NEW ROTORCRAFT DESIGN CRITERIA FOR MAXIMIZED PERFORMANCE AT MINIMIZED VIBRATORY LOADS

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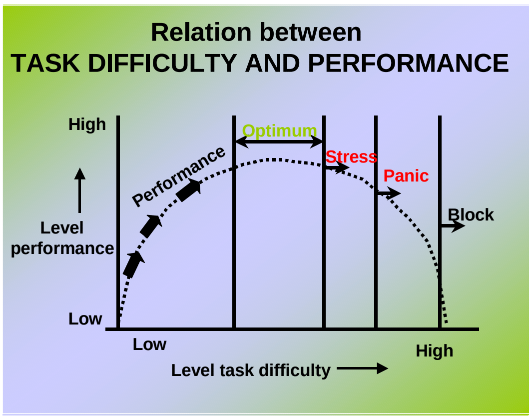
Abstract

Rotary wing configurations (helicopters and tiltrotors) are still more difficult and tiring to fly than fixed-wing aircraft. Usually, helicopter pilots are trained to cope with high workload and expect cross-couplings as "normal". In a recent study on helicopter accidents it was shown that the biggest discrepancy between the accident rates for fixed and rotary wing aircraft arises from the fact that helicopter operations are more dangerous than fixed wing operations. Performing difficult operations implies designing for high agility. However, high agility occurs at the boundaries of the performance where high vibratory loads are developed on the structure. Therefore, designing for high operational capabilities requires a trade-off between agility and vibrations. The aim of the present paper is to develop a logical reasoning, giving the designer the appropriate metrics and tools for 1) enhancing performance when the helicopter is operating close to the limit of their capabilities (in other words enhancing agility) and 2) for reducing the high vibration levels characteristic to helicopters. The paper summarizes the first results obtained on this subject initiated as research collaboration between The University of Liverpool and Delft University of Technology. The emphasis of the paper is on agility characteristics in the pitch axis. In this sense, new metrics will be presented linking agility to vibratory loads. The paper will explain why such new metrics can be used as potential candidates for defining the upper limits to flying qualities, using as an example the case of a tiltrotor. Especially in such configurations, this novel approach could be particularly useful, since this case requires the agility tools for fixed-wing mode and helicopter mode to merge together into new tools.

1 Introduction

At the Flight Simulation Conference in 2001, Hampson [1] discussed a study in which accident data collected by NASA [2] were used to compare the accident rates for fixed and rotary wing aircraft. The main conclusion of this study about helicopter operations was that "*it is ten times more likely to be involved in an accident in a helicopter than in a fixed wing aircraft*". A major cause for the high rate of helicopter accidents is statistically the pilot loss of control. In a different study, Pavel [3] using accident data collected by The World Aircraft Accident Summary [4] revealed that, since 1996, the rate of helicopters accidents caused by pilot loss of control is continuously increasing. The major cause for this might be the fact that today high-attained performances achieved with the helicopters are forcing these machines to operate closer to the limit of their capabilities where our engineering tools and criteria are still poor. The goal of the present paper is to develop a multi-disciplinary tool for designer by developing new criteria showing simultaneously how the pilot performance combines with the vibratory loads developed on the structure when flying different manoeuvres.

It is well known that the level of performance achieved by the pilot in manoeuvres depends on the task complexity. Figure 1 (from the Dutch magazine "Flying Safely", 2001) presents in a generic way this situation, showing that there is a line of saturation up to which the pilot is able to perform the specified mission optimally; increasing the task difficulty above this line leads quickly to stress, panic and even incapacity to cope anymore with the task complexity, sometimes with fatal consequences.



'Fig. 1: Correlation between task difficulty and performance (adapted from the Dutch magazine "Flying safely", 2001)

One of the most important concept defining the upper limits of performance is the so-called "agility". 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 measures the "ability to adapt and respond rapidly and precisely, with safety and poise, to maximize mission effectiveness" [5]. In the mid 80's a strong wave of interest arose in seeking metrics and criteria that could quantify the aircraft agility (see [5], [15]). 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!

