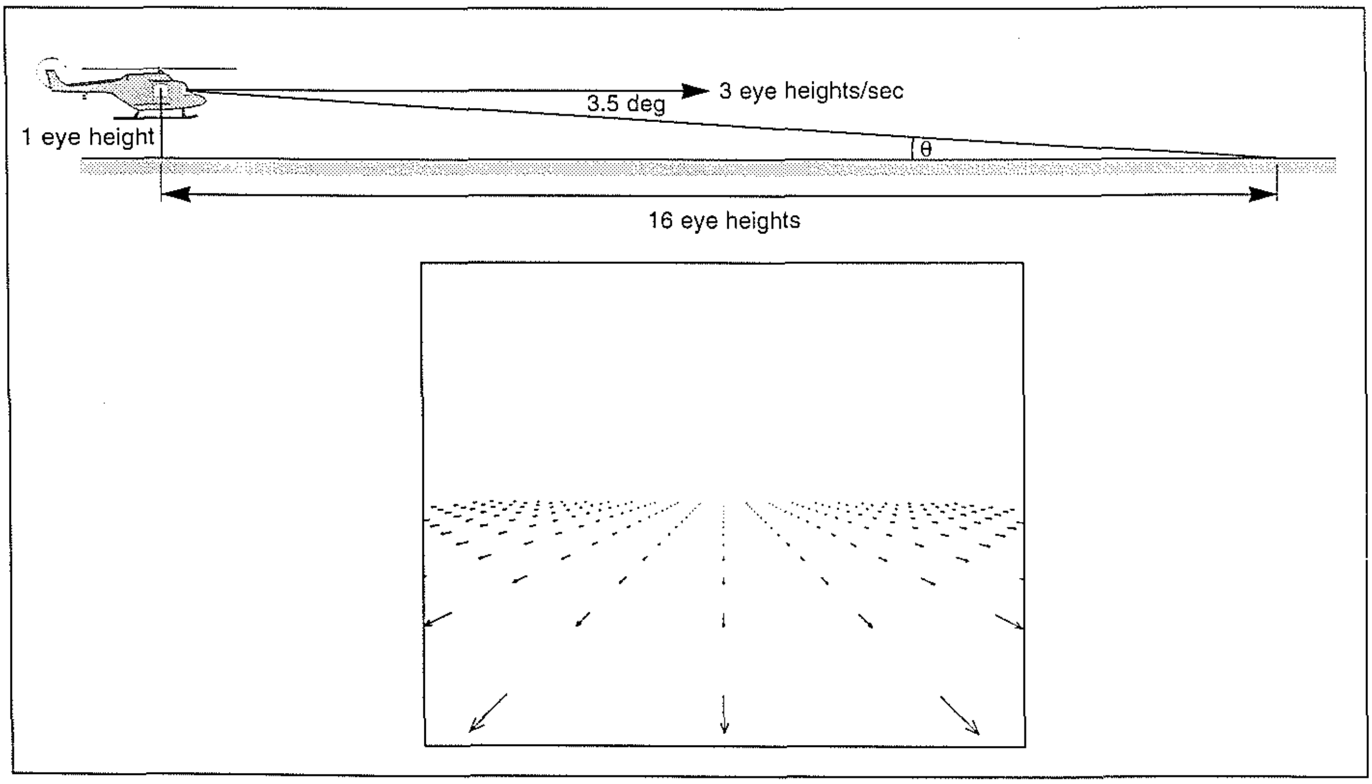

Fig 7. Optical Flowfield for Motion over a Flat Surface (speed 3 eye heights/sec, snapshot 0.25sec)

The length of the flow vectors give an indication of the motion cues available to a pilot; they appear to decrease rapidly with distance. If we consider the median plane, the angular velocity of points ($d\theta/dt$) is given by;

$$d\theta/dt = -dx/dt\ (z/(x^2 + z^2)) \qquad (1)$$

where θ is the elevation angle, dx/dt is the horizontal velocity, and z is the height of the observer. Velocity is seen to fall off as the square of the distance from the observer. Fig 8, also from Ref 19, shows how the velocity, in mins of arc/sec, varies with distance for an eyepoint moving at 3 eye-heights per sec.

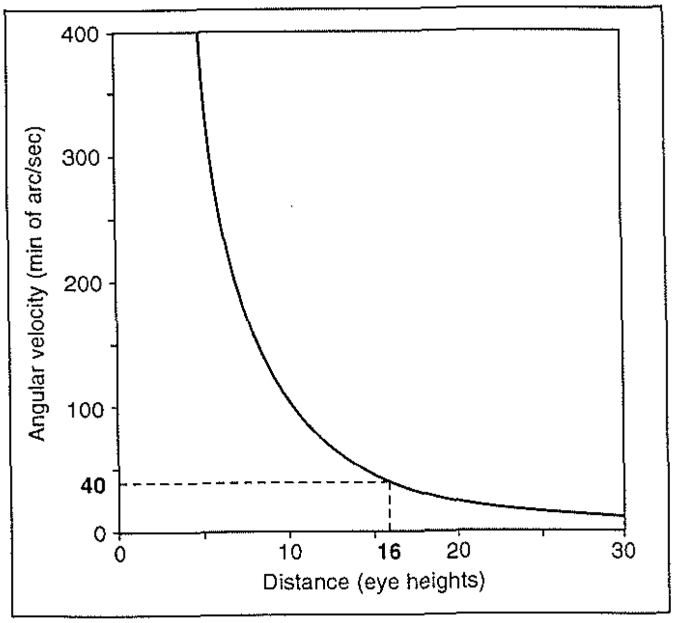

Fig 8. Angular Velocity vs Distance along Ground Plane

In Ref 19, Perrone suggests that a realistic value for the threshold of velocity perception in complex situations would be about 40 min arc/sec. On Fig 8, this corresponds to information being sub-threshold at about 15-16 eyeheights distant from the observer (viewing depression angle of about 3.5deg). To quote from Ref 19, "*This is the length of the 'headlight beam' defined by motion information alone. At a speed of 3 eye-heights/sec, this only gives about 5 seconds to respond to features on the ground that are revealed by the motion process.*" The value of optical streaming for the detection and control of speed and altitude have been discussed in a series of papers by Johnson et al (Refs 18, 20-22). Flow rate and texture/edge rate are identified as primary cues. In Ref 18 Johnson draws attention to the need for research into the connection between optical variables and environmental attributes, which would assist in the design of augmentation systems for UCE recovery. Velocity cues can be picked up from both fovial and ambient or peripheral vision. A problem with ambient information is the significant degradation in visual acuity as a function of eccentricity. The fovea of the human eye, where there is a massive concentration of visual sensors, has a field of regard of less than 1 deg (a thumb's width at arm's length). The visual acuity at 20deg eccentricity is about 15% as good as the fovea for resolution, although Cutting points out that this increases to 30% for motion detection (Ref 23). Cutting also observes that the product of motion sensitivity and motion flow (magnitude of flow vectors) when moving over a surface is such that "*the thresholds for detecting motion resulting from linear movement over a plane are roughly the same across a horizontal meridian of the retina*". This is good news for pilots and provides a natural strategy for pilots to locate the direction of motion - find the direction where stimulation is most uniform across the retina. It is interesting to reflect that, how well this capability is 'programmed' into an individual's perceptual system, may be a determining factor on piloting skill.

