Rotorcraft Design for Maximized Performance at Minimized Vibratory Loads

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1. Introduction

Rotorcraft (helicopters and tiltrotors) are generally reliable flying machines capable of fulfilling missions impossible with fixed-wing aircraft, most notably rescue operations. These missions, however, often lead to high and sometimes excessive pilot workload. Although high standards in terms of safety are imposed in helicopter design, studies show that "*it is ten times more likely to be involved in an accident in a helicopter than in a fixed-wing aircraft*" (Iseler et. al. 2001). According to World Aircraft Accident Summary (WAAS, 2002), nearly 45 percent of all accidents of single-piston helicopters is attributed to pilot loss of control, where - because of various causes, often involving vibrations, high workload, and bad weather - a pilot loses control of the helicopter and crashes, sometimes with fatal consequences. Quoting the Royal Netherlands Air Force ('Veilig Vliegen' magazine, 2003), "*for helicopters there is a considerable number of inexplicable incidents (…) which involved piloting loss of control*". The situation is likely to get worse, as rotorcraft missions are becoming more difficult, demanding high agility and rapid manoeuvring, and producing more violent vibrations. (Kufeld & Bousman, 1995; Hansford & Vorwald, 1996; Datta & Chopra, 2002)

The primary cause of pilot control difficulties and high-workload situations is that even modern helicopters often have poor Handling Qualities (HQs) (Padfield, 1998). Cooper and Harper (Cooper & Harper, 1969), pioneers in this subject, defined these as: "*those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform a mission*". Below, the current practice in rotorcraft handling qualities assessment will be discussed, introducing the key problem addressed in this chapter.

1.1 State-of-the-art in rotorcraft handling qualities – The aeronautical design standard ADS-33

Helicopter handling qualities used to be assessed with requirements defined for fixed-wing aircraft, as stated in the FAR (civil) and MIL (military) standards. In the 1960's, however, it became clear that these standards were not sufficient (Key, 1982). Helicopters have *strong cross-coupling effects* between longitudinal and directional controls, their behaviour is *highly non-linear* and requires *more degrees of freedom* in modelling than the rigid-body models used for aircraft. Therefore, the MIL-H-8501A standard (MIL-H-8501A, 1962) was developed. This standard was used up until mid 1980's. From a safety perspective, these requirements were merely 'good minimums', and a new standard was developed in the 1970's, that is used up until today, the Aeronautical Design Standard ADS-33 (ADS-33, 2000)

The crucial point, understood by ADS-33, is that helicopter HQ requirements need to be related to the mission executed, as this will determine the needed pilot effort. E.g., a shipboard landing at night and in high sea with strong ship motions demands more precision of control from the pilot than when flying in daytime and good weather.2 ADS-33 introduced handling qualities *metrics* (HQM), a *combination* of flight parameters such as rate of climb, turn rate, etc., that reflect how much manoeuvre-capability the pilot has *per specific mission*. These metrics are then mapped into handling qualities criteria (HQC) that yield boundaries between 'good' (Level 1), 'satisfactory' (Level 2) and 'poor' (Level 3) HQs.[1]

Despite their importance for the helicopter safety, its operators and, above all, the helicopter pilots, achieving good handling qualities is still mainly a secondary goal in helicopter design. The first phase in helicopter design is the 'conceptual design' phase in which the main rotor and fuselage parameters are established, based on desired performance and, to some extent, vibration criteria.20 Only in the following phase, that of preliminary design, are 'high-fidelity' simulation models developed and the handling qualities considered. The high fidelity models allow an analysis of helicopter behaviour for various flight conditions. Applying the ADS-33 metrics/criteria to these models results in predicted levels of HQs. When these are known, the *experimental* HQ assessment begins, illustrated in Fig. 1.
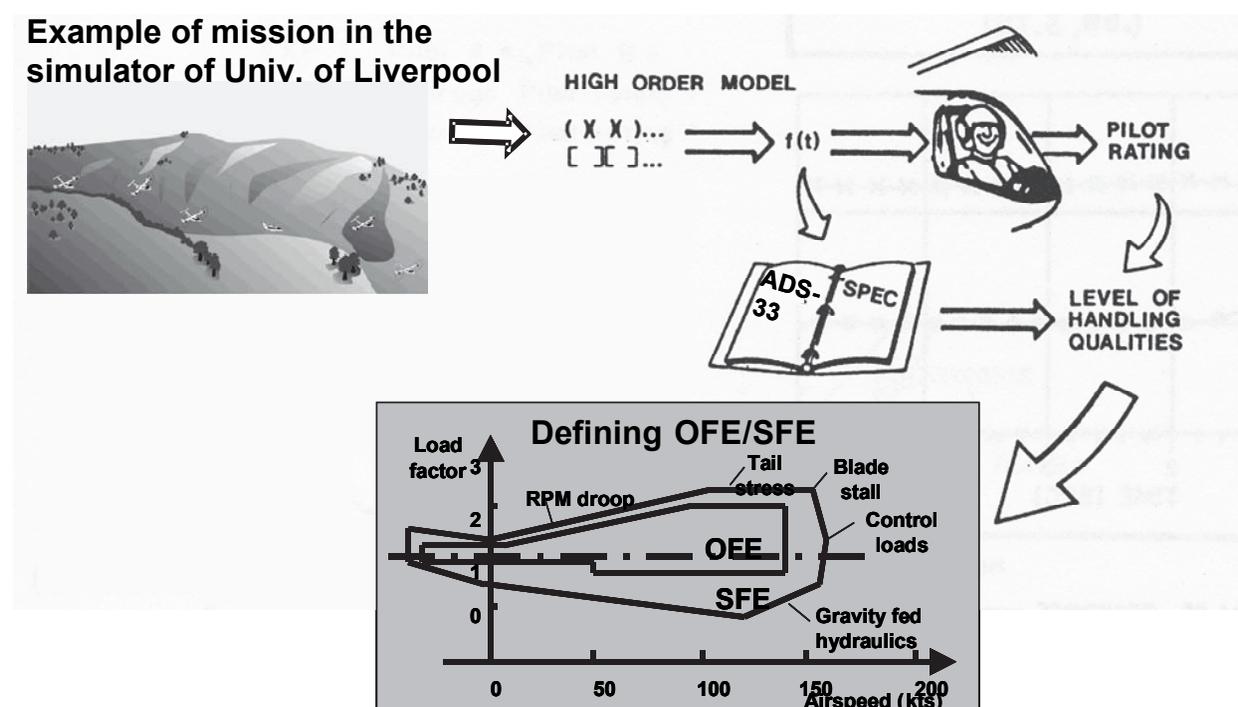

Fig. 1. Experimental assessment of helicopter handling qualities

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[1] Level 1 HQs means that the rotorcraft is satisfactory without improvements required from the pilot's perspective. Level 2 HQs means that pilots can achieve adequate performance, but with compensation; at the extreme of Level 2, the mission is flyable, but pilots have little capacity for other duties and can not sustain flying for longer periods without the danger of pilot error. Level 3 HQs is unacceptable, it describes rotorcraft behaviour in extreme situations, like the loss of critical flight control systems.

In this process, first databases of missions and environments are defined, according to customer requirements. Manoeuvrability, i.e., how easy can pilots guide the helicopter, and agility, i.e., how quickly can they change its flight direction, are critical performance demands. Second, experienced test pilots are asked to fly the missions in a flight simulator. Through insisting pilots to execute the mission very thoroughly, one aims to expose deficient handling qualities. Pilots rate the HQs they experience in each manoeuvre flown, generally using the Cooper-Harper rating scale.[2] Third, Operational Flight Envelopes (OFEs) and Service Flight Envelopes (SFEs) are defined, based on a mapping of the HQ ratings. OFEs represent the limits within which the helicopter must be able to operate in order to accomplish the operational missions. SFEs stem from the helicopter limits and are expressed in terms of any parameters believed necessary to ensure safety, see Fig. 1.

