PROGRESS IN THE DEVELOPMENT OF COMPLEMENTARY HANDLING AND LOADING METRICS FOR ADS-33 MANOEUVRES

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The aim of the present paper is to present a novel approach to handling qualities investigations by developing and testing new complementary metrics capable of being applied to both agility and structural loads analysis. Two questions are to be addressed: 1) how can one extend existing ADS-33 metrics to ones pertaining to both agility and vibratory loading analysis? 2) how can one extend and/or interrelate the current helicopter metrics to handling metrics originating from fixed-wing aircraft? Concerning the first question, the present paper focuses on two new metrics relevant to manoeuvring in forward flight: the *agility quickness* and the *vibratory load quickness.* While the agility quickness characterises the helicopter performance, the load quickness could be used to quantify the build up of loads in the airframe. For the agility metric the present paper proposes quality boundaries based on the performance standards during aggressive manoeuvring (high yo-yo, transient turns and pull-up manoeuvres). The trends in the load quickness are also presented and shown to increase with manoeuvre amplitude, where the designer would prefer them to decrease. Concerning the second question, the paper looks at how the *control anticipation parameter* (CAP) might be applicable to rotorcraft handling qualities investigations. It is demonstrated that while CAP could be used as a metric to correlate the flight path response with the attitude response for small-amplitude manoeuvres, agility quickness is a more logical extension of ADS-33 to account for more aggressive manoeuvring in forward flight. CAP charts are plotted for helicopter and Tiltrotor examples and then interpreted as a measure of quickness in highly agile manoeuvres. It is concluded that this novel approach could be particularly useful to Tiltrotor applications where the handling qualities in fixed-wing mode and in helicopter mode must merge together within new criteria.

NOTATION

CAP	control anticipation parameter [deg/sec^2/g]
g	gravity acceleration [m/sec^2]
$M_w, M_{\dot{w}}, M_q$	derivatives of pitch moment w.r.t. the heave velocity and pitch rate
n_z^{qs}	quasi-steady normal acceleration in manoeuvring flight [g's]
$n_{z\,pk}^{qs}$	peak quasi-steady normal acceleration in manoeuvring flight [g's]
$n_{z\,pk}^{vib}$	peak amplitude in the vibratory components of the hub shears and/or moments [g's]
n_T	normal load factor in steady climbing turn [g's]
n_z/α	normal load factor per unit angle of attack [g/deg]
R	blade radius; turn radius [m]
q	helicopter pitch rate [deg/sec]
q_{pk}	peak pitch rate in a pull-up manoeuvre [deg/sec]
Q_θ	attitude quickness parameter [sec^{-1}]
Q_γ	agility quickness parameter [g deg^{-1}]
Q_l	vibratory quickness parameter [g deg^{-1}]
U_0	trim forward speed [kn]
U_T, U_P	components of airspeed respectively normal and parallel to the tip-path plane [kn]
w	helicopter vertical speed [kn]
x	fraction of blade radius (x = r/R) [-]
Z_w	derivative of normal force w.r.t. the heave velocity
α	blade effective incidence w.r.t. the tip-path plane [deg]
β	blade flapping angle [deg]
Φ	bank angle [deg]
γ	Lock number [-]; flight path angle
$\Delta\gamma$	flight path change achieved in manoeuvres [deg]
λ	normalized inflow through the disc [-]
μ	helicopter advance ratio [-]
θ	helicopter pitch attitude [deg]
θ_{1s}	longitudinal cyclic input [deg]
$\Delta\theta_{pk}$	pitch angle change achieved in the pull-up [deg]
$\Delta\theta_{min}$	minimum attitude change in pull-up manoeuvre [deg]
τ_{θ_2}	time constant in the pitch response [sec]
ω_{nSP}	short period natural frequency [rad/sec]
Ω	rotor angular velocity [rad/sec]
Ω_{turn}	turn rate [deg/sec]
ψ	azimuth angle [deg]
ζ_{SP}	short period damping ratio [-]

INTRODUCTION

Rotorcraft are nowadays reliable flying machines capable of conducting missions impossible to achieve with fixed-wing aircraft. This reliability and flexibility is best achieved by adopting stringent design principles and methodologies. Experience has shown that a large percentage, perhaps as much as 65%, of the life-cycle cost of a helicopter is committed during the early design phases of a new development programme [Ref 1]. Within this, the most promising way of increasing the likelihood of constructing helicopters with excellent handling qualities (HQs) is to use a multi-disciplinary approach in design and development. The most comprehensive set of handling qualities requirements available to the design engineer are united in the ADS-33 [Ref. 2] design standard. Introduced in the mid 1980's, the handling qualities criteria and metrics of the ADS-33 depend primarily on the mission the helicopter has to execute rather than on the vehicle role or size as in previous standards. However, the criteria elaborated inside the ADS-33 concentrate mainly on the performance of both helicopter and the pilot. In recent years, a strong feeling exists among the helicopter specialists that new inter-disciplinary criteria are needed to give more insight into the structural and dynamic issues posed by the adoption of standards like ADS-33. Especially on the subject of how the pilot workload and complex control strategies influence the structural response, there is a considerable lack of knowledge. This is probably due to the fact that the HQs of many older helicopters were not seriously considered in the design phase and hence no link was made with the manoeuvre spectra used for structural design. This is no longer the case for helicopters in which pilots are expected to be able to use high levels of agility in a carefree manner [Ref. 3]. New design criteria and test methodologies are required.

A previous AHS paper [Ref. 4] presented a novel approach to handling qualities investigations by developing new metrics drawn from ADS-33, capable of being applied to both agility enhancement and structural load alleviation. The metrics presented pertained to vertical manoeuvres in forward flight. In this context, it has been showed how the ADS-33 low-speed pitch attitude quickness parameter could be converted into two new metrics: one metric to characterise the helicopter performance – the so-called *agility quickness (gamma quickness)*, and one metric to quantify the build up of loads in the rotor – the so-called *vibratory load quickness.* The present paper builds on this work.

The goals of the present paper are:

1) to extend the Ref. 4 metrics to mission task elements (MTE) from ADS-33 characterising aggressive manoeuvring and to define agility load quickness boundaries for the agility metric;
2) to consider existing criteria and metrics used to assess the handling qualities of fixed-wing airplanes and to establish inter-relations with the helicopter HQ criteria. From the multitude of fixed-wing HQs metrics, the present paper will particularly investigate the control anticipation parameter. The second goal of the paper is particularly relevant to Tiltrotor applications in which the handling qualities in fixed-wing mode and in helicopter mode must merge together to ensure smooth conversions.

The paper is structured as follows:

- The first section gives a summary of the agility and vibratory load quickness reported in Ref. 4 applied to vertical manoeuvres. Then, mission task elements from the ADS-33 are flown and the agility/vibratory loads are derived;
- The second section proposes agility quickness level 1/2 boundaries based on the performance standards required to fly the ADS-33 manoeuvres;
- The third section introduces the turn quickness for manoeuvres in the horizontal plane;
- The fourth section describes the so-called "control anticipation parameter (CAP)", a fixed-wing HQ parameter used to capture the longitudinal response characteristics of fixed-wing airplanes;
- The fifth section establishes the interrelation between the CAP and agility quickness. Extension of CAP to the rotorcraft applications facilitates the search for HQ criteria suitable for flight path control in forward flight.
- Finally, general conclusions and further extensions to this work are presented.