The present paper presents a rational development of fundamental metrics on agility and then relates agility to the design performance and, most important, to the structural design.

Within the framework of operational agility one can study 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 paper focuses on airframe agility and within this, the paper will relate to the airframe agility in the pitch axis (vertical-plane manoeuvres).

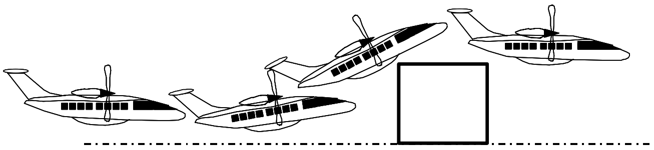
The paper is structured as follows:

- The second section presents an overview of traditional metrics for measuring pitch agility;
- The third section presents metrics proposed in the 90's linking agility to flying qualities;
- Then, based on a rational development of the previous two sections, the fourth section will propose a new approach useful for designer in quantifying both agility and vibratory loads.
- Finally, general conclusions and potential extension of this work will be discussed.

2 Traditionally Designing the Aircraft for Pitch Agility

A large number of agility metrics have been proposed during the years for determining the aircraft realm of agility. In 1994 the AGARD Working Group 19 on Operational Agility [5] put together all the different metrics and criteria existing on agility and fit them into a generalisable 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 for both fixed and rotary-wings. The tiltrotor considered as example in the present investigation is the Bel XV-15 aircraft. As model for this aircraft the paper will use the FLIGHTLAB model of the Bell XV-15 aircraft as developed by the University of Liverpool (model designated as FXV-15). For a complete description of this model and the assumptions made the reader is referred to ref. [6]. 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 refers to the ability to move, rapidly and precisely, the aircraft nose in the longitudinal plane and complete with easiness that movement. This implies that to explore the agility characteristics means searching for those sample manoeuvres to be carried out by the flight vehicle that are dominated by high flight path changes and high rate of change of longitudinal acceleration. A simple example of such a sharp manoeuvre in the pitch axis is a pull-up manoeuvre in which the tiltrotor is trying to fly over an obstacle when the pilot applies a pulse input in longitudinal cyclic (see Fig. 2).

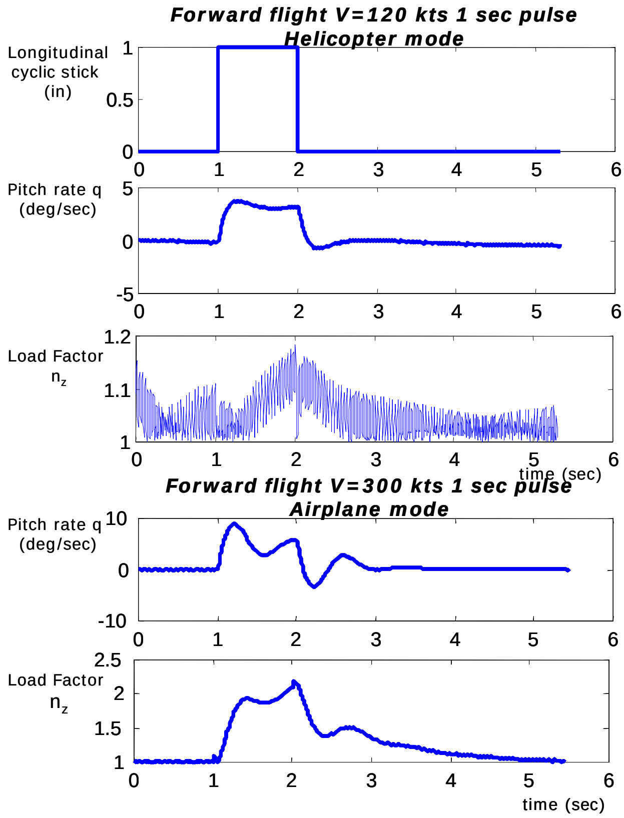


'Fig.2. Executing an obstacle-avoid manoeuvre in the pitch axis'