In this first experimental assessment of the helicopter's handling qualities, the first problems arise, as more often than not, large differences arise between the theoretical predictions and the experimentally-determined pilot judgments. The gaps that occur are bridged by applying optimisation techniques using the simulation models developed in preliminary design, to improve the designs of helicopter, load alleviation system and flight control system (Celi, 1991; Celi, 1999; Celi, 2000; Fusato & Celi, 2001, Fusato & Celi, 2002a,2002b; Ganduli, 2004; Sahasrabudhe & Celi, 1997). Computational approaches have three important disadvantages, however. First, many designs that "roll out" of the procedure are unfeasible, the optimisation "pushing" the solution along the boundaries of the problem and not inside of the feasible region. Second, optimising for ADS-33 requires calculations of the helicopter time-domain responses, and the numerical methods become computationally very intensive (Sahasrabudhe & Celi, 1997; Tischler et. al., 1997) Third, and most important, the lack of quantitative, validated helicopter pilot models, capable of accurately predicting the effects of helicopter vibrations on pilot control behaviour, prevents the proper inclusion of pilot-centred considerations in mathematical optimization techniques (Mitchell et. al., 2004; Tischler et. al., 1996)

Whereas the first and second disadvantages are common in multi-dimensional design problems, the lack of knowledge on how helicopter vibrations affect pilot performance is a typical and fundamental problem of modern helicopter design (Mitchell et. al., 2004, Padfield, 1998). Although ADS-33 proposes criteria and missions regarding helicopter limits, these only characterize a helicopter's performance, and do not require an adequate knowledge of helicopter vibratory loads (Kolwey, 1996; Tischler et. al., 1996). This shortcoming stems from the fact that, when the ADS-33 criteria were defined, helicopter missions were not so demanding, and the vibratory loads associated with them were low. In the last twenty years, however, ever-increasing performance requirements and extended flight envelopes were defined, for reasons of heavy competition, demanding manoeuvres that impose heavy vibrations on both structure and pilot. These vibrations, combined with cross-coupling effects, rapidly lead to pilot overload and degradation in performance (Padfield, 2007).

Key Problem: The current practice of assessing rotorcraft handling qualities reveals significant gaps in the ADS-33 HQ criteria, especially regarding the effects of vibrations.

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[2] The Cooper-Harper rating scale runs from 1 to 10. Rates from 1 to 3 1/2 correspond to Level 1 HQs; rates from 31/2 to 61/2 correspond to Level 2 HQs, and rates from 61/2 up to 10 correspond to Level 3 HQs.

1.2 Goal

The design of high-performance rotorcraft has become an arduous process, regularly leading to surprises, demanding 'patches' to safety-critical systems, and needing more iterations than expected, all contributing in very high costs. Unmistakably, the helicopter and flight control system design teams do not have up-to-date criteria to adequately assess the effects of helicopter vibrations on its handling qualities. There is an urgent need for a much more fundamental understanding of how helicopter vibrations affect pilot control behaviour (Mitchell et. al., 2004) and for new tools to incorporate this knowledge as early as possible in the design of both helicopter and flight control system. The goal of this chapter is to portray a novel approach to rotorcraft handling qualities (HQs) assessment by defining a set of consistent, complementary metrics for agility and structural loads pertaining to vertical manoeuvres in forward flight. These metrics can be used by the designer for making trade—offs between agility and vibrational/load suppression. The emphasis of the chapter will be on agility characteristics in the pitch axis applied to helicopter and tiltrotor. Especially in such new configurations, the proposed approach could be particularly useful as the performance tools for fixed-wing mode and helicopter mode must merge together within new criteria (Padfield, 2008).

The chapter is structured as follows: The second section will present an overview of traditional metrics for measuring pitch agility; The third section will present some alternative metrics proposed in the 90's for better capturing the transient characteristics of the agility; Then, based on the rational developments of the metrics from the previous two sections, fourth section will propose the new approach that can better quantify the agility from the designer point of view. Finally, general conclusions and potential extension of this work will be discussed.

2. Traditionally design of aircraft for pitch agility

One of the most important flying quality concepts defining the upper limits of performance is the so-called "agility". Generally, it is well known that the level of performance achieved by the pilot depends on the task complexity. Fig. 2 presents generically this situation, showing that there is a line of saturation up to which the pilot is able to perform optimally the specified mission; increasing the task difficulty above this line leads quickly to stress, panic and even incapacity to cope anymore with the task complexity and blocking, sometimes with fatal consequences.

It is difficult to point precisely to the origins of the concept of agility but probably these go back to the moment when it was realized that, in a combat, a "medium performance" fighter could win over its superior opponent if the first aircraft possesses the potential for faster transient motions, i.e. superior agility. In its most general sense, the concept of agility is defined with respect to the overall combat effectiveness in the so-called "Operational agility". Operational agility according to measures the '*ability to adapt and respond rapidly and precisely, with safety and poise, to maximize mission effectiveness*'(McKay, 1994). In the mid 80's a strong wave of interest arose in seeking metrics and criteria that could quantify the aircraft agility (Mazza, 1990; McKay, 1994). However, there have been developed almost as many criteria of agility as there were investigators in the field. The problem was partially due to the lack of coordination in the research studies performed but also due to a disagreement on the most fundamental level: there simply was very little agreement on what agility was.
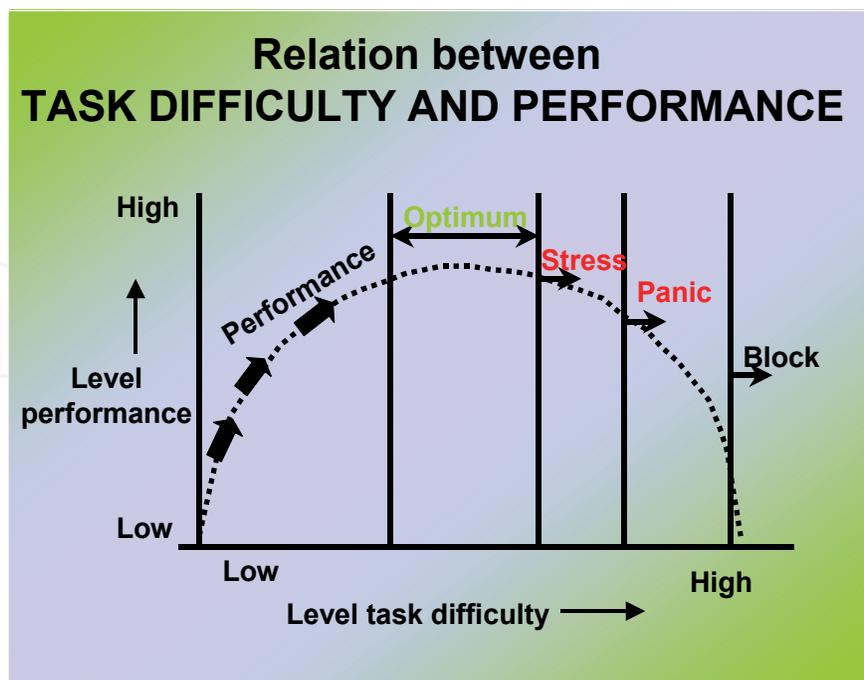
Fig. 2. Correlation between task difficulty and performance

Within the framework of operational agility one can see agility as a function of the airframe, avionics, weapons and pilot. Airframe agility is probably the most crucial component in the operational agility as it is designed in from the onset and cannot be added later. The present chapter focuses on airframe agility and within this, the chapter will relate to the airframe agility in the pitch axis.

A large number of agility metrics have been proposed during the years to determine the aircraft realm of agility. The AGARD Working Group 19 on Operational Agility (McKay, 1994) put together all the different metrics and criteria existing on agility and fit them into a generalizable framework for further agility evaluations. The present section presents the traditional approach on pitch agility using as example a tiltrotor aircraft. This specific aircraft combines the properties of both fixed and rotary-wing aircraft and can be used to define a unified approach in the agility requirements at both fixed and rotary-wings.

The tiltrotor example to be investigated in this study is the Bel XV-15 aircraft. Next, as vehicle model, the FLIGHTLAB model of the Bell XV-15 aircraft as developed by the University of Liverpool (this model is designated as FXV-15) will be used. For a complete description of this model and the assumptions made the reader is referred to (Manimala et. al., 2003). For the tiltrotor in helicopter mode, the pilot's controls command pitch through longitudinal cyclic, roll through differential collective (lateral cyclic is also provided for trimming), yaw through differential longitudinal cyclic and heave through combined collective. In airplane mode, the pilot controls command conventional elevator, aileron and rudder (a small proportion of differential collective is also included).