AGILITY AND VIBRATORY LOAD QUICKNESS – Two Complementary Metrics for Handling Qualities Investigations

ADS-33 introduced attitude 'quickness' to characterise the helicopter's ability to achieve rapid, precise attitude changes when performing sharp, moderate amplitude manoeuvres; *theta quickness* Q_θ is defined as:

$$Q_\theta \overset{def}{=} \frac{q_{pk}}{\Delta\theta_{pk}} \left(\sec^{-1}\right) \qquad (1)$$

where q_{pk} is the maximum pitch rate and $\Delta\theta_{pk}$ is the peak attitude angle change during the manoeuvre. Attitude quickness is an agility parameter used in ADS-33 to characterise manoeuvres in the pitch axis with $5 < \theta < 30$

deg). ADS-33 defines handling qualities boundaries for the attitude quickness parameter as a function of the minimum attitude change $\Delta\theta_{min}$. However, this criterion and these boundaries apply only to hover and low speed manoeuvres (< 45 kn). In forward flight (> 45 kn), ADS-33 is more qualitative in terms of flight path handling qualities, and no levels of aggressiveness are defined.

Reference 4 proposed the so-called *agility quickness parameter (gamma quickness)* defined as:

$$Q_\gamma \overset{def}{=} \frac{n_{z\,pk}^{qs}}{\Delta\gamma}, \tag{2}$$

where $n_{z\,pk}^{qs}$ is the peak quasi-steady normal acceleration in g units corresponding to a step change in flight path angle $\Delta\gamma$. It was demonstrated that thinking in terms of pilot performance, *gamma quickness* seemed to be a more suitable measure of short-term agility than *theta quickness*, as it is well-known that the mechanism for pulling g in such manoeuvres is given by using the pitch control which is mainly correlated with changing the flight path angle $\gamma = \theta - \alpha$ (where α is the angle of attack of the fuselage and θ is the helicopter pitch attitude). It was also demonstrated that while the small-amplitude agility quickness parameter is given by heave damping (or heave bandwidth), the large-amplitude agility quickness parameter depends mainly on the quasi-steady pitch rate and thus on the amplitude of the input (maximum load factor), in the limiting case being equivalent to the ADS-33 attitude quickness parameter.

Complementary to the agility quickness parameter, Ref. 4 defined the so-called *vibratory quickness* parameter to characterise the vibratory loads in the rotor as:

$$Q_l \overset{def}{=} \frac{n_{z\,pk}^{vib}}{\Delta\gamma} \tag{3}$$

where $n_{z\,pk}^{vib}$ represents the peak amplitude in g unit's of the vibratory components of the hub shears.

The agility and vibratory load quickness parameters were tested in pull-up manoeuvres flown with different levels of aggressiveness demonstrating consistent variations. Reference 4 also showed how these new metrics could be used to optimise the rotor loading for performance without increasing the vibratory loading. In this context, open-loop second harmonic cyclic control inputs were superimposed onto the primary longitudinal cyclic pitch control in the pull-up manoeuvre. It was demonstrated that selecting the proper magnitude and phase of the higher harmonic controls could alleviate the vibratory activity on the hub while not changing the helicopter agility characteristics.

BOUNDARIES FOR AGILITY METRIC

The present paper will seek to define performance boundaries for the agility quickness parameter. These boundaries are defined on charts representing the agility quickness parameter as a function of flight path change $\Delta\gamma$. Reference 4 only investigated the case of pull-up manoeuvres. The present work extends further these ideas and investigates aggressive manoeuvres achieving high load factors used to characterise the short-term agility of the helicopter. The corresponding results for the vibratory load quickness are presented but no attempt is made to define 'quality' boundaries on these charts. This task is well beyond the scope of the present paper but presenting the trends in this measure of structural usage shows how the correlation between performance and loads can be addressed in multi-disciplinary design.

Defining the Level 1/2 Boundary for Agility Quickness Metrics

The performance standards required to fly the ADS-33 manoeuvres can be used as a guide to defining Level 1/2 boundaries for the agility quickness. From the multitude of manoeuvres which can be flown in the ADS-33 it was thought that one has to find those in which the highest maximum 'g' loadings and flight path changes occur. Only these kind of manoeuvres would help to define boundaries characterising the agility of the helicopter. Perhaps the most demanding manoeuvre pair in ADS-33, achieving high g's and flight path changes, and requiring high pilot workload, is the high and low yo-yo. The yo-yo manoeuvre is used to check the helicopter characteristics in aggressive target acquisition and pitch pointing tasks. In the high yo-yo manoeuvre the test rotorcraft (attacker) is required to initiate a climbing turn toward the target with a nose-up pitch attitude of 15 to 30 degrees. Hence, the flight path change is likely to be similar. It was decided to fly pull-up manoeuvres with the FLIGHTLAB Generic Articulated Rotorcraft (FGR, UH-60 like) model, in which a pitch attitude change of 30 deg is achieved starting from different forward flight velocities (between 30 kn and 150 kn) and determine the values for the agility and vibratory load quickness metrics. These values can then be considered the minimum performance level required of the aircraft. The FGR features a 'rigid' blade element rotor with non-linear aerodynamics and a 3-state dynamic inflow model.

Fig. 1a presents the Level 1/2 boundary for agility quickness as defined in the performance standards for the yo-yo manoeuvre and Fig. 1b presents the corresponding results for the vibratory quickness. In addition, the agility quickness lines for flying pull-up manoeuvres obtained in the previous research [Ref. 4] (cases of 60 kn and 150 kn 1 in and 2 in pulses inputs) are plotted.

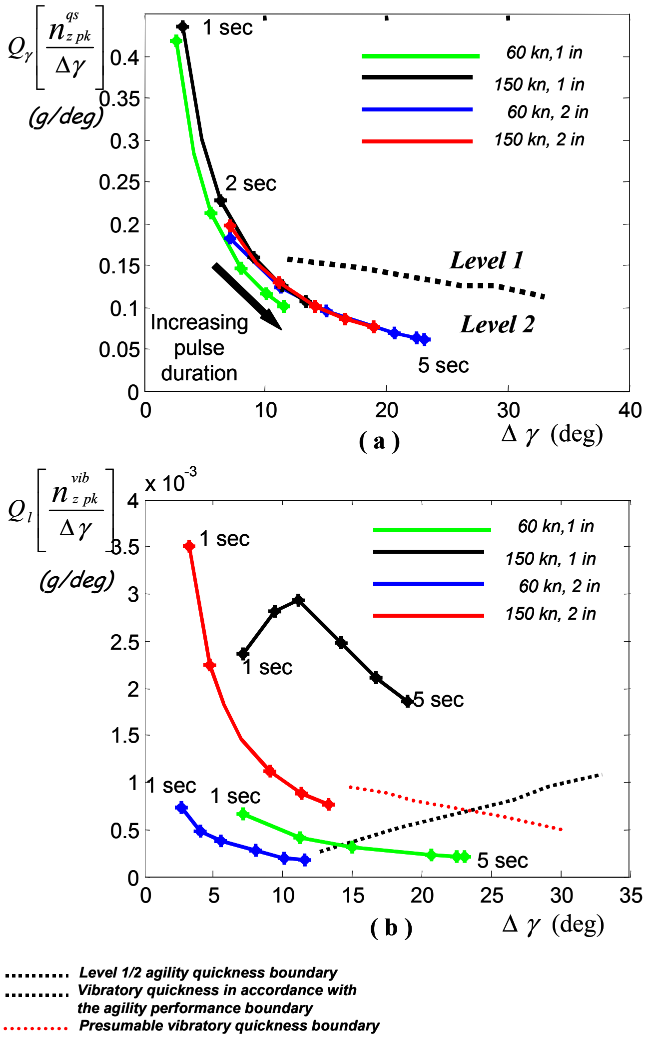


Fig. 1: Level 1/2 boundary (general) for the agility quickness (a) and corresponding variation on vibratory loading quickness chart (b)