Perrone goes on to discuss the question of how pilots might infer surface layout, or the slants of surfaces, ahead of the aircraft. This is particularly relevant to flight in a DVE where controlled flight into terrain is a major hazard and still all too common. The correct perception of slope is critical for achieving 'desired' height safety margins for flight over undulating terrain, and hence for providing good visual cue ratings for vertical translational rate for example. Fig 9 illustrates the flowfield when approaching a 60deg slope hill about 8 eye-heights away. The centre of optical expansion has now moved up the slope and the motion cues over a significant area around this are very sparse. If the pilot wants to maintain gaze at a point where the motion threshold cuts in (e.g. 5 secs ahead) he will have to lift his or her gaze, and pilots will tend to do this as they approach a hill.

However, any vision augmentation system that tries to infer slope based on flow vectors around the centre of expansion is likely be fairly ineffective because of the sparsity of information. In Ref 24 a novel vision augmentation system was proposed for aiding flight over featureless terrain at night. An obstacle detector system was evaluated in simulation, consisting of a set of cueing lights, each with a different look-ahead time, presenting a cluster of spots to the pilot of the light beams on the terrain ahead of the aircraft. As altitude or the terrain layout ahead

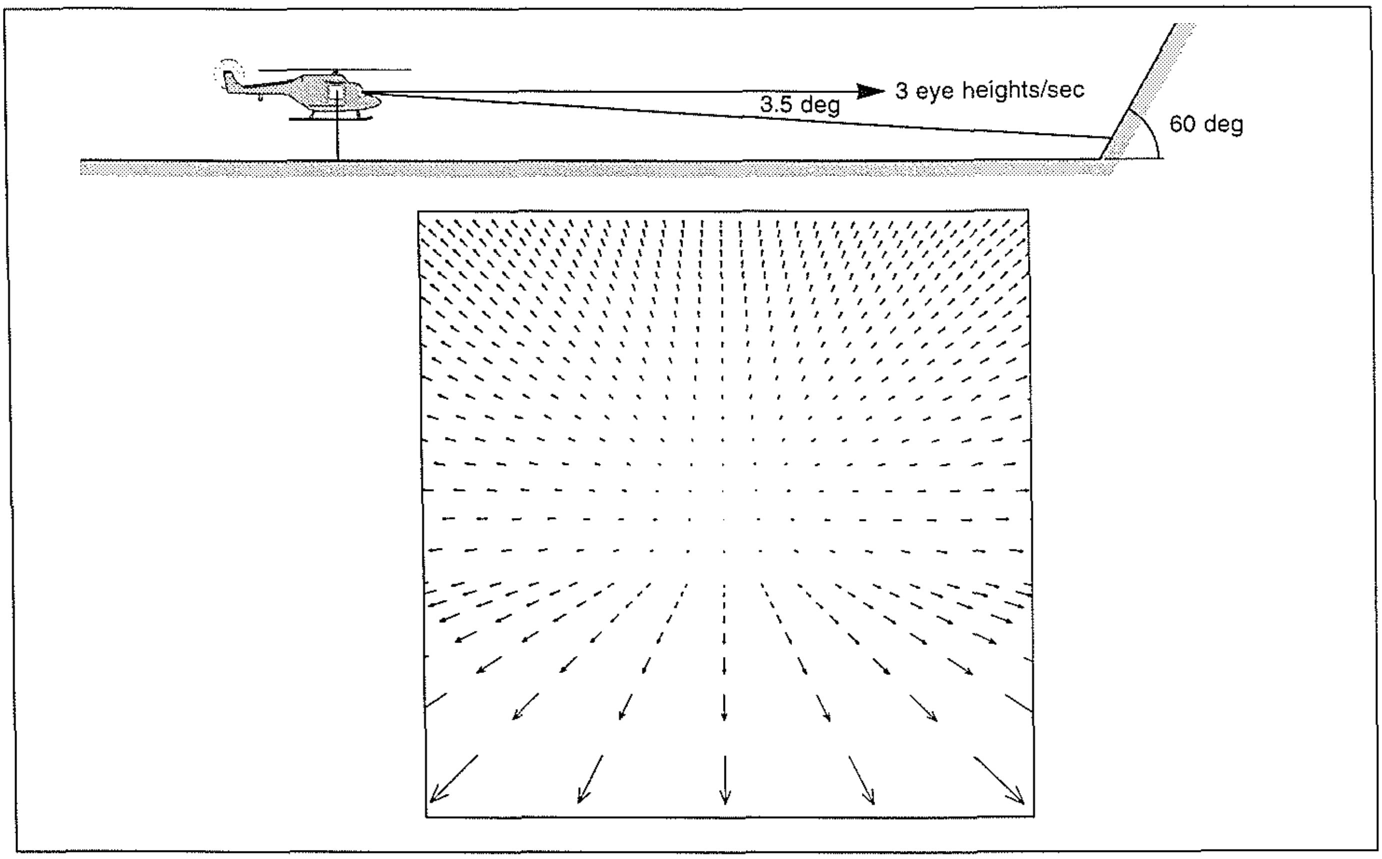

Fig 9. Optical Flowfield approaching a 60deg Slope

changed, so the cluster changed form, providing the pilot with an 'intuitive spatial motion cue' to climb or descend. This research points to useful ways of providing pilots with minimal surface layout cues in a cost-effective manner.

The optical flowfield is ubiquitous in motion suggesting that a fundamental design principle for good vision augmentation is to overlay the optical flowfield onto the required flight trajectory. However, the scarcity of information in the optical flow streams in the direction of flight can significantly impact on the pilot's ability to control two of the most important ego-motion attributes, particularly when flying in a cluttered environment where obstacle avoidance is critical to safety - rate of closure towards, and safe path through, obstacles.

3.1.2 Lee's Time to Contact; A clear requirement for pilots to maintain safe flight is that they are able to predict the future trajectory of their aircraft far enough ahead that they can stop, turn or climb to avoid a hazard. In a series of papers, Lee has advanced a development of Gibson's optical flow concept with emphasis on temporal optical variables, particularly the time to contact variable $\tau(t)$ and its derivatives (Refs 25-29). Lee makes the fundamental point that an animal's ability to determine the time to pass or contact an obstacle or piece of ground does not depend on explicit knowledge of the size of the obstacle, its distance away or rate of closure towards it. The ratio of the size to rate of growth of the image of an obstacle on the pilot's retina is equal to the ratio of distance to rate of closure, as shown in Fig 10, and given by the equation,

$$\dot{X}(t)/V = r(t)/v(t) \tag{2}$$

where X(t) and V are the distance and speed to approach and r(t) and v(t) are the size and expansion rate of the image on the retina, defined as a unit of distance behind the lens. The ratio in equation (2) is the elapsed time before the obstacle is reached if the speed V were constant. Lee designated this time to contact, or optical 'looming' variable, $\tau(t)$, and hypothesised it as a fundamental optical variable that animals have evolved to use, featuring properties of simplicity and robustness; the brain does not have to apply computations with the more primitive variables of distance or speed. Ref 25 also makes the point that this time to contact information can readily be body scaled in terms of eye-heights, using a combination of surface and obstacle $\tau(t)$'s, thus affording animals with knowledge of, for example, obstacle heights relative to themselves.