Pitch agility is the ability to move, rapidly and precisely, the aircraft nose in the longitudinal plane and complete with easiness that movement. This implies that in the agility analysis one has to search for sample manoeuvres to be carried out by the flight vehicle dominated by high flight path changes and high rate of change of longitudinal acceleration which can give a good picture of the agility characteristics. As starting point in this discussion on pitch

agility we will consider the kinematics of a sharp pitch manoeuvre – a simple example of this type is the tiltrotor trying to fly over an obstacle (see Fig. 3). Assume that the manoeuvre is executing starting from different forward speeds (helicopter mode 60 kts and 120kts; airplane mode 120 kts and 300 kts) and the manoeuvre aggressiveness is varied by varying the pulse duration (from 1 to 5 sec). The pilot flies the manoeuvre by giving a pulse input in the longitudinal cyclic stick of 1 inch amplitude.
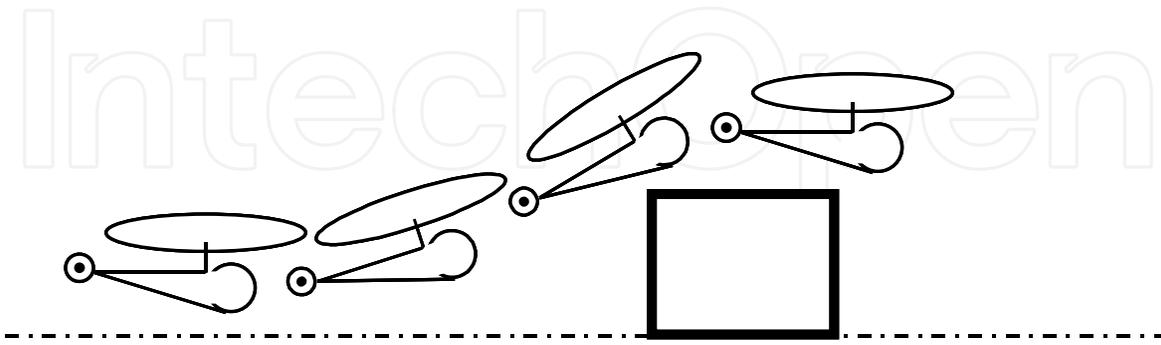

Fig. 3. Executing an obstacle-avoid manoeuvre in the pitch axis

2.1 Transient metrics

The first class of metrics developed to quantify the agility corresponds to the so-called "transient metrics". The transient class contains metrics which can be calculated at any moment for any manoeuvre. For pitch agility these metrics are pitch rate (entitled attitude manoeuvrability metric) and accelerations along the axes a_x, a_y, a_z (entitled manoeuvrability of the flight path). These metrics are next studied for the pull up manoeuvres flown with the FXV-15 in a 1 second pulse given from the initial trim at 120kts in helicopter mode and 300 kts in airplane mode. The presentation of the transient metric information is best achieved through a time history plot. Fig. 4 presents the transient metrics parameters of pitch rate q and vertical acceleration n_z (in the form of normal load factor). Looking at Fig. 4 one may see local maxima in the metric parameters q and n_z illustrating peak events in the agility characteristics. This clearly demonstrates that in a "real" manoeuvre sequence, the agility characteristics occur at key moments, depending on the manoeuvre.

2.2 Experimental metrics

The above conclusion gave the idea to develop a new class of agility metrics, the so-called "experimental metrics" formulated as discrete parameters during a real manoeuvre sequence. These metrics are actually the basic building blocks for understanding the agility and can be related to flying qualities and aircraft design. The metrics describing pitch agility during aggressive manoeuvring in vertical plane were defined by (Murphy et. al., 1991) and are described in the next section. They referred to the ability of an aircraft to pint the nose in at an opponent and commented that what was not clear in such manoeuvres was the behaviour of the flight path. Was the nose pointing w.r.t. the velocity vector or did it include the flight path bending or perhaps both? The authors noted that longitudinal stick displacements would be expected to command the flight path in addition to the aircraft nose pointing pitch angle for agile aircraft. The study pointed out that current aircraft behave differently in the high speeds and slow speed regimes. In the high speed case the flight path displaced as per the nose pointing displacement. The low speed case exhibited no flight path or even opposite flight path displacements.
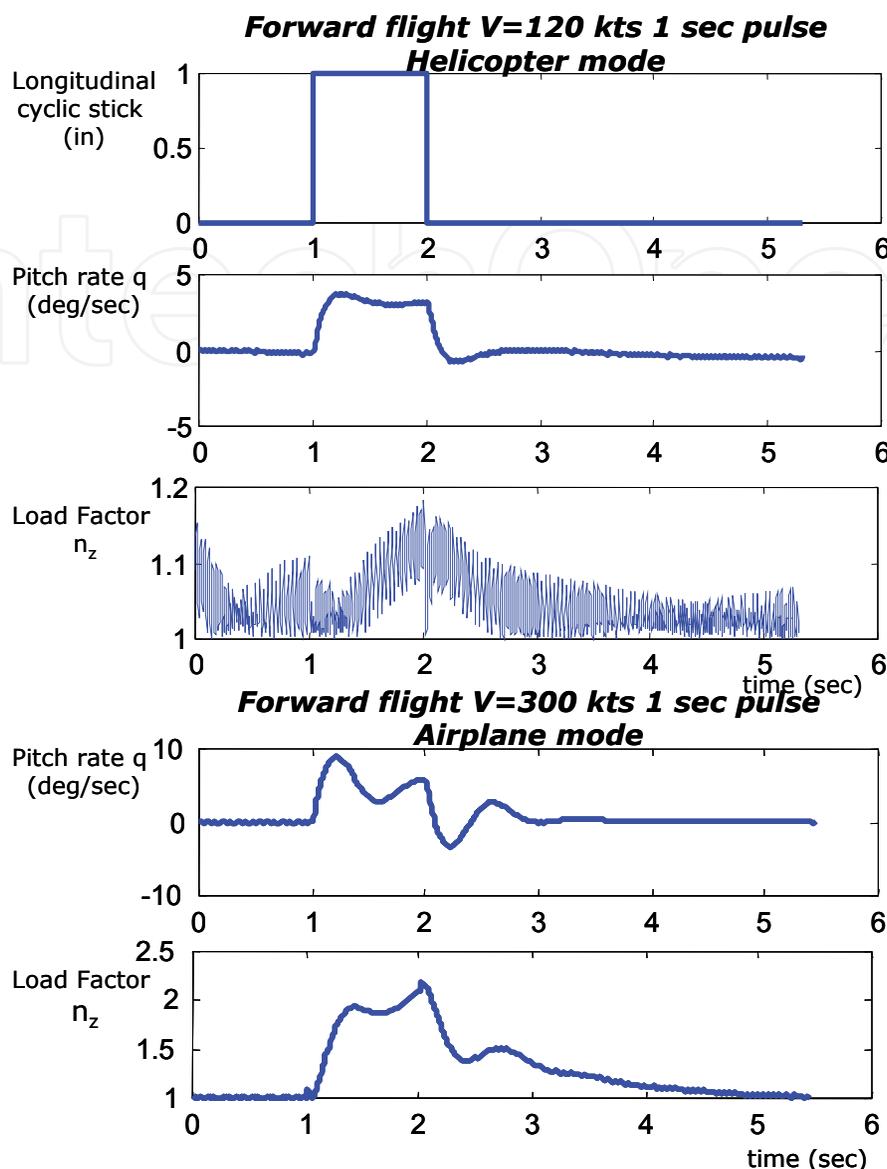
Fig. 4. Transient agility metrics for pull-up manoeuvres with the tiltrotor