The charts highlight the nature of quickness as a sensitivity function. One can see that while the performance boundary (requirements) for agility decreases with increasing flight path change, this actually leads to an increase in vibratory quickness. The vibratory loads due to blade stall result in an increase in sensitivity to flight path angle (see the black dotted line in Fig. 1b). Increasing the flight path change enables the pilot to pull more g's of course but also increases the vibratory activity in the rotor. One can imagine load quickness requirements that slope in a similar direction to the agility quickness (see the red dotted line in Fig. 1b).

In practice the yo-yo and pitch change manoeuvres are often flown in combination with a turn and this requires an extension of our agility quickness concept.

TURNING DYNAMICS

Fig. 2a presents the trajectory when flying a transient turn (helicoidally motion) and Fig. 2b the force diagram for level turning flight.

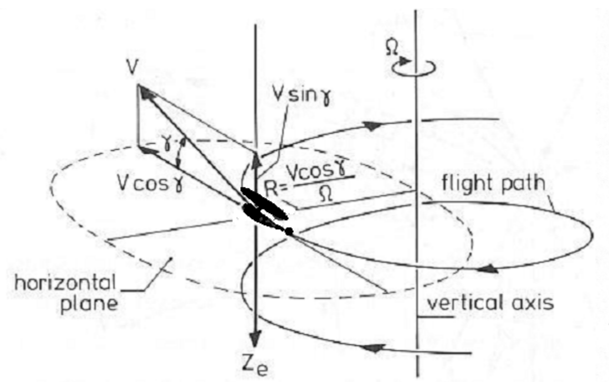


Fig. 2a: Flying a transient turn

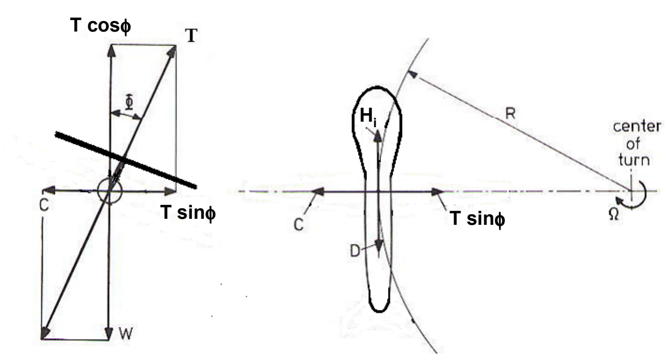


Fig.2b: Forces in the steady level turn

From the equilibrium of the forces of Fig. 2b one may derive:

- the load factor $n = 1/\cos\Phi$
- the radius of turn $R = \dfrac{V^2}{g\tan\Phi} = \dfrac{V^2}{g\sqrt{n^2-1}}$

- the rate of turn $\Omega_{turn} = \dfrac{g \tan \Phi}{V} = \pm \dfrac{g\sqrt{n^2 - 1}}{V}$

  (positive sign for a right turn and negative sign for a left turn).

For a climbing turn these formula's are modified since the component of the velocity in the horizontal plane is now $V\cos\gamma$ and the load factor defined as normal acceleration in units of g is $n_T = n\cos\gamma$:

- the radius of turn $R = \dfrac{(V\cos\gamma)^2}{g\sqrt{{n_T}^2 - 1}}$

- the rate of turn $\Omega_{turn} = \pm \dfrac{g\sqrt{{n_T}^2 - 1}}{V\cos\gamma}$

Let's fly different steady turns to the right / left and vary the aggressiveness of the manoeuvre by varying the helicopter speed (60 kn and 150 kn) and the rate of turn (from 4 deg/sec to 60 deg/sec).

The agility quickness parameter in the steady helicoidally turn can be obtained as a function of the rate of turn:

$$Q_\gamma = \frac{\sqrt{1 + \left(\dfrac{V\Omega_{turn}\cos\gamma}{g}\right)^2}}{\Delta\gamma} \qquad (4)$$

Fig. 3 presents the variation of the agility quickness parameter with flight path change for the climbing turns executed when applying this simple theoretical model.

Fig. 3 extends the performance boundaries for agility quickness for more complex manoeuvres. The 'vertical' yo-yo boundary from Fig 1a is included on the chart showing that increased performance is required for the combined manoeuvre.

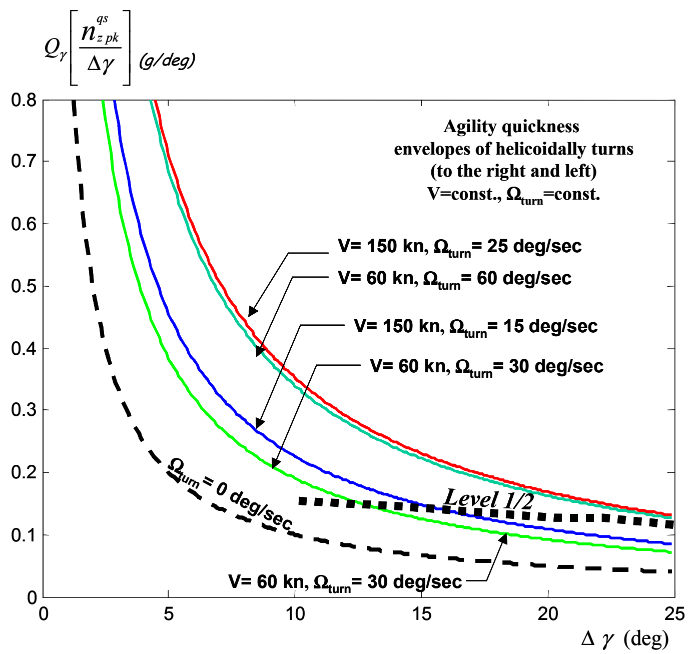


Fig. 3: Agility quickness envelopes in steady turns of varying turn rate

When studied closely, the transient turn manoeuvre as defined in the ADS-33 requires a re-formulation of the agility quickness concept.

ADS-33 Transient Turn

To develop more insight into the way a pilot flies a turn manoeuvre consider next the transient turn performed as required in the ADS-33 standard.