Pull-up manoeuvres will be performed throughout the paper starting from different forward speeds (helicopter mode, i.e. 90^o nacelle, 60 kts and 120kts; conversion mode at 60^o nacelle 120 kts and airplane mode, i.e. 0^o nacelle at 120 kts, 200kts and 300 kts) and applying an 1 in cyclic stick input, the manoeuvres aggressiveness being varied by varying the pulse duration (from 1 to 5 sec).

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 the attitude manoeuvrability metric given by the pitch rate q(t)) and the manoeuvrability of the flight path metric given by the vertical acceleration as expressed in g units. The presentation of the transient metric information is best achieved through a time history plot. Figure 3 presents the transient metrics parameters of pitch rate q(t) and normal load factor n_z(t) for a pull-up manoeuvre flown with the FXV-15. Assume the cases of a 1 second pulse from the initial trim at 120kts in helicopter mode and 300 kts in airplane mode.



'Fig. 3. Transient agility metrics for pull-up manoeuvres with the FXV-15 tiltrotor'

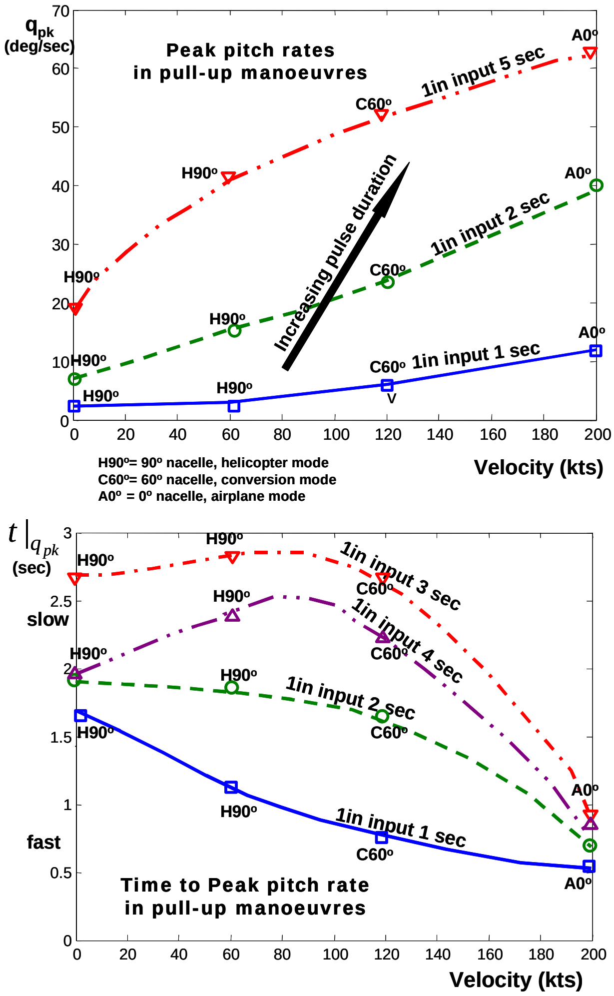
Looking at Fig. 3 one may see local maxima in the metrics q(t) and $n_z(t)$ illustrating peak events in the agility characteristics. These peaks clearly demonstrate that in a "real" manoeuvre sequence, <u>the agility characteristics occur at key moments, depending on the manoeuvre</u>.