2.2.1 Peak and time to peak pitch rates

The peak and time to peak pitch rates metrics were proposed by (Murphy et. al., 1991) for fixed wing aircraft. These metrics measure the time to reach peak pitch rate and the corresponding pitch rate. Fig. 5 presents charts of peak pitch rate and time to reach this peak as a function of the velocity for the tiltrotor flying pull-up manoeuvres of increasing pulse duration. The pull-up manoeuvres are executed gradually increasing the velocity and the nacelle angle from the helicopter mode (90deg nacelle, hover and 60 kts) to conversion (60deg nacelle 120 kts) and ending in airplane mode (0deg nacelle 200 kts). Looking at these figures one can see that as the velocity increases the pilot is able to achieve higher pitch rates, the time to achieve these peaks being and faster especially if the pulse duration is short. As attributes, the peak and time to peak pitch rates metrics have the advantage that can be related to design.
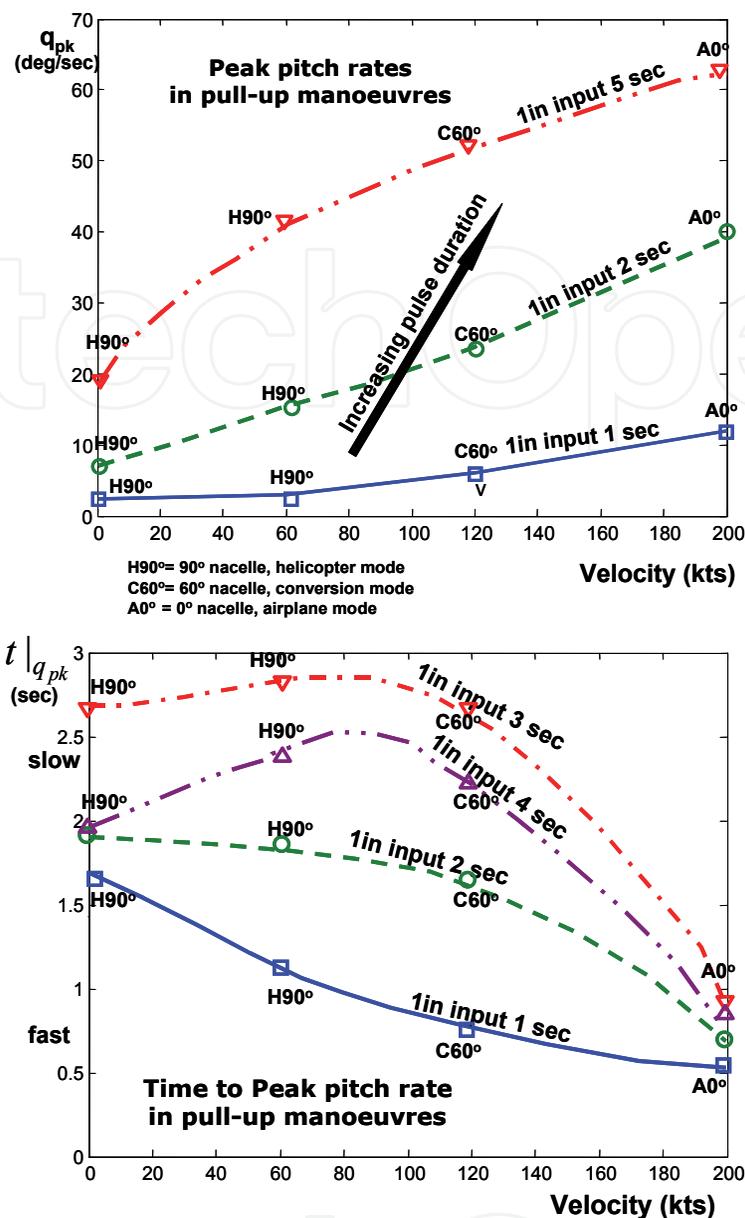
Fig. 5. Peak and time to peak pitch rates in pull-up manoeuvres

2.2.2 Peak and time to peak pitch accelerations

(Murphy et. al., 1991) considered the so-called peak and timer to peak pitch accelerations as the primary metrics for pitch motion agility. The time to peak acceleration provides insight into the jerk characteristics of pitch motion: if it is too slow, then the pilot may complain that the aircraft is too sluggish for tracking-type tasks; if it is too fast, then the pilot may complain of jerkiness or over-sensitivity. Fig. 6 presents charts of peak and time to leak pitch acceleration as a function of velocity when flying pull-ups manoeuvres. One can see that as the velocity increases the pilot is able to obtain higher pitch accelerations but as is passing from the helicopter to aircraft mode this capability diminishes. For fixed wing aircraft, (Murphy et. al., 1991) commented on the differences in the data for the peak accelerations in the body and wind axes. This effect has implications on the pilot selection of flight path or nose pointing control during manoeuvring.
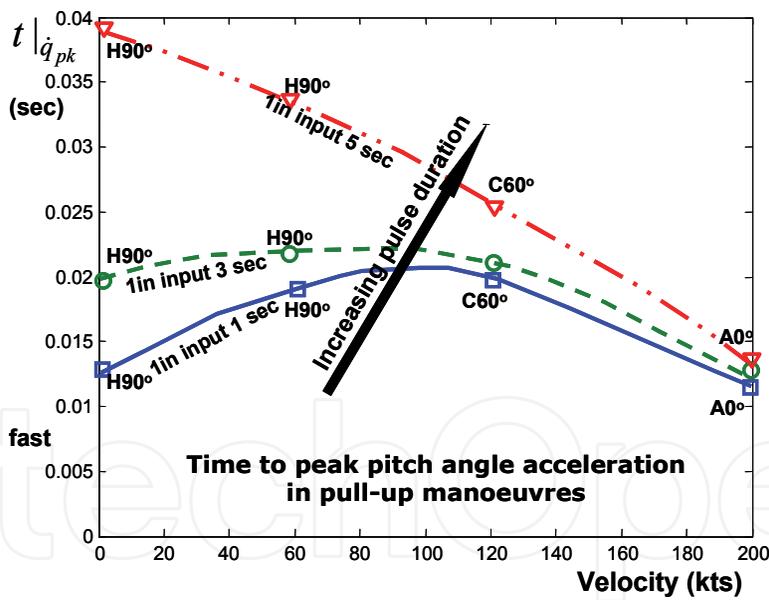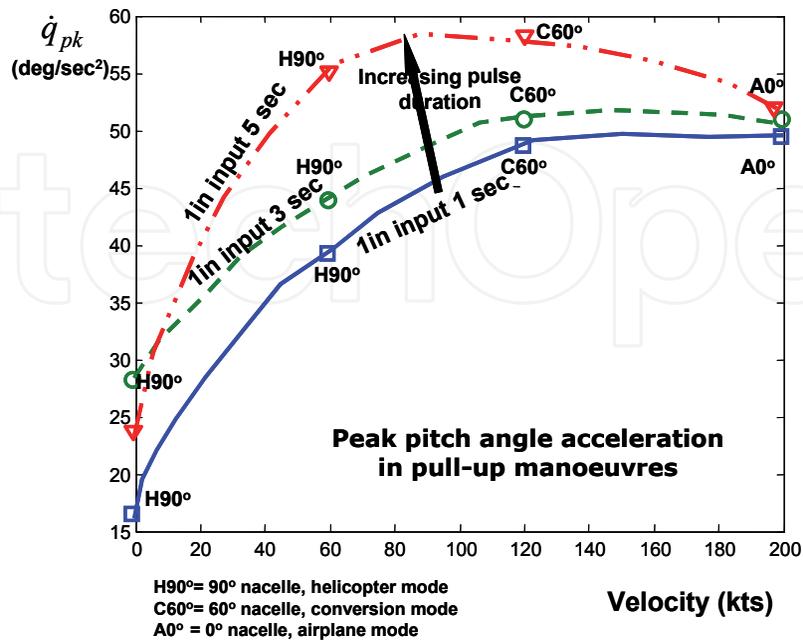
Fig. 6. Peak and time to peak pitch angle acceleration in pull-ups with the tiltrotor