The ADS-33 transient turn [Ref.2 pp.41] is characterised as being aggressive in roll, pitch and yaw axes and is used for checking primary response and for any undesirable couplings which can develop during aggressive manoeuvring. This manoeuvre can be used to understand how the pilot is able achieve high load factors, high agility, and still deal with demanding response cues. The manoeuvre is described as follows in the ADS-33 standard:

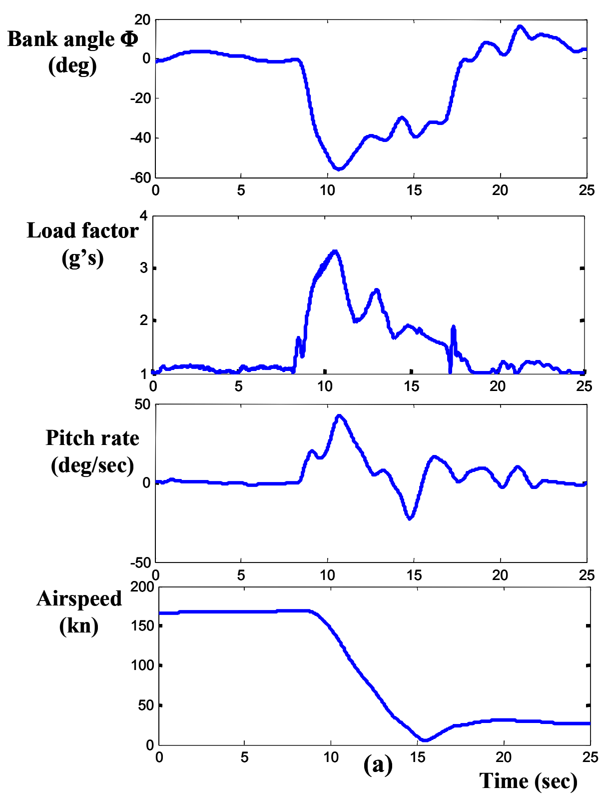
From level unaccelerated flight, accomplish a 180-degree change in directional flight path (both to the left and right) and achieve wing-level attitude in as little time as possible.

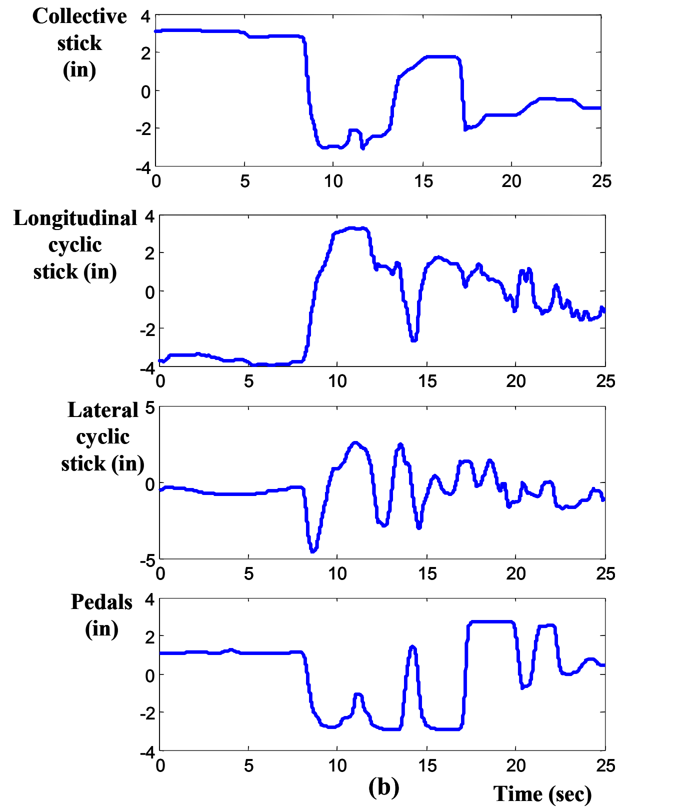
It is acceptable to use the pedals to induce a lateral acceleration in the direction of the turn is acceptable; it is acceptable to reduce collective to increase the rate of speed bleed-off and thereby maximize the turn rate. The performance requirements are:

- *achieve a desired peak normal load factor of at least 100% - 0.2g or 80% (adequate) of the OFE $n_L(+)$;*
- *complete manoeuvre within 10 sec (desired) or 15 sec (adequate);*
- *maintain altitude within ±50 ft (desired) or below 200 ft (adequate);*
- *maintain the rotor RPM within the limit of OFE (desired) or SFE (adequate).*

In these requirements OFE stands for Operational Flight Envelope and is the envelope within which the helicopter must be capable of accomplishing all the operational missions; SFE stands for Service Flight Envelope and is the envelope defined by the rotorcraft limits as distinguished from the mission requirements.

The ADS-33 transient turn was flown with two pilots in the full-motion simulator at The University of Liverpool [Ref. 5] using the FGR model. The pilots were asked to fly turns to the left and right from level flight at 60 kn, 80 kn, 120 kn and maximum continuous power speed for level flight (approximately 160 kn). A typical time history of a tight turn is presented in Fig. 4a. The pilot is trying to execute a 180 deg turn to the left (a complete reversal of flight direction) at maximum continuous power speed (~160 kn) maintaining the altitude within ± 50 ft throughout the manoeuvre.





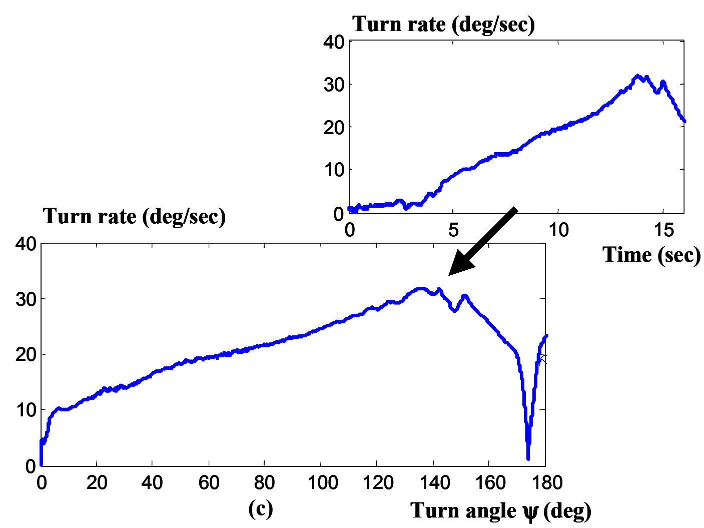


Fig. 4: Time histories, tight turn to the left

From Fig. 4a one may read a maximum bank angle of 56 degrees with a pitch rate of 42 deg/sec and a load factor of 3.2, all these values indicating that the helicopter is close to its maximum 'g' capability. Note that the helicopter is rapidly decelerating during the turn, the velocity being reduced in 6-7 secs from 160 kn to almost hover. The high level of pilot workload is reflected in the control activity in Fig. 4b. Fig. 4c presents the turn rate against the turn angle for the whole manoeuvre showing how this builds up in time to a maximum value of more than 30 deg/s when the aircraft has decelerated to about 50 kn.

The handling qualities ratings (HQRs) and the comments given by the pilots when flying the transient turns are summarized in Table 1. As shown, the pilots awarded Level 2 and 3 ratings for these manoeuvres.