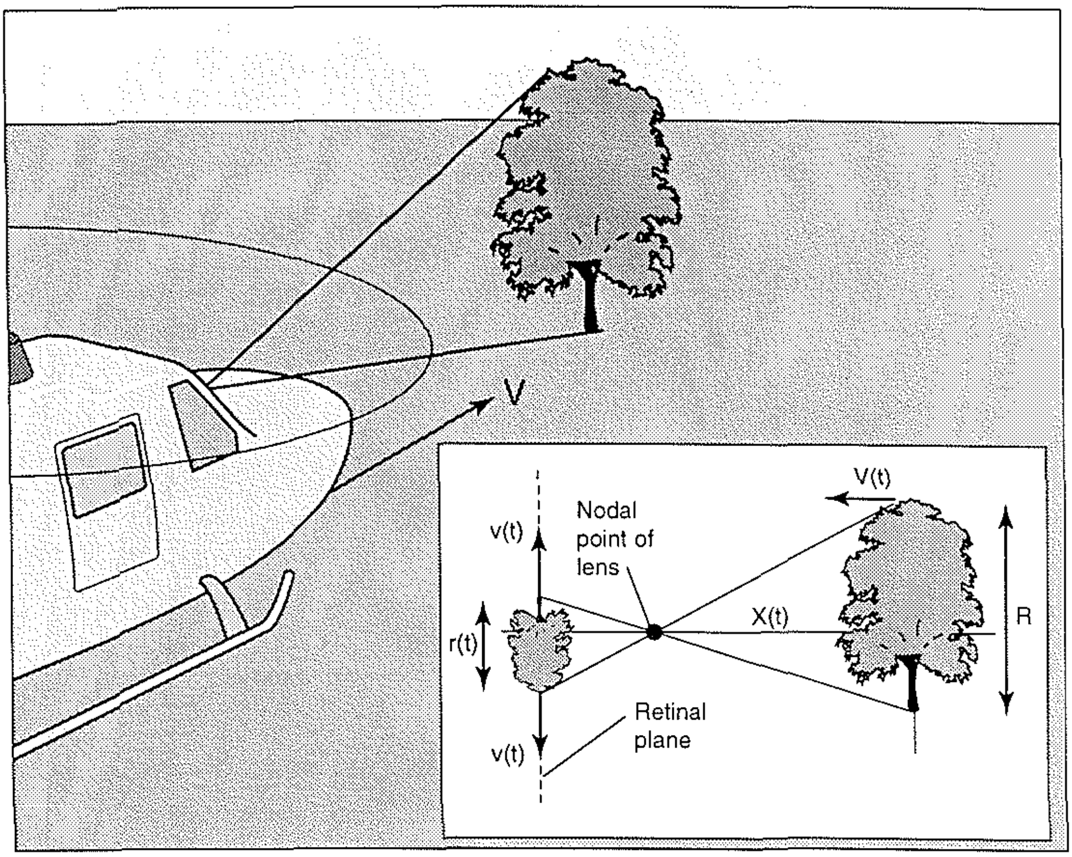

Fig 10. The Growth of an Obstacle Image on the Pilot's Retina

This is also useful to a helicopter pilot flying NoE. Lee has applied his concepts to develop an improved understanding of how animals control their motion and humans control vehicles. A particular interest is how a driver or pilot avoids getting into a crash state (or animals alight on obstacles). A driver approaching an obstacle, distance X(t), with velocity V needs to apply a braking (deceleration) strategy that will avoid collision. Lee shows that this corresponds to maintaining the rate of change of optical $\tau(t)$ less than a critical value (Refs 25, 29),

$$d\tau(t)/dt < 0.5 \qquad (3)$$

A constant braking strategy results in $d\tau(t)/dt$ progressively decreasing with time and the driver stopping short of the obstacle, unless $d\tau(t)/dt = 0.5$ when the driver just reaches the destination. Data discussed by Lee indicates that drivers typically adopt a braking strategy such that $d\tau(t)/dt$ is constant at a value of 0.425, which requires braking hard for the first phase of the manoeuvre and easing off as the destination is reached. Helicopter pilots (and presumably flying animals) find this strategy impossible because the amount of decelerative force that can be generated by the rotor (or by a bird's wing) in a constant height quickstop manoeuvre reduces as forward speed increases, because of rotor over-speeding problems (or wing loading problems in the case of the bird). Pilots therefore have to adopt a different strategy and will also be significantly influenced by the need to pitch up to decelerate, degrading the visual cues and hence UCE in the final phase of an accel-decel manoeuvre. Lee's hypothesis that optical $\tau(t)$ and $d\tau(t)/dt$ are the variables that evolution has provided humans and animals with the ability to detect and rapidly process, suggests that these should be key variables to guide the design of vision augmentation systems. In Ref 28, Lee extends the concept to the control of rotations (angular as oppose to linear $\tau(t)$) related to how somersaulters land on their feet. For helicopter manoeuvring, this can be applied to the control of turn rate, time to turn through heading, etc., thus providing direct connection with another fundamental component of ego-motion. Ref 30 discusses the application of Lee's optical $\tau(t)$ to flight control, concurring with its value in maintaining a "*window of safe manoeuvrability*"; Ref 30 also highlights a degenerate case of 'time to collide' when two objects are moving towards each other on different tracks. Angular $\tau(t)$ remains constant which can mislead a pilot that there is not a dangerous situation until the linear looming effect comes into play; such situations are particularly dangerous at night and when the looming is the result of the combined velocities of two aircraft on a collision course.

Finally in this discussion on time to contact variables, Fig 11 shows a sample of results from a DERA trial on the Advanced Flight Simulator (Ref 31). The research is aimed at developing measures of effectiveness for pilotage systems to aid helicopter flying qualities in low level flight particularly in degraded visual conditions. Fig 11 shows the track of the helicopter being flown through an undulating, wooded terrain (dark areas are woods, contours are at 10ft intervals) in good visual conditions. The pilot is flying between 50 and 70kn, at heights between 50ft and 10ft above the ground. The tangents and end circles show points during the manoeuvre where 'linear' $\tau(t)$ falls below 10 seconds. In the Introduction to this paper, we suggested 10 seconds as a possible safety margin that pilots may choose to adopt to give adequate situation awareness. Fig 11 shows that linear τ falls below 4 seconds during the first turn through the gap in the trees; the collision in this region would be with the trees themselves. At about 10 seconds into the manoeuvre, τ again falls to about 3 seconds, as the pilot approaches the rising ground in the middle of the Figure. Finally, as the narrow gap in the trees is negotiated, τ falls to below 2.5 seconds. This manoeuvre was flown with a moderate level of tempo by a test pilot using the trees for tactical cover. Was the flight unsafe ? The margins for error appear very low according the τ analysis, yet the pilot felt in control of the situation throughout; but was he aware of the low values of linear τ ? These questions need to be addressed in the context of research into vision augmentation for recovering UCE.

In a cluttered environment, a particular optical variable provides important information on motion - parallax, or the motion of objects relative to one another. Cutting has developed this in his theory of 'Directed Perception' to differential motion parallax (Ref 23), the third topic in this study of visual perception in flight control.