2.2.3 Peak and time to peak load factor

Peak and time to peak load factor metrics describe the peak and the transition time to the peak normal load factor during a manoeuvre in pitch axis. They can be used at best to determine the flight path bending capability of an aircraft. Fig. 7 presents these two metrics as a function of the velocity for the tiltrotor example. One may see that as the velocity increases the pilot is able to pull more g's as going from the airplane to helicopter mode.
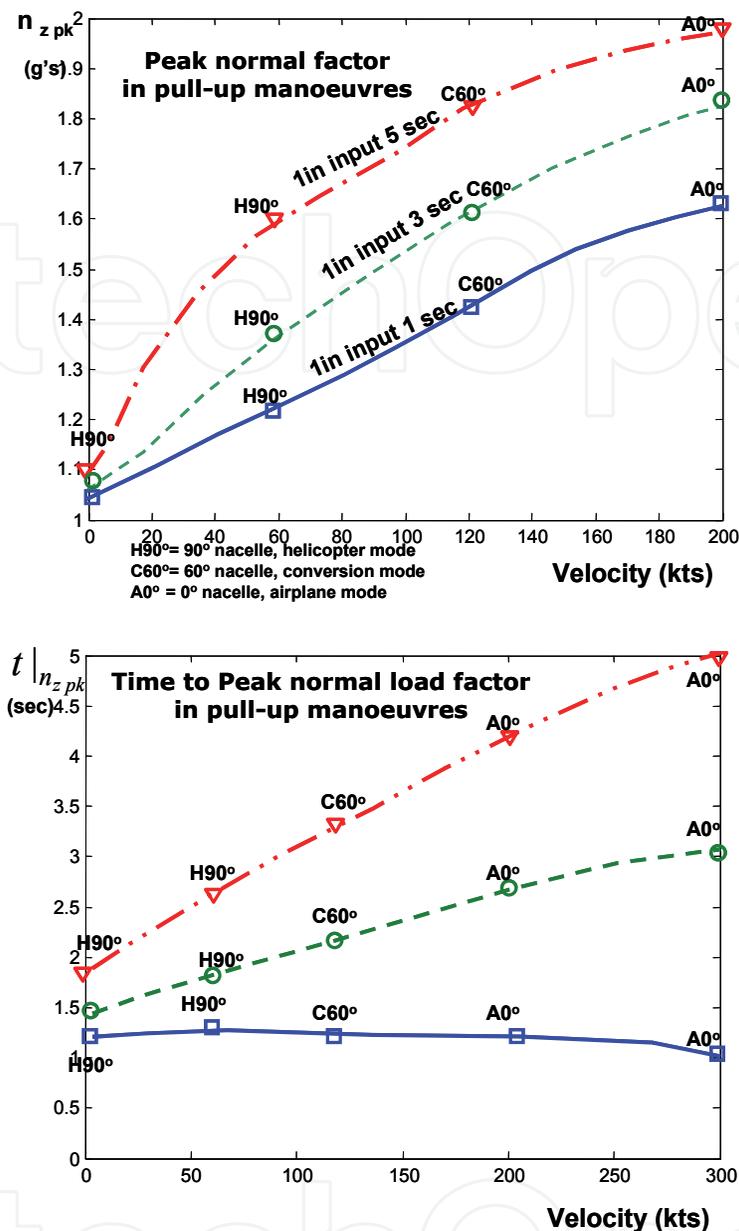
Fig. 7. Peak and time to peak normal load factor

2.2.4 Pitch attitude quickness parameter

One of the most important pitch agility metrics introduced by ADS-33 helicopter standard (ADS-33, 2000) is the so-called "pitch attitude quickness" parameter and is defined as the ratio of the peak pitch rate to the pitch angle change:

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

The advantage of this parameter is that it was linked to handling qualities so that potential bounds for agility could be identified. In this sense, ADS-33 presents HQs boundaries for the pitch quickness parameter as a function of the minimum pitch angular change $\Delta\theta_{min}$

(considered as the pitch angle corresponding to a 10% decay from q_{pk}). These boundaries are defined to separate different quality levels, but because they relate too to an agility metric, they become now boundaries of available agility. Fig. 8 illustrates the attitude quickness charts for the tiltrotor executing pull-up maneuvers of 1 to 5 sec 1in amplitude input at 60, 120 and 300 kts in helicopter and airplane mode. The figure shows also the Level 1/2 boundaries as defined by 1) ADS-33 for a general mission task element, low speed helicopter flight (<45kts) and 2) MIL STD 1797A for fixed wing aircraft. One may see that whereas in helicopter mode FXV-15 hardly meets Level 1 performance in ADS-33 standard, being mostly at Level 2 performance, in airplane mode FXV-15 meets Level 1 performance in AHS-33 but exhibits Level 2 performance according to the MIL standard for airplanes (MIL HDBK-1797, 1997).
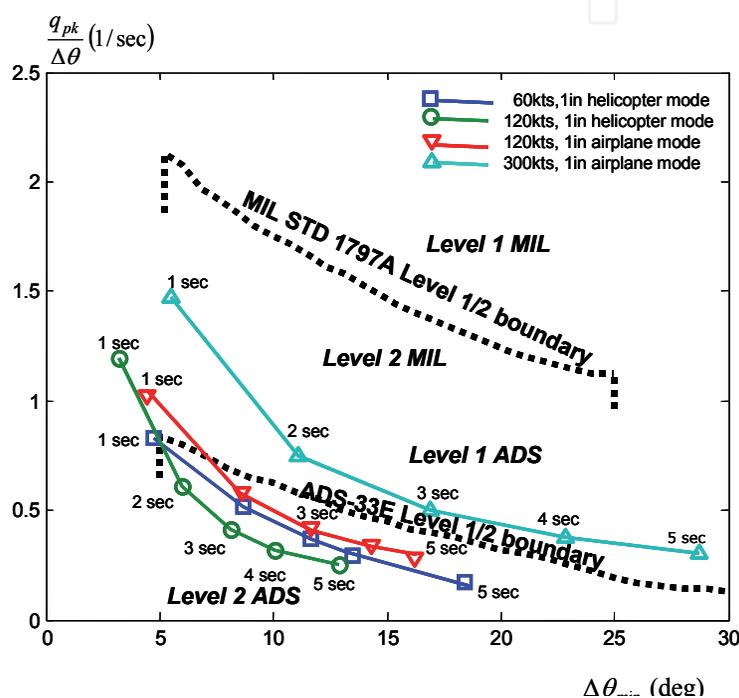

Fig. 8. Pitch quickness for the tiltrotor

3. Flying qualities metrics for agility designing

Linking the agility to flying qualities raised up a new question: is agility limited by pilot handling parameters or in other words what are the upper limits to agility set by flying qualities considerations? Flying qualities considerations do limit agility according to (Padfield, 1998). In this sense, in a series of flight and simulation trials research conducted at DERA (now Qinetics) the pilots were asked to fly maneuvers with increasing tempo until either performance or safety limit was reached. The results showed that in all cases the safety limit came first, thus the agility was constraint by safety.

3.1 Agility factor

A new metric was therefore introduced as a measure of performance margin (Padfield & Hodkinson, 1993), the so-called agility factor A_f, defined as the ratio of used to usable performance. For the simple case of the pull-up maneuver this metric can be easily calculated as the ratio of ideal task time T_i to actual task time T_a.