	Pilot 1		Pilot 2	
Turn right 80kn (TR80)	stabilisation during terminal phase very difficult	HQR = 6	exceed torque limits, heavy workload, descending all the time	HQR = 6
Turn left 80kn (TL80)	height outside desired	HQR = 7	height within desired, but heavy workload	HQR = 7
Turn right 120kn (TR120)	height outside desired, difficult to control height, yaw oscillations, exceed torque limits	HQR = 8	height outside desired, heavy workload	HQR = 7/8
Turn left 120 kn (TL120)	spirally unstable	HQR = 8	heavy workload, power management problems, high torque, probably blade stall	HQR = 7/8
Turn right max. cont. power speed (~160kn) (TRMCP)	more controllable than at 120kn !!!	HQR = 6	height and time outside desired, power management very difficult, torque higher than 120%, definite blade stall	HQR = 7
Turn left max. cont. power speed (~160kn) (TLMCP)		HQR = 7	big power management problem due to blade stall, great tendency to climb	HQR = 7

Table 1 Transient Turn Results

It is interesting to comment on the meaning of agility and handling qualities on the quickness charts. In ADS-33, the Level 1/2 boundary represents a performance requirement. There is a certain minimum performance required to fly the MTE family for a given mission requirement. It follows that the higher the agility quickness parameter Q_γ the better the HQs should be. However, in practice, the closer the pilot flies to the performance boundary, the more difficult it becomes to fly the manoeuvre – and the likelihood is that the HQRs will degrade into the Level 2 or even 3 Level areas as the workload increases. Therefore, one has to realise that in high performance manoeuvring one can achieve high values of agility quickness Q_γ while the pilot returns poor HQRs. This kind of inverse trend – increasing agility and degradation the HQs – has been previously reported [Ref 1] and will be also seen in the next paragraph for the transient turns.

In the transient turn the performance standards do not actually require a flight path change but rather a heading change. Therefore, it is more appropriate for this type of manoeuvres to define a new parameter – the turn quickness, as the ratio of peak quasi-steady normal acceleration achieved in the turn manoeuvre to the heading angle change at the time when this peak is achieved:

$$Q_\psi \overset{def}{=} \frac{n_{z\,pk}^{qs}}{\Delta\psi(t_{pk})} \qquad (5)$$

thus combining the roll quickness and 'g' quickness into a turn quickness. Figure 5 presents the turn quickness charts for the theoretical and piloted turns discussed in this paper as a function of the heading change $\Delta\psi$ at the time of the peak normal acceleration.

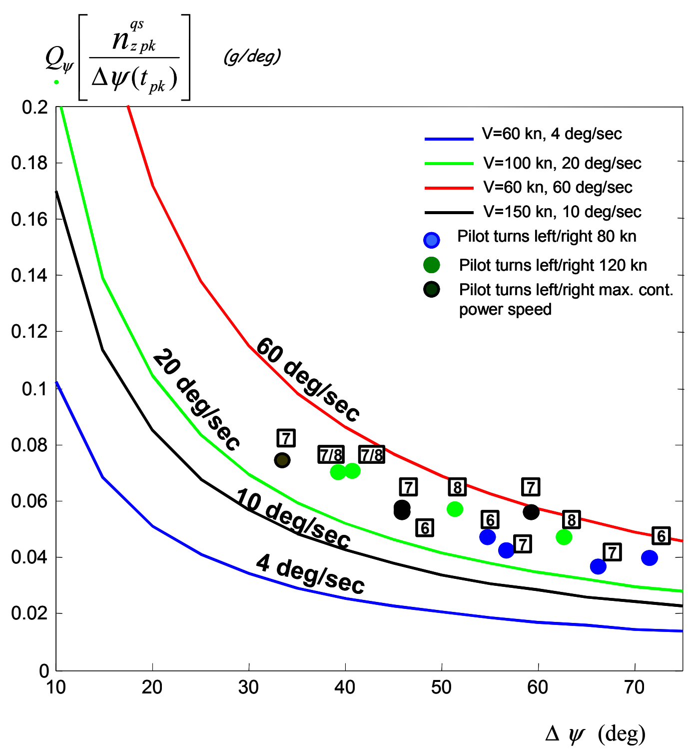


Figure 5: Turn quickness envelopes in steady turns of varying turn rate and piloted transient turns

From Fig.5 one may observe that during a 180-degree transient turn the maximum 'g' loadings build up quickly, being achieved in the first 30 to 60 degree of the heading change. After this the turn continues and the pilot workload stays high but the dynamic part of the turn is over. Increasing the initial flight speed at which the turn is executed results in more aggressive manoeuvring with maximum g's achieved at lower headings. Maximum turn quickness values increase toward 0.1g/deg when the maximum g is achieved in the first 30 degrees of turn. One can also observe maximum turn rates of nearly 60deg/sec. These high levels of performance were achieved with unacceptably high workload of course, but the results indicate the required performance to fly the very aggressive ADS-33 transient turns.

Returning to the main theme of the paper, the assessment of pitch axis HQs in forward flight can be aided by drawing on fixed-wing handling criteria, particularly the control anticipation parameter. In fact, many handling qualities criteria developed for fixed wing aircraft could be directly applied to helicopters with appropriate revisions in the numerical limits and boundaries [Ref. 10].

CONTROL ANTICIPATION PARAMETER (CAP) REVIEW

The concept of the Control Anticipation Parameter (CAP) was introduced by Bihrle [Ref. 6] as a mean of quantifying longitudinal response characteristics of fixed-wing airplanes. At the time of its introduction, CAP was intended to capture short-term response properties, which would otherwise be overlooked. The short period mode of an aircraft is a rapid motion (frequencies typically between 2 to 4 rad/sec) governing the transient changes in angle of attack, pitch, flight path and normal load factor following a rapid control or gust input. The properties of this mode are thus important in order to characterise the aircraft agility. Good longitudinal short-term response properties provide the pilot with good anticipatory handling cues. For a long time, to characterise the short period mode, it seemed sufficient to use its two modal parameters – the damping ratio ζ_{SP} and undamped natural frequency ω_{nSP}. These two parameters were plotted against each other in a so-called 'thumberprint' criterion. Thumberprint plots were also used in rotorcraft design.

However, Bihrle observed that '*for airplanes having high inertia or low static stability (which implies that the natural frequency of the short period mode is low), the angular pitching acceleration accompanying small adjustments to flight path may fall below the threshold of perception'*. In other words, the anticipatory nature of the response cues may become insignificant, thereby giving rise to poor handling qualities. It was established experimentally that there is a tendency for the pilot to overcorrect, or overdrive an aircraft exhibiting these characteristics, making it difficult to control the flight path with precision. In order to assess handling qualities of aircraft with these characteristics, Bihrle defined a quantifiable measure of the anticipatory nature of the response, which he called the 'control anticipation parameter' (CAP). CAP is used to characterise the precision achieved in flight path control. Level 1, 2 and 3 handling qualities for CAP are specified either in a chart of the short period natural frequency ω_{nSP} as a function of acceleration sensitivity (see eq. (7)) or a chart giving the CAP parameter as a function of the short period mode damping ratio ζ_{SP}.