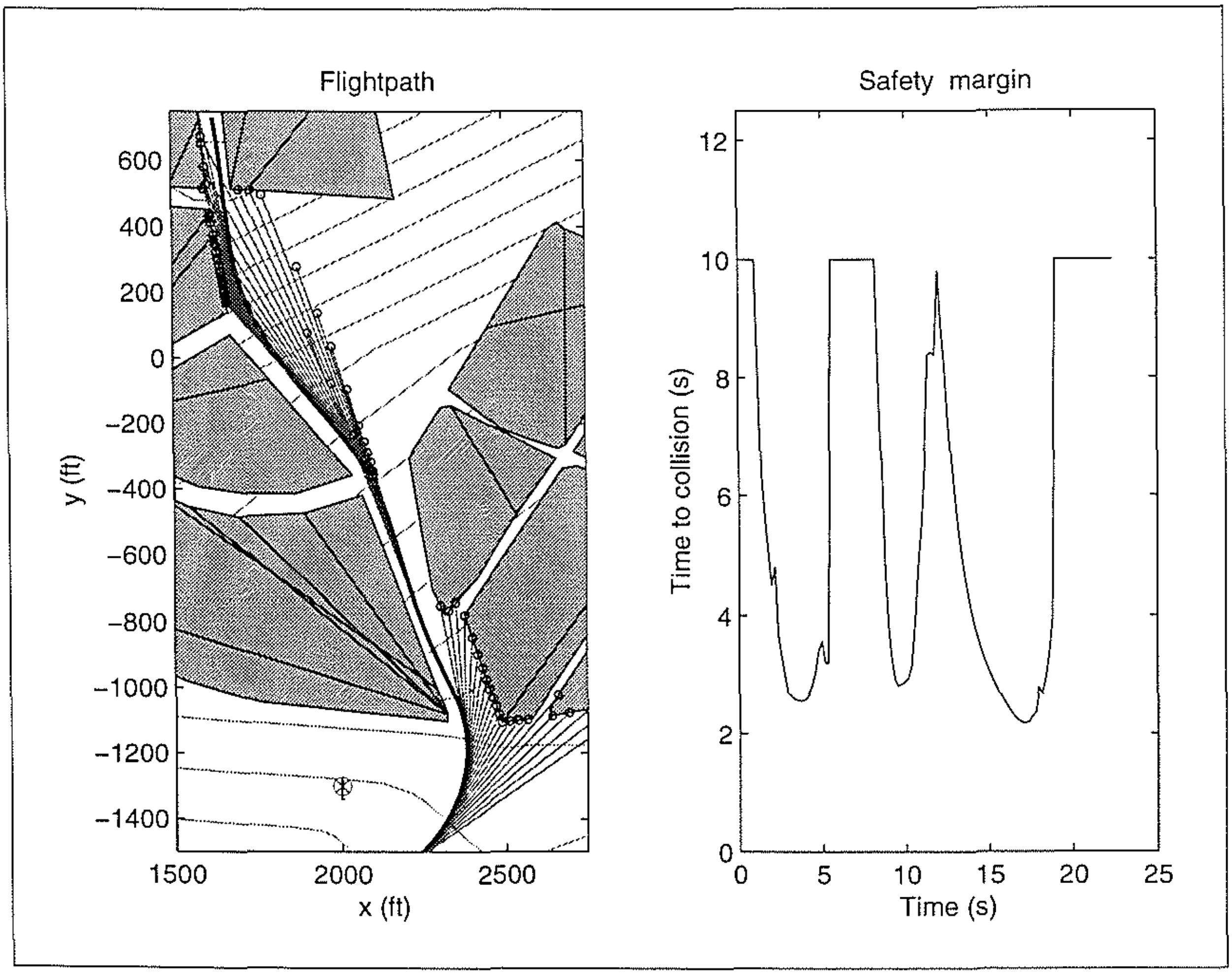

Fig 11. Time to Contact Analysis for Helicopter Flight Through a Cluttered Environment

3.1.3 Cutting's Directed Perception and Differential Motion Parallax; In Ref 23, and later in Ref 32, Cutting introduced the notion of directed perception. He developed the optical flowfield concept, arguing that people and animals make more use of the retinal flowfield, fixating with the fovea on specific parts of the environment and deriving information from the way in which surrounding features move relative to that point on the retina. In this way the concept of differential motion parallax (DMP) was hypothesised as the principal optical variable used for wayfinding in a cluttered environment. Fig 12 illustrates how motion and direction of motion can be derived from DMP. The helicopter is flying through a cluttered environment. The pilot fixates his/her gaze on one of the obstacles (to the left of motion heading) and observes the motion parallax effects on objects closer and farther away. Objects farther away move to the right and those close in move to the left of the gaze (as seen on the retinal array). The pilot can judge which objects are closer and further away by the relative velocities. Fig 12 indicates that closer objects move more quickly across the line of gaze. As with optical τ, there is no requirement to know the actual size or distance of any of the objects in the clutter. The pilot can judge from this motion perception that the direction of motion is to the right of the fixated point. He can now fixate on a different object. If objects further away (slower movements) move to the left and those close by (faster movements) move to the right, then he will perceive that motion is to the left of the fixated object. By applying a series such fixations the pilot will be able to keep updating his/her information about direction of motion, and home in on the true direction with potentially great accuracy (the point where there is no flow across the line of gaze). In Ref 23, Cutting observes that safe driving (horizontal) and safe landing (vertical) both require direction perception/control accuracies of about 1 deg; in higher performance situations, for example racing cars and deck landings of helicopters, required accuracies might need to be 0.5 deg or better. DMP does not always work however, as Cutting points out, e.g., in the direction of motion itself or in the far field, where there is no DMP, or in the near field, where DMP will fail if there are no objects nearer than half the distance to the point of gaze.

3.1.4 The Importance of Integrated Control Augmentation; A pilot flying a helicopter in the nap-of-the-Earth can be expected to make use of simple and reliable optical variables like DMP, τ and its derivatives and optical flow streaming in the service of the control of ego-motion guidance variables like

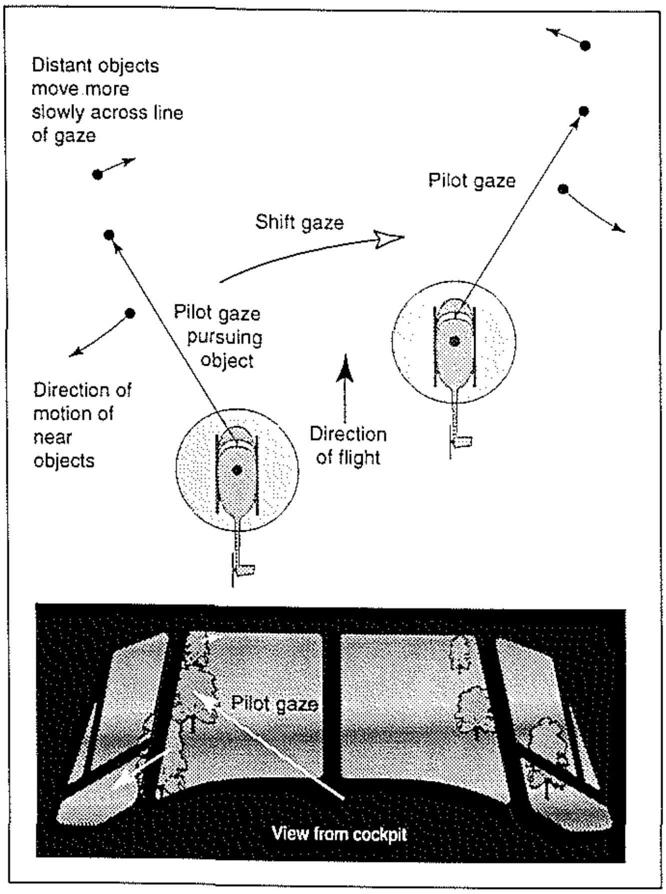

Fig 12. Differential Motion Parallax as an Optical Invariant to Aid Wayfinding

speed, height and heading. The designers of synthetic vision systems to enable flight at low level in a cluttered environment can utilise these natural, reflexive pilot skills and several pathway-in-the-sky type formats are currently under development or being explored in research (Ref 33) that exhibit such properties. Designers also have the freedom to combine such formats with more detailed display structures for precision tracking, e.g. the pad-capture mode on the AH-64A (Ref 34). This type of format requires the pilot to apply cognitive attention, closing the control loop using detailed individual features to achieve the desired precision, hence risking a loss of situation awareness with respect to the outside world. Achieving a balance between precision and SA (performance and safety) is the pilot's task and what is appropriate will change with different circumstances. Quite generally however, when equipped with an adequate sensor suite, there seems no good reason why a large part of the precision workload in tracking tasks should not be accomplished by the automatic flight control system. Moreover, pilots not only guide their aircraft through and over a cluttered environment; they also need visual cues to perform the attitude stabilisation function. Manoeuvring an aircraft has some similarities to cycling or walking over uneven or flexible ground. Vestibular motion cues are generally unreliable; turn the lights off and the cyclist or walker would fall over very quickly. Attitude stabilisation cues for helicopter flight are derived from knowledge of the horizon, an awareness of spatial orientation and rotational motion.