2.2 Experimental metrics

As the agility seems to happen at key moments, a new class of agility metrics was defined, 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. in ref. [7] and will be illustrated below. They refer to the ability of an aircraft to point the nose at an opponent. Murphy et. al. commented that what is not clear in pitch manoeuvres is the behavior of the flight path: is the nose pointing w.r.t. the velocity vector or does it include the flight path bending or perhaps both? For agile aircraft, longitudinal stick displacements would be expected to command the flight path in addition to the aircraft nose pointing pitch angle. However, while in high speed regimes the flight path seem to displace with every nose pointing displacement, at low speeds there is no displacement of the flight path or even opposite flight path displacements may appear. The next paragraphs describe several experimental metrics as defined by ref. [7] determined for the example of the tiltrotor aircraft.

2.2.1 Peak and time to peak pitch rates

Peak pitch rate metric and the time to peak pitch rate metric were proposed by Murphy et. al. [7] for the fixed wing. Figure 4 presents charts of peak pitch rate q_{pk} and time $t\,|_{q_{pk}}$ 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 (90^o nacelle in hover and 60 kts) to conversion (60^o nacelle 120 kts) and finally airplane mode (0^o nacelle 200 kts).

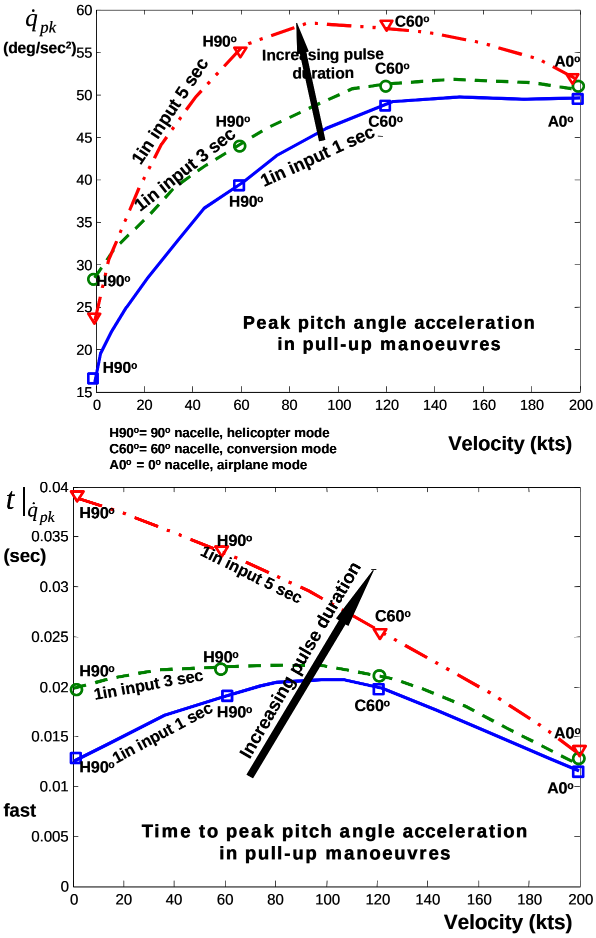


'Fig. 4. Peak and time to peak pitch rates in pull-up manoeuvres'

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 faster especially if the pulse duration is short. As attributes, the peak and time to peak pitch rates metrics have the advantage of being easily related to the design.

2.2.2 Peak and time to peak pitch accelerations

Alternative well-accepted metrics for agility are the pitch acceleration and time to peak pitch acceleration. These metrics are considered by Murphy et. al. [7] to be the <u>primary metrics for pitch motion agility</u>. Figure 5 presents charts of peak $\dot{q}_{pk}$ and time $t|_{\dot{q}_{pk}}$ to peak pitch acceleration as a function of velocity when flying pull-ups manoeuvres.