CAP is defined as the ratio of the initial pitch acceleration to the steady state load factor, after a step-type control input:

$$CAP \overset{def}{=} \frac{\dot{q}}{n_z^{qs}} \qquad (6)$$

Bihrle [Ref. 6] expressed CAP as a function of the basic aircraft stability derivatives and the short period modal characteristics as follows:

$$CAP = \frac{\omega_{nSP}{}^2}{n_z / \alpha} \qquad (7)$$

where n_z / α is the so-called "acceleration sensitivity" and is defined as the steady state normal load factor per steady state angle of attack:

$$n_z / \alpha \overset{def}{=} \frac{\Delta n_z}{\Delta \alpha} \approx \frac{U_0}{g} \cdot \frac{1}{\tau_{\theta_2}} \equiv -\frac{U_0 Z_w}{g} \qquad (8)$$

Acceleration sensitivity parameter can be expressed as a function of the stability derivative Z_w as:

$$n_z / \alpha \approx -\frac{U_0 Z_w}{g} \approx \frac{U_0}{g} \cdot \frac{1}{\tau_{\theta_2}} \qquad (9)$$

where U_0 is the flight speed; Z_w the normal force due to heave velocity w; τ_{θ_2} the numerator time constant in pitch response to longitudinal control (see (14)), i.e. the time lag between attitude and flight path response:

$$\tau_{\theta_2} \approx -1 / Z_w \qquad (10)$$

The short period mode damping and frequency are obtained by using the short-period approximation (neglecting the surge velocity u) in the longitudinal equations of motion:

$$\begin{cases} \dot{w} = Z_w w + U_0 q + Z_\delta \delta \\ \dot{q} = M_w w + M_{\dot{w}} \dot{w} + M_q q + M_\delta \delta \end{cases} \tag{11}$$

where $Z_w, M_w, M_{\dot{w}}$ and M_q are respectively the vertical force and pitching moment derivatives due to vertical velocity w, vertical velocity rate $\dot{w}$ and pitch rate q; U_0 is the flight speed; Z_δ and M_δ are the derivatives due to a control input δ. Neglecting the $M_{\dot{w}}$ derivative, the short period natural frequency and damping ratio follow as:

$$\begin{aligned} {\omega_{nSP}}^2 &= Z_w M_q - U_0 M_w \\ 2\zeta_{SP}\omega_{nSP} &= -\left(Z_w + M_q\right) \end{aligned} \tag{12}$$

Substituting (9) into (7) leads to the following expression for the CAP parameter:

$$CAP = \frac{{\omega_{nSP}}^2}{\frac{U_0}{g}\frac{1}{\tau_{\theta_2}}} = -\frac{{\omega_{nSP}}^2}{\frac{U_0}{g}Z_w} \tag{13}$$

Bihrle specified that due to the approximations implied in the derivation of the short period approximation, equation (13) calculates CAP within about ± 10% of the true value. Equation (13) shows that CAP is very much related to the natural frequency of the longitudinal short period mode and also shows the CAP dependency on the term $1/\tau_{\theta_2}$.

Recalling system (11), the pitch response to a perturbation δ can written in transfer function form as:

$$\frac{\theta(s)}{\delta(s)} \approx \frac{1}{s}\frac{M_\delta\left(s - Z_w\right)}{\Delta} = \frac{1}{s}\frac{M_\delta\left(s + 1/\tau_{\theta_2}\right)}{\Delta} \tag{14}$$

where $\Delta = 0$ is the characteristic equation of system (11).

Looking at (13), one can see that, additional to the thumberprint criterion, CAP accounts not only for the characteristics of the short period mode but also for the effect of the flight path response to a rapid control input, through the term $1/\tau_{\theta_2}$. On the other hand, the transfer function of the flight path response to pitch attitude can be expressed as:

$$\frac{\gamma(s)}{\theta(s)} = \frac{1/\tau_{\theta_2}}{s + 1/\tau_{\theta_2}} \tag{15}$$

In [Ref. 8] and [Ref. 9], Hoh comments on the physical implications of CAP, underlining the double character of the CAP parameter:

- on the one hand as a measure of the pitch attitude response;
- on the other hand as a measure of the manoeuvre margin which is a measure of the flight path response.

Concluding, CAP refers to both attitude and flight path (inc. normal load factor) control, giving the frequency separation between the pitch attitude response (ω_{nSP}) and the flight path response $1/\tau_{\theta_2}$.

The derivation of the CAP parameter above is commonplace in airplane flight dynamics. The next section will try to extend the CAP parameter to rotorcraft flight and connect it to ADS-33 HQ parameters. The extension of CAP is particularly relevant to tiltrotor applications in which the handling qualities in airplane and helicopter modes must merge together in the conversion mode.

THE RELATIONSHIP OF CAP TO ATTITUDE AND AGILITY QUICKNESS

To the best of the authors' knowledge, the CAP parameter has not been used to quantify the short period characteristics of helicopters in forward flight. One reason for this could be the fact that the CAP definition (13) was based on a short period approximation that makes use of the low order equivalent system (LOES) method. This method requires that the attitude and flight path responses of the airplane are conventional and that the higher order dynamics effects in the response can be neglected. This assumption is often true for conventional airplanes, but higher order dynamics cannot usually be neglected in the so-called "region of pilot crossover", situated in the range of frequencies between $1/\tau_{\theta_2}$ and ω_{nSP}. This region corresponds exactly to where CAP is directed. For example, [Ref. 9] presents cases where the aircraft did not fit the CAP boundaries as defined for conventional aircraft because the configuration analysed could not be approximated with the LOES method.

It is well known that with helicopters, higher order dynamics and inter-axis couplings play an important role in defining the system characteristics. Usually, for such systems, the pitch attitude and flight path control criteria are defined separately, based on the concern that the mixed criteria would fall in the region of pilot crossover where the effects of higher order dynamics are difficult to physically understand and therefore quantify. The CAP parameter is a measure of the system properties in the region of crossover. Another reason for the concern to extend the CAP parameter to helicopters could be the fact that the short period mode for helicopters is not always the classical stable pitch/heave oscillation. For example, the short period and phugoid modes of hingeless rotor helicopters are non-classical and sometimes exhibit aperiodic behaviour. Here, we consider configurations where equation (11) could be also applied to helicopters leading to relation (13) for the CAP parameter.

Since CAP relates on the one hand to the airplane attitude and on the other side to the flight path control, one would think that this parameter should be correlated to the attitude quickness parameter Q_θ and to the agility quickness parameter Q_γ as defined earlier.

Recalling the definition of the agility quickness (2) (see [Ref. 3]) it can be deduced that:

- for small flight path changes $\Delta\gamma$,

$$Q_\gamma \,|_{0<\gamma<5\,\deg} \approx -\frac{U_0}{g} Z_w \tag{16}$$

hence the agility quickness is a measure of the heave damping;

- for large $\Delta\gamma$,

$$Q_\gamma \,|_{\gamma>30\,\deg} \approx \frac{U_0}{g} Q_\theta \tag{17}$$

where the agility quickness characterises more the pitch attitude control.