The requirements of ADS-33 are quite clear about the importance of stability augmentation when the UCE degrades below 1 (see Fig 4) - increased attitude stabilisation as the UCE degrades to 2 and increased velocity stabilisation as the UCE degrades to 3. In a recent study, Ref 35, Hoh has applied the UCE/VCR approach to quantifying the risk of spatial disorientation when flying in the DVE. The work reported in Ref 35 addresses the wide class of ground/obstacle collisions that occur when aircrew are unaware that they have an inaccurate perception of their position, altitude or motion. Hoh's analysis models situations where the overall pilot workload is a combination of the attentional demands (AD) of flight control and that required to maintain situation awareness (SA). The greater the requirements for control attention, the less capacity remains for SA. To quote from Ref 35, "*The risk of a spatial disorientation accident is linked to the attentional demand required for control as follows. High risk is defined when attentional demand exceeds 42% of the total available workload capacity. Extreme risk is defined when the AD exceeds 66% of the available workload capacity. The attentional demand for rotorcraft control in the DVE depends on two factors, 1) the basic handling qualities in the GVE and 2) the Response Type (Rate or ACAH + HH). The relationship between these factors is summarised in Fig 13, where the attitude VCR and translational VCR are assumed to be equal to simplify the presentation of the effects. These results indicate that as the visual environment is degraded: 1) the use of ACAH+HH is highly effective in minimising the increase in AD, and 2) helicopters with a rate response type (conventional) suffer a rapid increase in AD. Any factor that degrades the HQR in the GVE (e.g. marginal basic handling qualities or turbulence) exacerbates the second result*".

In presenting and discussing the results summarised in Fig 13, Hoh acknowledges that the relationship between handling qualities, control workload and UCE proposed are approximate and have not been fully validated. However, they represent an intuitive and very plausible argument for the importance of providing the pilot with augmented attitude control in the DVE. Moreover, Hoh concludes that providing additional instruments or displayed information to cue the pilot can actually increase, rather than decrease, the attentional demand, further increasing the risk of disorientation.

When considering flight in degraded visual environments, the questions raised by the above discussion become part of research to understand how best to develop vision and control augmentation that improve both attitude and translational rate

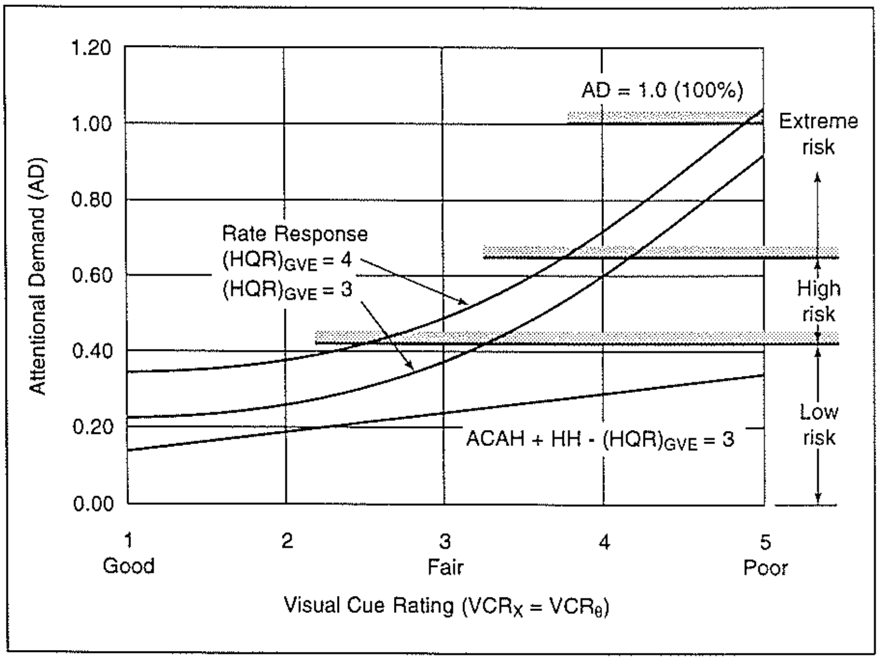

Fig 13 Summary of the Effect of the DVE on Attentional Demand (from Ref 35)

contributions to the UCE. The goal of a pilotage augmentation system designed to extend operational capability in DVE must be to achieve performance without compromising safety, reducing fatigue by reducing cognitive workload and increasing confidence to allow aggressive manoeuvring. It is argued that significant breakthroughs in such technology will be spurred by the creative integration of controls and displays, and a coming together the underlying human sciences and engineering disciplines into a new flying qualities design and evaluation methodology.

Without vision and control augmentation, flight in degraded visual conditions corresponds to handling qualities in the Level 3 region and loss of situation awareness can also lead to a loss of effective control. Loss of control is also a major issue following critical system failures, the next topic in this paper.

3.2 Flying Qualities Criteria in Failed Conditions

When a system failure results in a degradation to Level 4 flying qualities, that system should be extremely reliable. But systems can also fail for operational reasons e.g. battle damage, impact with obstacle, when the issue is survivability rather than reliability. Where a failure results in degradation to no worse than Level 3 HQ then there needs to be advice to pilots on how to manage the situation. Developing flying qualities criteria for these failure cases presents a problem for substantiation, because of the safety risks in testing. Nevertheless, failure analysis is absolutely critical for minimising the risk to safe flight in operation. The first step is to define and tabulate all the possible failure types that may lead to a degradation in flying qualities, in terms of response type, dynamic response characteristics, control modes, UCE etc. A failure modes and effects analysis (FMEA) should then lead to an understanding of the levels of degradation. FMEA applied from a flying qualities standpoint requires quantification of the nature of the degradation due to the failure. ADS-33 defines the acceptable level of degradation in the failed condition in terms of the likelihood of occurrence. Table 1 presents the maximum probabilities allowable for degradation to Level 2 and 3, derived from equivalent fixed-wing requirements for a 4-hour mission (Ref 14).

The flying qualities methodology requires that failure types, for example control system components failing, need to be evaluated for the effects on response type, long term stability etc. In addition to the analysis in the failed state is the requirement to quantify the handling qualities during the failure transient and recovery to a safe flight condition. ADS-33 addresses these transients in the context of possible loss of control, exceedance of structural limits or collision with nearby objects. Table 2 summarises the requirements in terms of attitude excursions, translational accelerations and proximity to the Operational Flight Envelope.

Probability of Encountering	Within OFE	Within SFE
Level 2 after failure	$< 2.5 \times 10^{-3}$ per flight hour	
Level 3 after failure	$< 2.5 \times 10^{-5}$ per flight hour	$< 2.5 \times 10^{-3}$ per flight hour

Table 1 Levels for Rotorcraft Failure States (ADS-33)

	FLIGHT CONDITION		
LEVEL	HOVER AND LOW SPEED	FORWARD FLIGHT	
		NEAR EARTH	UP-AND-AWAY
1	3 deg roll, pitch, yaw 0.05g n_x, n_y, n_z no recovery action for 3 secs	both hover and low speed & forward flight up-and-away reqts apply	stay within the OFE no recovery action for 10 seconds
2	10 deg roll, pitch, yaw 0.2g n_x, n_y, n_z no recovery action for 3 secs	both hover and low speed & forward flight up-and-away reqts apply	stay within the OFE no recovery action for 5 seconds
3	24 deg roll, pitch, yaw 0.4g n_x, n_y, n_z no recovery action for 3 secs	both hover and low speed & forward flight up-and-away reqts apply	stay within the OFE no recovery action for 3 seconds

Table 2 Failure Response Transients (ADS-33)

The probabilities associated with failures of critical powerplant and drive-train components, including the tail rotor, should normally be remote. Scrutiny of accident and incident records of both civil and military helicopters reveal that tail rotor failures, from both mechanical failure and operational causes (e.g. tail rotor striking ground), continue to occur at rates greater than remote, and this has prompted an investigation by DERA into flying qualities associated with tail rotor failures.