$$A_f \overset{def}{=} \frac{T_i}{T_a} = \frac{\omega_m \Delta t}{\omega_m \Delta t - \ln(0.1)} \tag{2}$$

where $T_i = \Delta t$ is the control pulse duration (1 to 5 sec), Ta is the time to reduce the pitch angle to 10% of the peak value achieved and ωm is the fundamental first-order break frequency or pitch damping which for this simple case represents the maximum achievable value of quickness. Fig. 9 illustrates the variation of Af with $\omega_m \Delta t$ -thus the quickness. The values considered for ω_m were: ωm=1.81 rad/s in hover helicopter mode, ω_m=2.6 rad/s at 60kts helicopter mode, ω_m=3.6 rad/s at 120kts 60deg conversion mode. Fig. 9 underlines an important aspect of the link between handling and agility: the higher the quickness, the higher the agility but when this agility is connected to Fig. 8 one may see that at the highest agility poor Level 2 ratings are awarded, i.e. the performance degrades rather than improves. This shows that actually, in practice, the closer the pilot flies to the performance boundary the more difficult it becomes to control the maneuver and thus the higher the agility the worse the HQs. In conclusion, handling qualities considerations do limit the agility.
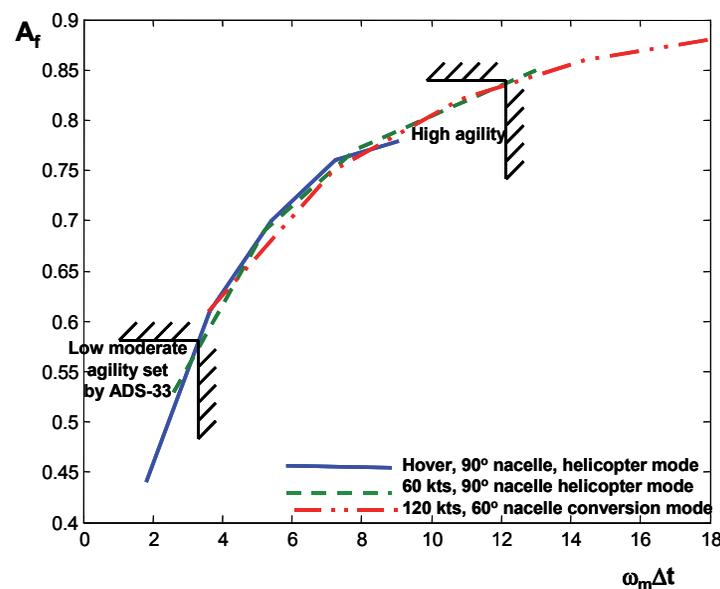

Fig. 9. Agility factor as a function of quickness

3.2 Control anticipation parameter

The discussion on the experimental metrics suggests that on the one side the best metric for pitch motion agility is the peak pitch acceleration and on the other side the best metric for determining the aircraft flight path bending capability is the peak load factor. In order to capture both the transients of the maneuver and the precision achieved in flight path control, MIL standard on fixed-wing aircraft (MIL-HDBK-1797, 1997) introduced as metric a combination between these two metrics, the so-called 'control anticipation parameter CAP'. CAP is defined as the ratio of the initial pitch acceleration to the steady state load factor (effectively pitch rate) after a step-type control input:

$$CAP \overset{def}{=} \frac{\dot{q}(0)}{n_z^{qs}} \tag{3}$$

MIL standard defines CAP boundaries for fixed-wing aircraft. Fig. 10 presents the agility of the FXV-15 CAP as a function of speed (60 kts, 120 kts and 200 kts) in the MIL boundaries. Looking at this figure one can see the tiltrotor meets Level 1 MIL performance and some degradation to Level 2 is seen when flying at high speeds in airplane mode.
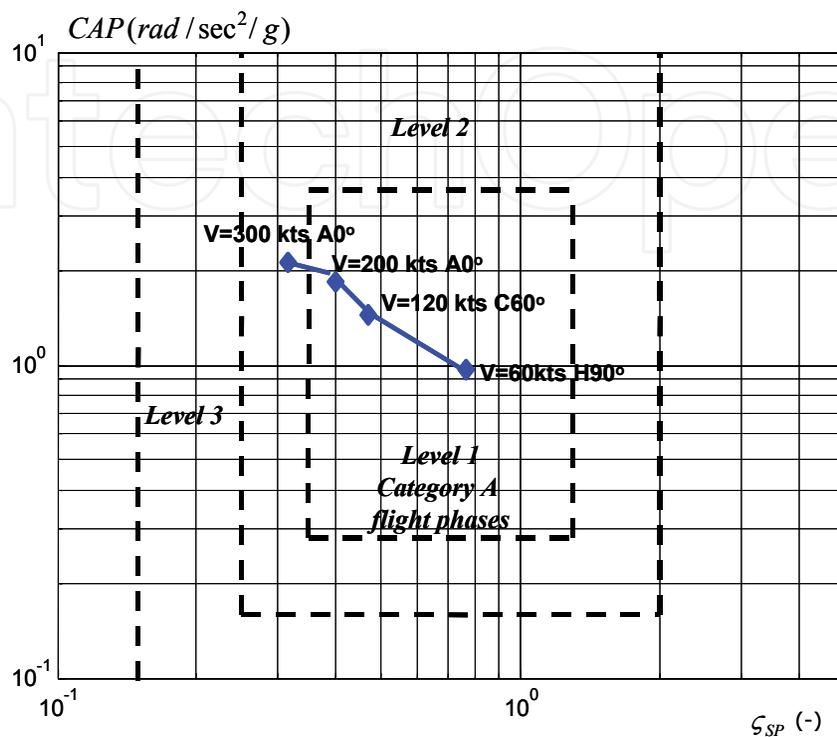

Fig. 10. CAP boundaries for the tiltrotor

3.3 Rate pitch quickness

For helicopters a similar metric to CAP was introduced by (Padfield & Hodkinson, 1993). This metric was called 'rate pitch quickness' and was defined as the ratio of pitch acceleration to the pitch angle change:

$$\dot{Q}_\theta \stackrel{def}{=} \frac{\dot{q}_{pk}}{\Delta\theta} \left(\sec^{-2}\right) \tag{4}$$

and can be used to determine upper limits to agility based on maneuver acceleration. Fig. 11 plotted the rate quickness in the normalized form as a function of acceleration time constant $\omega_m t_{pk}$ (where t_{pk} is the time to peak acceleration).

One can see that as the rate quickness increases the time to peak that rate is decreasing, so the agility is increasing. However, (Padfield & Hodkinson, 1993) commented that simply increasing the agility in terms of acceleration rates would lead to over-responsiveness and thus decreasing in operational capability since an over-responsive vehicle would not be controllable. In this sense, also CAP was quoted as an example of a criterion defining over-responsiveness. Unfortunately, there were no boundaries defined in this chart, although it was mentioned that intuitively there are likely to be upper and lower bounds for this metric. '*Hard and fast may be as unacceptable as soft and slow, both leading to low agility factors*' (Padfield & Hodkinson, 1993).
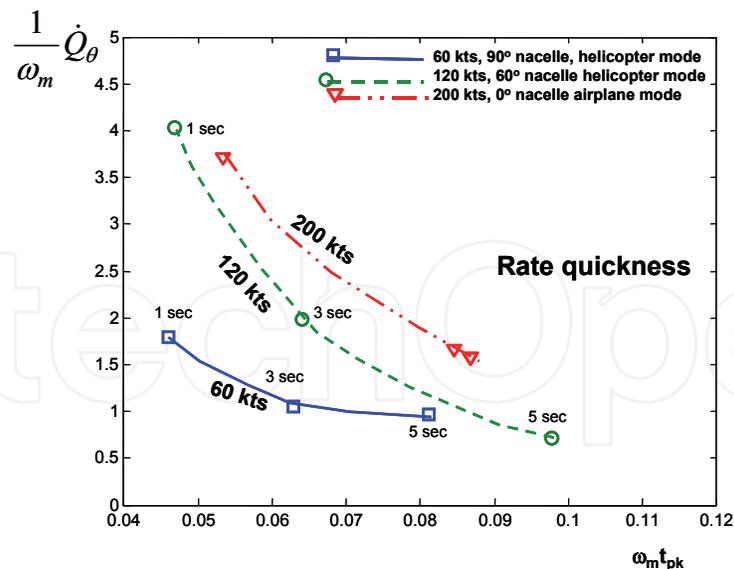
Fig. 11. Rate quickness as a function of time peak acceleration

4. A rational development of a multi-disciplinary approach to agility

Combining equation (3) for CAP with equation (4) for rate quickness it follows that:

$$\dot{Q}_\theta = CAP \cdot \frac{n_z}{\Delta\theta} \tag{5}$$

Equation (5) gives the idea that rate quickness and CAP can be related to each other through a new metric which will be presented in the next paragraph.