Based on the CAP definition (6), Ref. [7] defined a generic GCAP parameter which evaluates satisfactorily the value of CAP in the case of full order aircraft models:

$$GCAP \overset{def}{=} \frac{\dot{q}}{n_z^{qs}} \equiv \frac{\dot{q}}{n_{z\,pk}^{qs}} \frac{n_{z\,pk}^{qs}}{n_z^{qs}} = \frac{\dot{q}}{n_{z\,pk}^{qs}} \left(1 + e^{-\frac{\varsigma_{SP}\pi}{\sqrt{1-\varsigma_{SP}^2}}} \right) \tag{18}$$

Recalling equations (2), (6) and (7) it follows that:

$$\dot{q} = \omega_{nSP}^{\;2} \cdot \Delta\alpha \tag{19}$$

$$n_{zpk}^{\;qs} = Q_\gamma \cdot \Delta\gamma \tag{20}$$

Substituting (19) and (20) into (18) one obtains:

$$Q_\gamma \cdot GCAP = \omega_{nSP}^{\;2} \frac{\Delta\alpha}{\Delta\gamma} \left(1 + e^{-\frac{\varsigma_{SP}\pi}{\sqrt{1-\varsigma_{SP}^2}}} \right) \tag{21}$$

Referring to (18) and (7) one may connect the acceleration sensitivity to the agility quickness as follows:

$$n_z / \alpha = \frac{n_z^{\;qs}}{n_{zpk}^{\;qs}} \frac{n_{zpk}^{\;qs}}{\Delta\alpha} = Q_\gamma \frac{\Delta\gamma}{\Delta\alpha} \left(1 + e^{-\frac{\varsigma_{SP}\pi}{\sqrt{1-\varsigma_{SP}^2}}} \right)^{-1} \tag{22}$$

For small-amplitude flight path changes (< 5 deg) $\Delta\gamma \cong \Delta\alpha$ so that from (21) and (22) it follows that $\omega_{nSP}^{\;2} \cong Q_\gamma \cdot GCAP$ and $n_z / \alpha \cong Q_\gamma$. Then for small flight path changes the product of the agility quickness and the generic CAP parameter does not depend on the manoeuvre type and is a constant equal to the short period natural frequency. Also, for small-amplitude flight path changes, the agility quickness parameter is equal to the acceleration sensitivity. The same conclusions could be obtained when using the linear approximation for the CAP parameter (9) and the interpretation of the agility quickness (16).

For large-amplitude flight path changes $\Delta\gamma \cong \Delta\theta$ and the product $Q_\gamma \cdot GCAP$ characterises more the pitch attitude control.

Essentially quickness represents a logical extension to the short-term small-amplitude criteria (as given by CAP) to account for more aggressive manoeuvring, being a more representative parameter for the moderate amplitude range (5 to 30 deg flight path changes).

The next section will map the time domain flight path response of an example helicopter into the GCAP criterion. The CAP boundaries for fixed-wing aircraft are specified in the MIL-STDS as charts of ω_{nSP} as a function of n_z / α (see [Ref. 11]). This relationship will be connected to the agility quickness parameter Q_γ. From (21), it follows that knowing Q_γ for a manoeuvre gives the parameter n_z / α. Then, from (21) it follows that if Q_γ and CAP are known, the short-period natural frequency can be determined as:

$$\omega_{nSP} = \sqrt{Q_\gamma \cdot GCAP \cdot \frac{\Delta\gamma}{\Delta\alpha}\left(1+e^{-\frac{\varsigma_{SP}\pi}{\sqrt{1-\varsigma_{SP}^2}}}\right)^{-1}} \qquad (23)$$

The FGR model has been used to fly longitudinal manoeuvres at various levels of aggressiveness (these pulses were used for developing the agility quickness envelopes in Fig. 3 of [Ref. 4]). Pulses of different duration (from 1 sec to 5 sec) were input with different pulse amplitudes (1 in and 2 in) and from different initial forward speeds (60 kn and 150 kn) and the values of the following parameters were computed: $n_{z\,pk}^{qs}$, $\Delta\gamma$ as defined in Q_γ, and $\dot{q}$ was calculated as the first peak pitch acceleration in the time response. The relationship given in (2) was then used to compute the agility quickness and (18) to compute the GCAP parameter.

The relationships in (22) and (23) were then used to represent the CAP boundaries in charts $\omega_{nSP} = func(n_z/\alpha)$ for the manoeuvres considered. Fig. 6 presents the results obtained for the FGR when flying the pulse manoeuvres. In order to give an impression of where the helicopter stands w.r.t. the fixed-wing aircraft, the CAP boundaries from the MIL-STD for the fixed-wing class IV aircraft (fighter)/category A flight phases (demanding tasks) are also shown ([Ref. 12]). This figure also includes the Level 1/2 boundary for the agility quickness as defined in the performance standards for the yo-yo manoeuvre (see Fig. 1a).

Looking at Fig. 6 one may interpret the results in two ways, i.e.:

- in terms of agility, as the pulse duration increases, the flight path and 'g' increase; however, the pilot's ability to use the quickness decreases;
- in terms of control anticipation, as the pulse duration increases, the acceleration sensitivity decreases when the helicopter is flying with a forward speed of 60 kn. From (9) it follows that the term $1/\tau_{\theta_2} = \frac{g}{U_0}\frac{n_z}{\alpha}$ also decreases and from (15) it follows that the lag between the flight path response and the attitude response also decreases. As a general comment, from the fixed-wing experience it is known that if the short period frequency ω_{nSP} is much below the value $1/\tau_{\theta_2}$, the flight path response is closely in phase with the attitude response; alternately, if ω_{nSP} is much above $1/\tau_{\theta_2}$, the flight path response lags the attitude response. At high speeds (150 kn) the acceleration sensitivity is independent of the pulse duration.

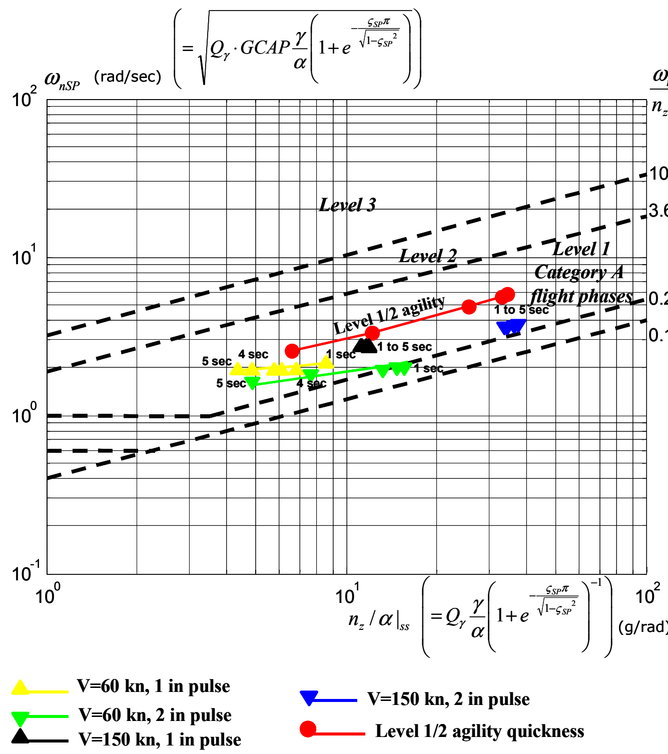


Fig. 6: Relating GCAP requirements to the agility quickness for the FGR

Fig. 6 also shows the consistency between the agility requirement based on flight path quickness and the Level 1/2 CAP HQ region. Thus, representing the manoeuvres flown with the FGR model in the form of Fig. 6, one may obtain the correlation between the frequency separation of attitude and flight path response as referred in CAP and the agility capabilities as given by Q_γ. Looking at the pilot ratings for transient turns it follows that decreasing the agility results in a degradation of the HQs as the task difficulty is increasing. In such cases the pilot tries to use more of the quickness but she/he has difficulty managing the cues and aircraft performance in high aggression manoeuvres.

CAP boundaries can also be plotted as a function of the short period damping ratio $(G)CAP = func(\varsigma_{SP})$. Figure 6 was converted into new CAP boundaries as seen in Fig. 7.