3.2.1 Tail Rotor Failures. Tail rotor malfunctions can take one of 2 forms - a drive failure, where the drive-train is broken and a complete loss of tail rotor effectiveness results, and a control failure, where the drive is maintained but the pilot is no longer able to control the tail rotor. Either can occur because of technical faults or operational damage. Ref 8 discusses a UK programme aimed at developing better advice to aircrew on the actions required following a tail rotor failure in flight. The activity was spurred by the findings of the UK MOD Tail Rotor Action Committee (TRAC), viz.;

(i) tail rotor failures continue to occur at an unacceptably high rate in the UK helicopter fleet. MOD statistics between 1974-1993 show a tail rotor technical failure rate of about 11 per million flying hours; the design requirements require the probability of transmission/drive failure that would prevent a subsequent landing to be remote (<1 per million flying hours, Ref 7); a review of UK civil accident and incident data has revealed a similar failure rate,

(ii) tail rotor drive failures are more prevalent than control failures,

(iii) there appear to be significant differences in the handling qualities post tail rotor failure, between different types (e.g. some designs appeared to be uncontrollable, the probability of an accident resulting from a failure is greater with some types than others), although there is a dearth of knowledge on individual types,

(iv) improved handling advice would enhance survivability.

TRAC recommended that work should be undertaken to develop appropriate and validated advice for aircrew action in the event of a tail rotor failure for the different types in the UK military fleet, and also that airworthiness requirements should be reviewed and updated to minimise the likelihood of tail rotor malfunctions on future designs. Ref 8 presents results for the first aircraft type to receive attention, the GKN Westland Lynx. In a joint programme between DERA and GKN Westland, advice validation was classified into three types/levels - validation type 1 corresponds to full demonstration in flight, validation type 2 corresponds to demonstration in piloted simulation and best analysis, validation type 3 corresponds to engineering judgment based on calculation and read-across from other types. The Lynx study provided the opportunity to create this kind of framework for developing improved advice; it was judged that the best advice validation that could be achieved was type 1 for control failures and type 2 for drive failures.

When investigating flying qualities in failed conditions, 3 aspects need to be addressed - characteristics during the failure, post-failure and during the emergency landing. All three are, to some extent, influenced by the flight condition from which the failure occurred. For example, the failure transients and optimum pilot actions will be quite different when in a low hover compared with high speed cruise, well clear of the ground. The required actions will also be different for drive and control failures. Furthermore, in the case of control failures, the aircraft and pilot responses will be different depending on whether the control fails to a high pitch or low pitch, or some intermediate value designed as a fail safe mechanism to mitigate against the adverse effects of a control linkage failure. The implied situation-response hierarchy exacerbates the whole problem of tail rotor failures, but also reinforces the need for improved understanding, coherent advice and comprehensive pilot training programmes.

In the Lynx tailfail programme, a DERA research Lynx was used to develop advice following control failures in flight test and the Advanced Flight Simulator, in concert with GKN Westland desk-top simulations, was used to develop drive failure advice (Ref 8). In the flight trial the failures were 'simulated' by the second pilot (P2) applying pedals to the failure condition; while P2 held the failed condition, P1 endeavoured to develop successful recovery strategies. An example from both activities will be used to illustrate the approach taken and the nature of the findings.

Example 1; high pitch control failure in cruise

The high pitch control failure mode results in a nose left yaw (for anti-clockwise rotors), the severity of which depends on the initial power setting and aircraft speed. The magnitude of control and yaw excursions will be greater from flight at minimum power speed than cruise for example. Accompanying the yaw will be roll and pitch motions, driven by the increasing sideslip. In the Lynx flight trials, a number of different techniques were explored to recover the aircraft to a stable and controllable flight condition. For failures in high speed cruise, attempts to decelerate through the power bucket to a safe landing speed were unsuccessful; the right sideslip (left yaw) built up to limiting values and controlling heading with cyclic demanded a very high workload. A successful strategy was developed as illustrated in Fig 14.

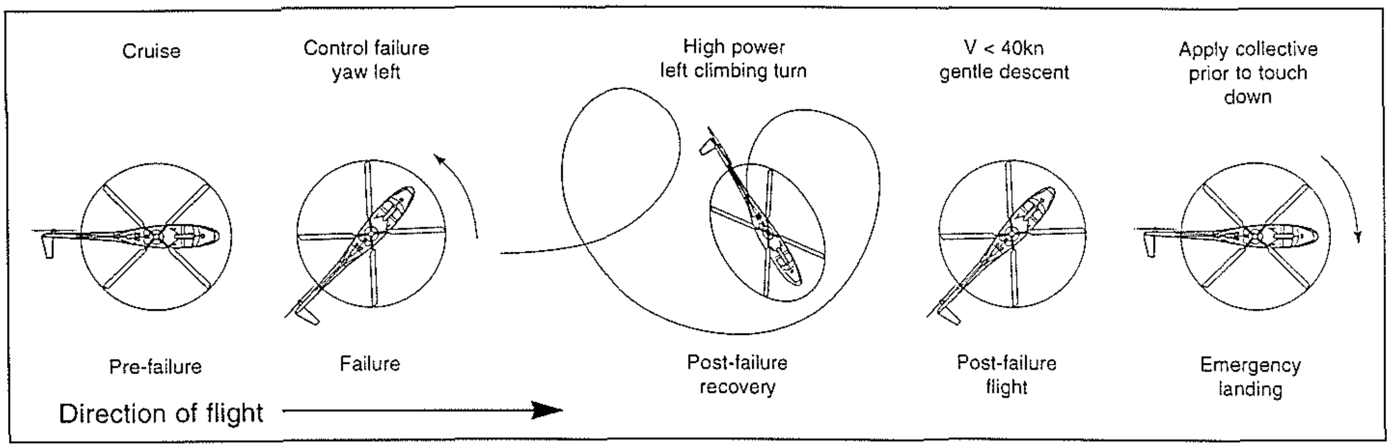

Fig 14 Sequence of Events following High Pitch Tail Rotor Failure in Cruise

A high power left climbing turn provided the pilot with a sufficiently stable and controllable flight condition that deceleration could be accomplished without the aircraft losing yaw stability and control. The aircraft can be levelled out at about 40kn and a slowly decelerating descent initiated. Gentle turns to both right and left (preferred) are possible in this condition. The landing is accomplished by lining the aircraft up with the nose well to port and applying collective, and levelling the aircraft, just before touchdown to arrest the rate of descent and align the aircraft with the flight path. Running landings between 20 and 40kn could be achieved with this strategy. In comparison, low thrust control failures result in the aircraft yawing to starboard; reducing power arrests the yaw transient and allows the aircraft to be manoeuvred to a new trimmed airspeed. During recovery it is important that the pilot yaws the aircraft with collective to achieve a right sideslip condition, so that collective cushioning prior to landing yaws the aircraft into the flight-path.