4.1 Agility quickness metric as a measurement of performance

As a potential successful metric for agility, (Pavel & Padfield, 2002) proposed a new metric for characterizing agility, the so-called 'agility quickness' defined as the ratio of peak quasi-steady normal acceleration n_{zpk}^{qs} in g units corresponding to a step change in flight path angle Δγ:

$$Q_\gamma \stackrel{def}{=} \frac{n_{zpk}^{qs}}{\Delta\gamma} \quad \left(\frac{g's}{\deg}\right) \tag{6}$$

Observe that the pitch angle from (5) was substituted by the flight path angle, this has been done because actually during vertical axis maneuvering agility is more related to how quickly the flight path can be changed, the pilot being in reality more interested in the flight path angle change than in the pitch change. Furthermore, (Pavel & Padfield, 2003) proposed a Level 1/2 performance boundary for agility quickness by flying yo-yo maneuvers in the full motion simulator at the University of Liverpool the UH-60A model. Fig. 12 presents the example of tiltrotor on the agility quickness charts as determined in (Pavel & Padfield, 2003).

One can see that the tiltrotor is mostly at Level 2 performance in helicopter and airplane modes. (Pavel & Padfield, 2003) derived a relation between CAP and Q_γ and (Padfield & Meyer, 2003; Cameron & Padfield, 2010) connected CAP to other flying qualities parameters. One of the reasons the attitude quickness criterion has gained large acceptance was due to its physical interpretation (in the limiting case gives the time constant of the aircraft as a function

of the time constant of the maneuver). It can be demonstrated that agility quickness has also a physical interpretation, in the limiting case for small-amplitude maneuvers giving the heave damping, for large amplitudes giving the attitude quickness (Pavel & Padfield, 2002).
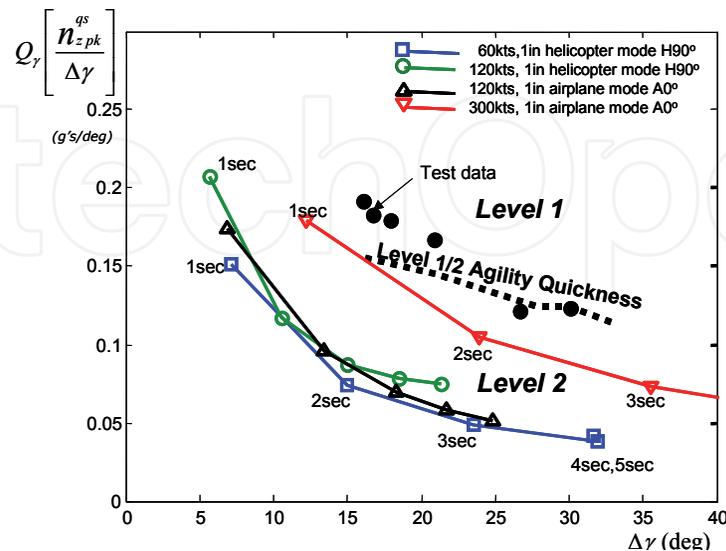

Fig. 12. Tiltrotor on Agility quickness chart

4.2 Vibratory quickness metric as a measurement of vibratory activity

The advantage of the agility quickness metric as above defined is that it could be linked to a complementary vibratory for structural alleviation. In this way, the designer is able to optimize in parallel both the performance and the vibratory loads in maneuvering flight. This novel approach may reform the methods presently used to accomplish agility of a new design as it is well known that, in practice, performance is itself often compromised by the need to control and minimize vibration.

(Pavel and Padfield, 2002) define an parallel metric, so-called 'vibratory load quickness' quantifying the buildup of loads in the rotor during maneuvering flight:

$$Q_l \stackrel{def}{=} \frac{F_{pk}^{vib}}{W\Delta\gamma} \left(\frac{1}{\deg}\right); \quad Q_l \stackrel{def}{=} \frac{M_{pk}^{vib}}{\Delta\gamma}\left(\frac{lbf \cdot ft}{\deg}\right) \tag{7}$$

where F_{pk}^{vib}, M_{pk}^{vib} represent the peak amplitudes in the critical vibratory components for respectively hub shears and hub moments corresponding to a change $\Delta\gamma$ in flight path angle. The peak load amplitude can be calculated by using the FFT and time representations of the hub shears ($F_{x\ hub}$, $F_{y\ hub}$ or $F_{z\ hub}$) and/or moments ($M_{x\ hub}$, $M_{y\ hub}$, $M_{z\ hub}$) during a maneuver flown and determining the critical loads (i.e. the loads achieving the highest peaks) during the maneuver.

For example, for the pull-up maneuver flown with the tiltrotor it was found that when flying in helicopter mode at 60 and 120 kts the critical loads developed were the 3/rev vibratory component of the hub vertical shear, the 1/rev and 2/rev components of the blade inplane moment and the 1/rev component of the blade flapping moment. When flying in the airplane mode at 120 and 300 kts, the critical loads measured by the FXV-15 were the 2/rev and 3/rev components of the vertical shear, the 1/rev and 2/rev components of the blade inplane moment.

Fig. 13 presents the equivalent vibratory quickness charts for the critical 3/rev component of the hub vertical shear in helicopter mode and 2/rev and 3/rev components of hub vertical shear in airplane mode when flying respectively at 60 and 120 kts and 120 and 300 kts, giving an 1 in input in longitudinal cyclic and varying the pulse duration (1 to 5 seconds). Each of these vibratory chart can be associated with an equivalent agility quickness chart as plotted in Fig. 12.
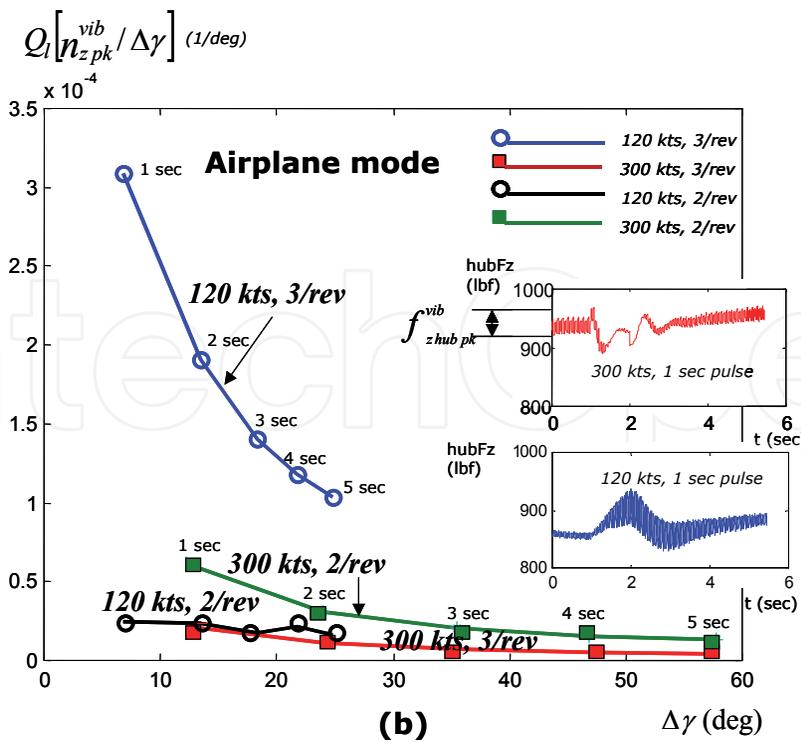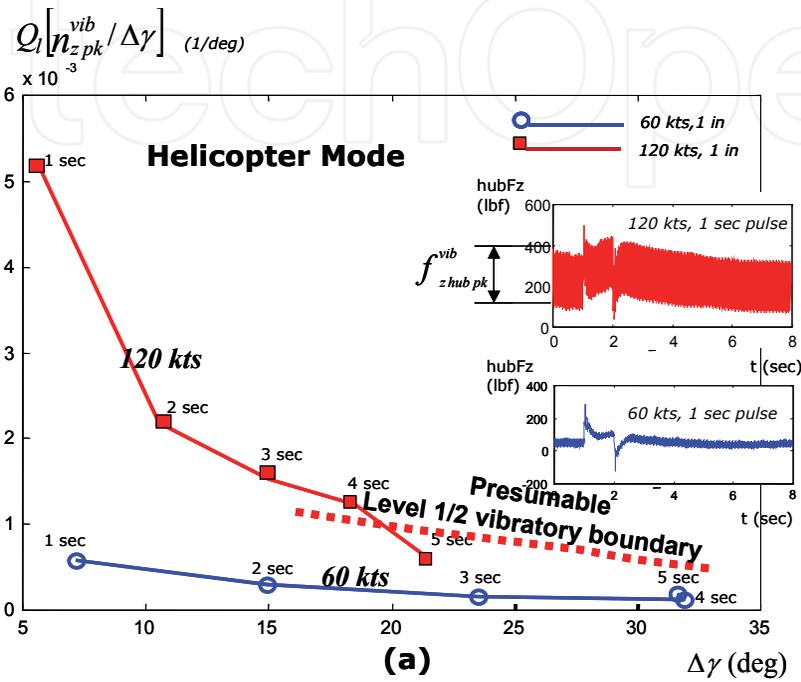