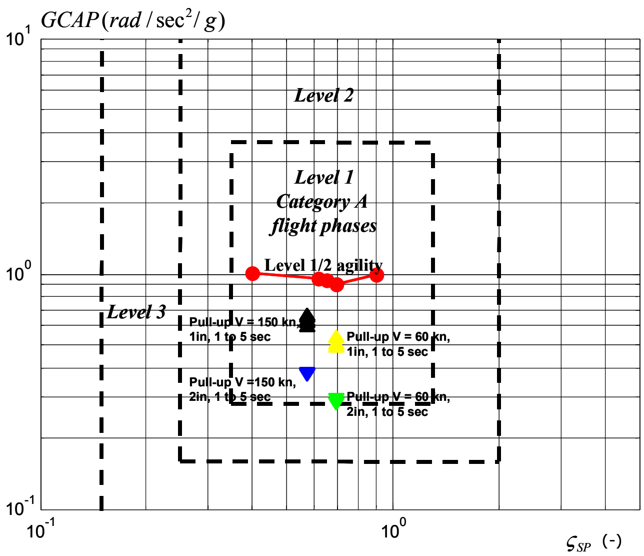


Fig. 7: GCAP boundaries as a function of the short period damping ratio for the FGR pulses

The above reasoning for the CAP–agility relationship was further extended to the case of tiltrotor flight dynamics. The FLIGHTLAB model of the XV-15 as developed by the University of Liverpool was used ([Ref. 5]). Once again, different pull-up manoeuvres were flown. The pulse inputs applied in the longitudinal plane varied in duration (1 to 5 sec) and the tiltrotor was considered to be operating in pure helicopter mode (at 60 kn and 120 kn) and in pure airplane mode (at 120 kn and 300 kn). Charts of $\omega_{nSP} = func(n_z/\alpha)$ were again produced as shown in Fig. 8.

From Fig. 8 one may observe that the helicopter mode results, not unexpectedly, fall in a similar region to the FGR helicopter. The airplane mode results stray into the Level 2 region however both at low and high speed. At low speed the elevator effectiveness is relatively weak while at high speed the de-stabilising effects of rotor flapping reduce the short period damping. This story will be picked up in a future publication.

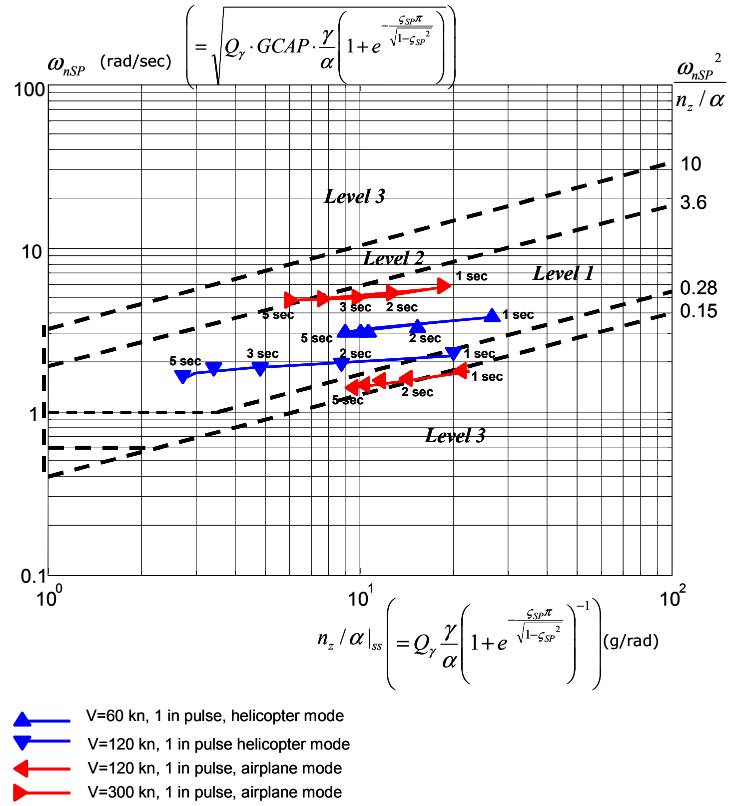


Fig. 8: CAP requirements connected to the agility quickness for the tiltrotor XV-15

CONCLUSIONS

The exercise of the paper was to develop new perspectives on ADS-33 and innovative criteria and techniques to enhance the effectiveness of multi-disciplinary design. The paper has concentrated on two questions:

1) where is the performance boundary for the new agility metric based on MTE performance requirements and how does this relate to structural usage?

2) what correlations could be established between pitch/flight path handling qualities criteria for airplanes and helicopters? The paper analysed this question in the case of the control anticipation parameter (G)CAP.

Concerning the first question, the paper has proposed a Level 1/2 handling qualities (performance) boundary for agility quickness based on the ADS-33 yo-yo manoeuvre. The performance boundary was mapped out into an equivalent plot in the vibratory load quickness chart. It was concluded that while the pilot needs a certain performance for the HQs, the consequences on the rotor and airframe vibratory activity was unfavourable. While the performance boundary for agility decreases with increasing flight path change, the vibratory quickness increases. It was not the exercise of this paper to define boundaries for vibratory quickness, but one could imagine load quickness requirements that slope in a similar direction to the agility quickness boundary.

The paper enlarged the database of situations to which the agility quickness was applied w.r.t. the previous work [Ref. 4], in particular to rotorcraft turning manoeuvres. As in the previous paper, the present work utilised the FLIGHTLAB Generic Articulated Rotorcraft model featuring rigid blades, non-linear aerodynamics and 3-state dynamic inflow model.

Agility quickness charts in steady climbing turns were plotted demonstrating that, to achieve the same flight path change in a turn, the pilot needs more agility (higher agility quickness parameter) than in the pull-up manoeuvre. To develop more insight into the way a pilot flies a turn, ADS-33 transient turns were flown in the full-motion simulator at the University of Liverpool. The pilots awarded Level 2 and 3 ratings to these manoeuvres. The closer the pilot flew to the performance boundary, the higher the workload. The paper went further and defined a so-called 'turn quickness' to characterise the agility in a turn manoeuvre. It was demonstrated that the dynamic development of a 180-degree turn manoeuvre and with it the highest maximum 'g' loading is achieved in the first 30 to 60 degree of the heading change. After this the turn continues and the pilot workload stays high but the dynamic part of the turn is over.

Concerning the second question, the paper analysed the control anticipation parameter (CAP) from fixed-wing airplane requirements and established its relationship to agility and attitude quickness parameters as used in rotorcraft HQs investigations. It was underlined that CAP is a unique HQ parameter in the fixed-wing world as it provides a measure of both pitch attitude response and flight path response for longitudinal manoeuvres. The agility quickness charts for the FGR model and for the XV-15 Tiltrotor model were mapped into equivalent (G)CAP charts in the case of pull-up manoeuvres. It was demonstrated that for small-amplitude flight path changes, agility quickness is equivalent to the acceleration sensitivity in the CAP parameter. Increasing the pulse duration results in a decrease in the lag between the flight path response and attitude response.

The performance boundary for the level 1/2 agility quickness metric was shown to be equivalent to CAP when transposed onto the fixed wing HQ charts.

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