Example 2; drive failure in cruise

The drive failures were conducted in the relative safety of the DERA AFS, with high fidelity motion and visual cueing systems. The trial was conducted within the broad framework of the handling qualities methodology with ultimate task performance judged by the ability to land within the airframe limits, i.e. touchdown velocities and drift angle. With control failures, the tail rotor continues to provide directional stability in forward flight, but with drive failures, this capability reduces to zero as the tail rotor runs down. For failures from both hover and forward flight, survival is critically dependent on the pilot recognising the failure and reducing the power to zero as quickly as possible. Fig 15 shows the sequence of events in response to a drive failure from a cruise condition. The aircraft is likely to yaw violently to the right as tail rotor thrust reduces. The pilot should reduce power to zero as quickly as possible by lowering the collective lever. Once the yaw transients have been successfully contained, and the aircraft is in a stable condition, the engines should be shut down and the aircraft re-trimmed at an airspeed of about 80kn. With the Lynx, this gives about a 20% margin above the speed where loss of yaw control is threatened. Any attempt to find a speed-power combination that enabled continued powered flight risked a yaw breakaway tendency which could drive the aircraft into a flat spin. Gentle turns to right and left (more stable) can be made from the 80kn autorotation. The pilot approaches the landing with the aircraft nose to starboard and, in this case, raising collective to cushion touchdown will yaw the nose to port and align with the flight path.

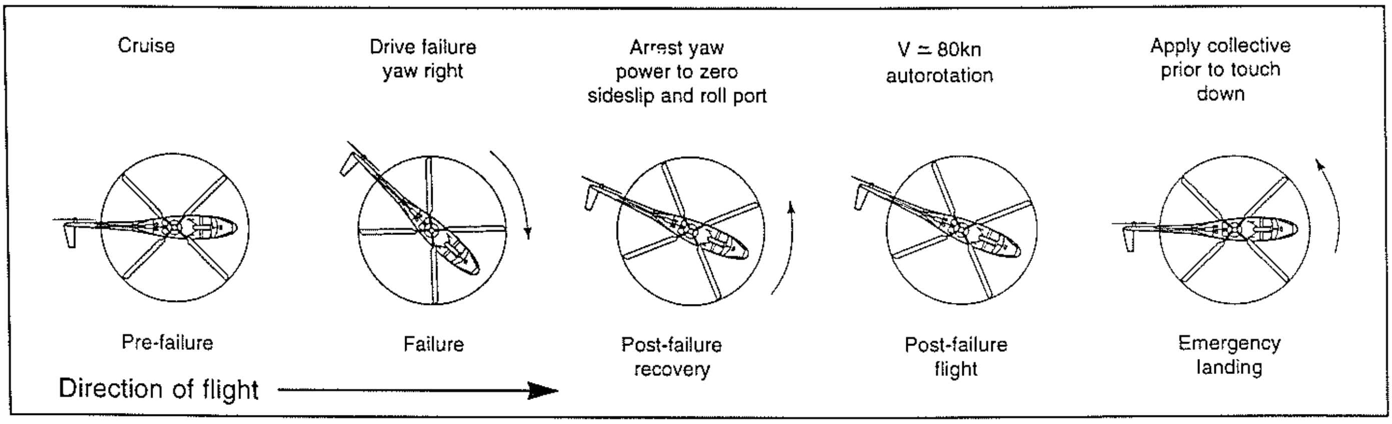

Fig 15 Sequence of Events following a Tail Rotor Drive Failure in Cruise

Ref 8 discusses several other failure conditions including both high and low hover; the paper also identifies a number of candidate technologies that could serve to mitigate against the effects of tail rotor failure, e.g. warning systems integrated with health and usage monitoring systems, emergency drag parachutes. This is an important line of development in the context of this paper. The accident data highlights that drive failures on most types are not very survivable. The two figures used to illustrate the two failure types show a straightforward transition from the failure, through the recovery to the landing. However, in practice, the pilot may well be initially confused by what has happened and can quickly become disoriented as the aircraft not only yaws, but also rolls and pitches, as sideslip builds up. Also, the accident/incident data show that on several occasions, the pilot has successfully recovered from the failure but the aircraft has turned over during the landing. Tail rotor failures make undue demands on pilot skill and attention and the way forward for the longer term has to be to ensure that designs have sufficiently reliable drive and control systems that the likelihood of component failure is extremely remote in the life of a fleet. In the shorter term, and in the context of upgrading current types, a priority should be to confer fail-safe flying qualities. Developing criteria for quantifying such requirements is part of an ongoing UK research programme involving DERA and Industry. Criteria for the acceptable failure transients (the ADS-33 approach of specifying attitude change in 3 seconds provides a useful starting point, but needs validation for tail rotor failures), stability and manoeuvrability when in the recovered flight condition and handling during the landing and run-on phases are all required. Such criteria would form the basis for evaluating the effectiveness of retrofit technologies, including contributions from the automatic flight control system, as well as new designs.

Tail rotor failures require the pilot to exercise supreme skill to survive what is, quite simply, a loss of control situation. If flying qualities degradation could be contained to the Level 3 regime, with controllability itself not threatened (HQR < 8.5), then the probability of losing aircraft to such failures would be reduced. This leads us to the final topic of this paper, where we consider an aircraft to possess flying qualities across the whole range of the Cooper-Harper scale, depending on the circumstances; a perspective that allows an assessment to be made of the value of good flying qualities in a broader operational context.

4. PILOT FAILURES AND THE PROBABILITY OF LOSS OF CONTROL

Tail rotor failures account for between 10-20% of accidents for both military and civil rotorcraft. Failures of other critical components like the powerplant and transmission also account for too many accidents but if the number of accidents attributed to so-called 'human-error' are considered, then the element of the flight system most susceptible to 'failure' would appear to be the pilot. In a series of papers, Hodgkinson and co-workers have presented an analysis of the contribution of flying qualities to flight safety and effectiveness (Refs 2, 9, 36). The pilot is considered as a safety critical component of the flight system who can be stressed to failure in an operational context. Using the HQR as a safety/effectiveness metric, pilot failure can be manifested in a failure to achieve the adequate performance standard (i.e. HQR >6.5), or in a loss of control, corresponding to an HQR >9.5. Following this approach, a probabilistic analysis of flying qualities provides a useful perspective on the value of flying qualities, which we summarise here in Figs 16 and 17.