Fig. 13. Vibratory quickness envelopes for the critical components of the hub vertical shear during a pull-up maneuver

For helicopter mode it was plotted a presumable vibratory quickness boundary as derived in (Pavel & Padfield, 2003) when flying piloted yo-yo's in the simulator with the UH-60A helicopter. It was there showed that actually, increasing the flight path change enables the pilot to pull more g's of course but also increases the vibratory activity in the rotor. The presumable vibratory boundary would mean then that the structural designer would aim for a
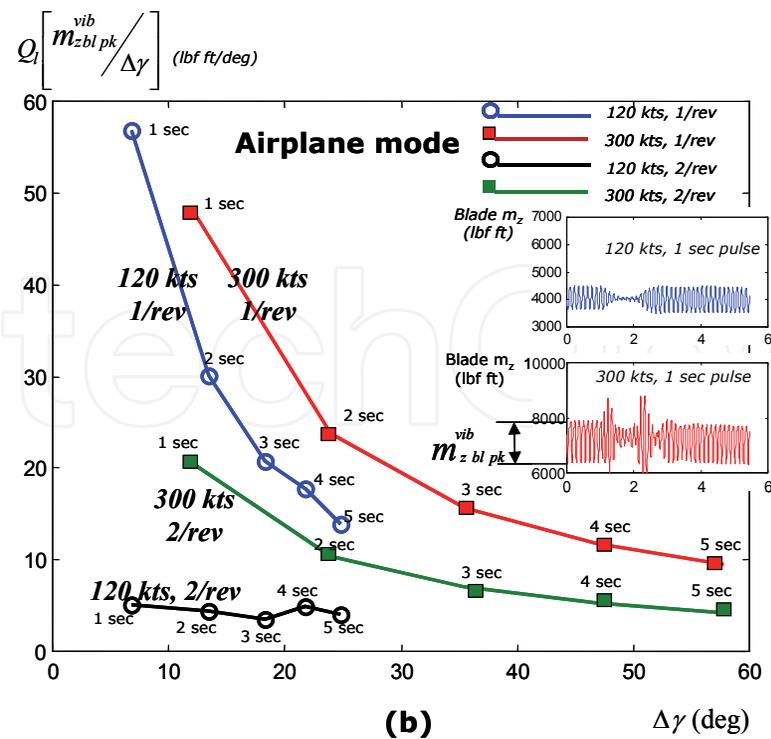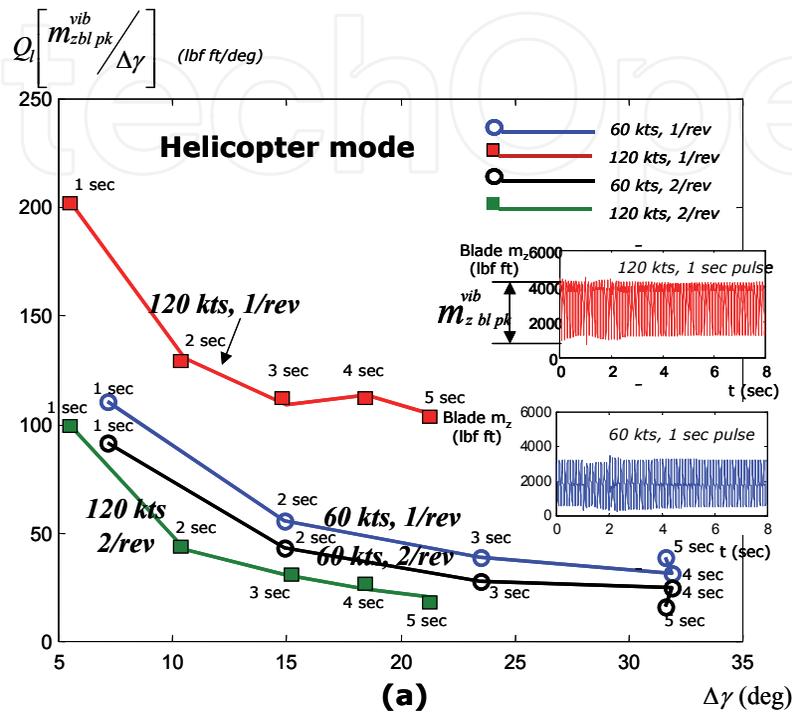

Fig. 14. Vibratory quickness envelopes for the critical components of the blade inplane moment during a pull-up maneuver

boundary that slope in a similar direction to the agility quickness boundary as plotted in Fig. 13. Looking at this figure one may see that as the pulse duration is increasing the vibratory quickness is decreasing. This is because the vibratory activity in the hub reaches its absolute peak rather quickly, depending mainly on the initial velocity, the input amplitude (which is a measure of the level of aggressiveness in executing the maneuver) and not on the pulse duration. However, for very aggressive maneuvering, (Pavel & Padfield, 2002) showed that it might appear the situation in which, increasing the flight path change enabled the pilot to pull more g's (so, increased performance) but also increased the vibratory activity in the rotor. The goal of the structural designer would be then to alleviate these high peak loads to lower levels and reduce the sensitivity of the vibratory loads to flight path angle.

Fig. 14 presents other critical load for the tiltrotor, namely the blade inplane moment. Both, for the helicopter and airplane mode, the critical components measured during the simulation of the pull-up maneuvers with the FXV-15 were corresponding to the 1/rev and 2/rev vibratory components.

Looking at Fig. 14 one may see again that the vibratory quickness parameter Q_l varies approximatively inversely with the flight path change. This means that the vibratory activity in the blade in the inplane direction reaches its absolute peak rather quickly, depending on the aggressiveness of the pulse (pulse amplitude) and not on pulse duration.

5. Conclusion

This chapter has presented a rational development of key metrics and criteria used to design for airframe agility. Concentrating on the agility in the pitch axis (vertical-plane maneuvers) and taking as case study the unique example of a tiltrotor aircraft, the chapter demonstrated how, starting from the more traditional way of quantifying the agility, the designer can develop new agility metrics that do a better job of capturing the aircraft transient motion characteristics. This chapter discussed on the many correspondences that exist between the study of agility and the study of flying qualities, emphasizing the fact that flying qualities do limit agility. In this sense, providing the pilot with a high level of maneuverability, without a high level of controllability, will reduce agility. However, especially for the tiltrotor, higher agility cannot be achieved without increasing the vibratory loads on the rotor, which means also an increasing in pilot workload. The chapter proposed therefore a unique approach by presenting a first set of complementary metrics capable of being applied to both agility and structural load analysis.

Subsequent phases of this study will include the expansion of this new approach and studying it in axial, turning (horizontal-plane maneuvers) and roll (torsion) axes. It is hoped that in this way a more unified set of design criteria will be developed enhancing multi-disciplinary design optimization.

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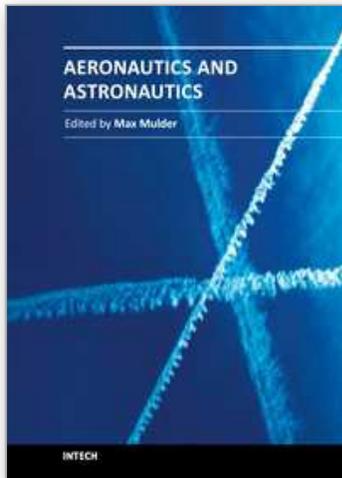
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