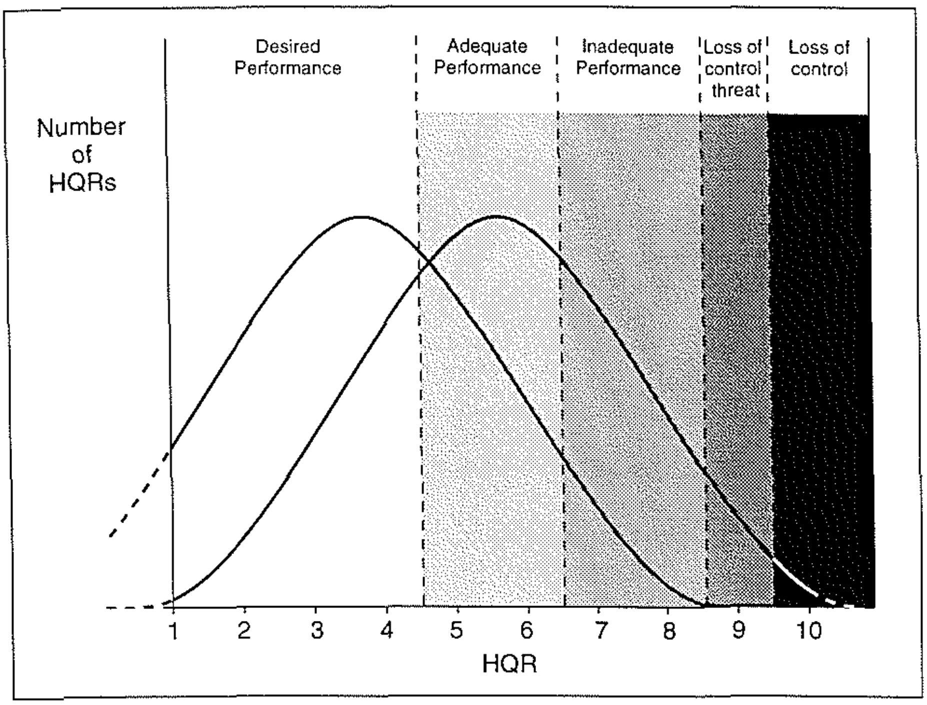

Fig 16 Notional Distribution of HQRs

We assume that missions are made up of a contiguous series of MTEs, each having an assigned (virtual) HQR. Over the life of a particular aircraft these are assumed to be distributed normally as shown in Fig 16. The average handling qualities or mean HQR defines the probability of achieving the desired, adequate, inadequate standards, and also loss of control. The worse the mean, as illustrated in Fig 16, the more chance of experiencing Level 3 HQ or worse. In Fig 17, the probabilities are shown as functions of mean HQR derived by integrating the HQRs within the different regions in Fig 16. In producing Fig 17, we have included ratings greater than 10 and less than 1, on the basis that there are especially bad and good aircraft and situations (e.g. tail rotor drive failures may be considered in this category), whose qualities correspond to ratings in the extended scale; however, the HQ methodology enforces recording them as 10 or 1.

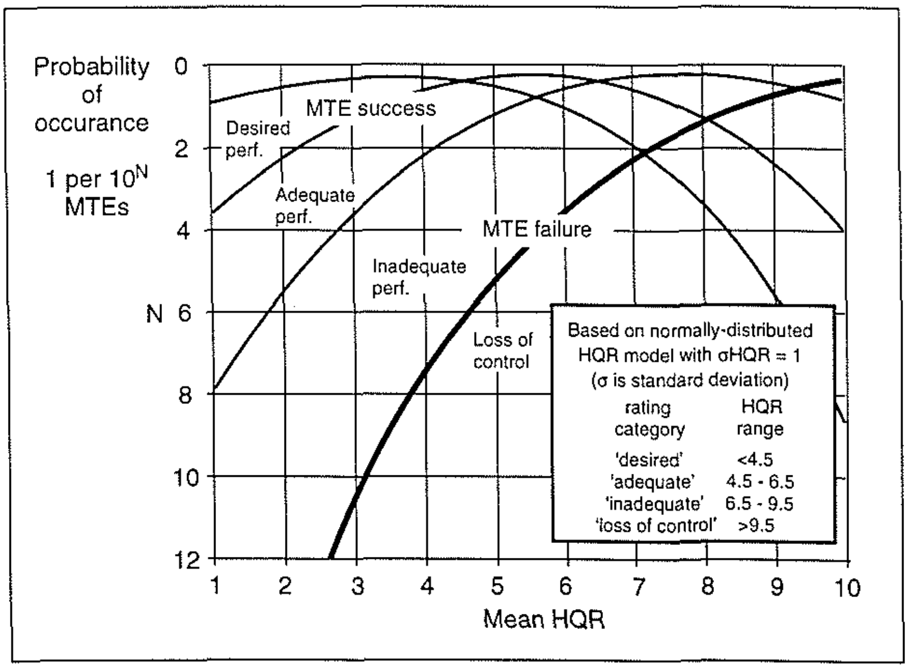

Fig 17 Relationship between Mean HQR and Probability of Loss of Control, Mission Task Success and Failure

Several features on Fig 17 stand out. Improving the handling qualities from Level 2 (mean HQR 5) to Level 1 (mean HQR 3.5) reduces the probability of loss of control from about 1 in 10^6 MTEs (perhaps one per year for a fleet of 100 aircraft, Ref 11) to 1 in 10^9 MTEs (never ?). Similarly, degrading the mean HQR of a type from 3.5 to 5 will increase the chance of MTE failure by about 2 orders of magnitude. Conferring mean Level 1 characteristics on a helicopter simply means that, most of the time, pilots will be able to achieve the desired performance standards with low workload, which is an attractive and feasible flight safety goal.

This analysis serves as a reminder that, in high workload situations, the pilot needs assistance in controlling the tension between safety and performance. Adopting a design philosophy that does not require pilots to have to compensate for handling qualities deficiencies forms the crux of this assistance and, this author argues, will make future helicopter operations safer. This requires greater emphasis on what might be described as 'fail-safe' flying qualities in the requirements-capture and design processes. The first, and most important, step is to design for Level 1 performance for normal operations according to the new standards. Degraded handling, into Level 3 or worse - through flight in poor visibility or following critical system failures or through exceedences of the Safe Flight Envelope (a topic not covered in this paper) - can be protected against, or the effects mitigated, with new technologies that are in development or subjects of research; examples are integrated control and vision augmentation, integrated flight control and health management systems and carefree handling systems, particularly power management and integrated flight and engine control. The emphasis in these new technologies is integration.

5. CONCLUDING REMARKS

This paper on controlling the tension between performance and safety in helicopter operations has been written from the author's perspective of research into future flying qualities requirements. The importance of robust, task-oriented criteria has been emphasised as critical to realising operational benefits from good flying qualities without compromising safety. It has been argued that future designs will benefit from greater emphasis placed on flying qualities, particularly automation, to relieve the pilot in his/her management of the safety-performance trade-off and in controlling the underlying tension. Assistance is particularly needed in situations of degraded flying qualities, e.g. following entry into conditions of poor visibility, and when flight critical components fail; the paper has described examples in these areas.

The author has tried to provide an application-oriented qualitative analysis and pointers to outstanding challenges. The principal conclusions of the paper are;

(i) for the first time in the history of helicopter development, comprehensive and substantiated criteria for how to make helicopters exhibit Level 1 flying qualities are available; a priority should be to adopt the new standards in any new aircraft or type upgrade programme

(v) design for fail safe flying qualities in emergency situations has the potential for reducing the number of accidents on future helicopters; a goal should be that pilots never have to compensate for handling qualities deficiencies.

It is arguable that the four most important things that will need to improve before there is a significant increase in the number of helicopters used in the service of the general public and commerce are, (a) safety, (b) affordability, (c) noise levels and (d) comfort. Of these, it is suggested that safety is the most important. A 'design for safety' goal could be to eradicate the contributing factors that lead to so-called pilot error, and flying qualities technologies have a major part to play here. While design teams for new projects can adopt this goal ab initio, a real challenge to the helicopter community is how to upgrade the significant number of helicopters already in the field to confer them with Level 1 in normal operations and fail-safe flying qualities in emergencies.

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7. ACRONYMS

ACAH	attitude command, attitude hold
AD	attentional demand
ADS-33	aeronautical design standard - 33
AFS	advanced flight simulator
DERA	Defence Evaluation and Research Agency
DMP	differential motion parallax
DRC	dynamic response criteria
DVE	degraded visual environment
FMEA	failure modes and effects analysis
FTM	flight test manoeuvre
GVE	good visual environment
HH	height hold
HMD	helmet mounted display
HQR	handling qualities rating
IMC	instrument meteorological conditions
MTE	mission task element
NVG	night vision goggles
OFE	operational flight envelope
PH	position hold
PIO	pilot-induced-oscillation
RAE	Royal Aircraft Establishment
RC	rate command
RCDH	rate command direction hold
RCHH	rate command height hold
SA	situation awareness
SFE	safe flight envelope
TR	translational rate
TRAC	tail rotor action committee
TRCPH	translational rate command position hold
UCE	usable cue environment
VCR	visual cue rating
VMC	visual meteorological conditions

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