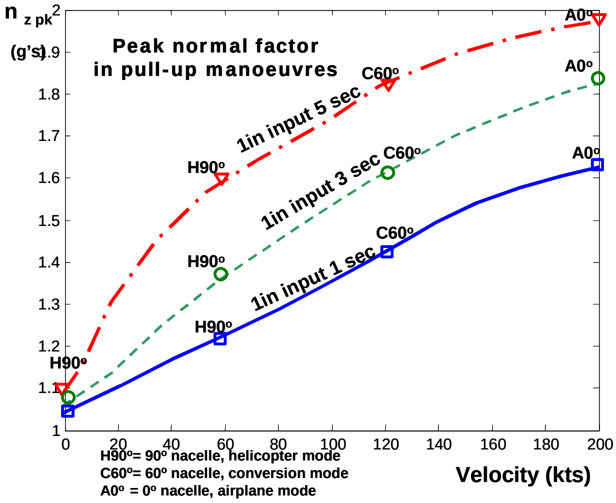


‘Fig. 5 Peak and time to peak pitch angle acceleration in pull-ups with the tiltrotor’

One can see that as the velocity increases the pilot is able to obtain higher pitch accelerations but going from the helicopter to aircraft mode this capability diminishes. Murphy et. al. [7] commented on the fact that, interestingly, the data for the peak accelerations for the body and wind axes may show differences. These differences have implications on the pilot selection of flight path or nose pointing control during manoeuvring. 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; if it is too fast, then the pilot may complain of jerkiness or over-sensitivity.

2.2.3 Peak and time to peak load factor

The metrics peak normal load factor and transition time to this peak can be used at best to determine the flight path bending capability of an aircraft. Fig. 6 presents the peak normal load factor 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 is going from the airplane to helicopter mode.



‘Fig. 6 Peak and time to peak normal load factor’

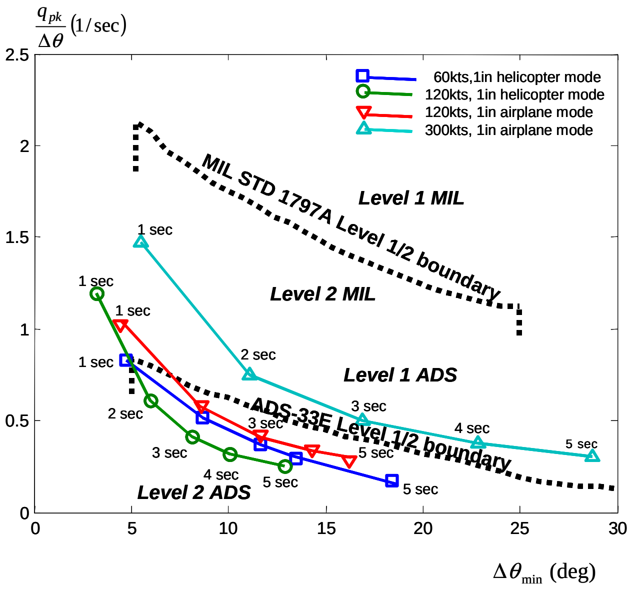
2.2.4 Pitch Attitude Quickness parameter

One of the most important agility metrics introduced by ADS-33 [8] for rotary wing aircraft in the pitch axis is the so-called “pitch attitude quickness” metric. This metric is defined as the ratio of the peak pitch rate q_{pk} to the pitch angle change $\Delta\theta$:

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

The advantage of this parameter is that it was linked to handling qualities (HQs) 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 $\Delta\theta_{min.}$ These boundaries are defined to separate different handling qualities levels, but because they relate as well to an agility metric, they become now boundaries of available agility.

Fig. 7 illustrates the attitude quickness charts for the tiltrotor executing pull-up manoeuvres of 1 to 5 sec, 1 in amplitude input at 60, 120 and 300 kts in helicopter and airplane mode (for $\Delta\theta_{min}$ consider the pitch angle corresponding to a 10% decay from q_{pk}). 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.



‘Fig. 7 Pitch quickness for the tiltrotor’

One may see that whereas in helicopter mode FXV-15 hardly meets Level 1 performance in the ADS-33 standard in airplane mode FXV-15 meets Level 1 performance in AHS-33 but exhibits Level 2 performance according to the MIL standard for airplanes [11].

3 Flying Qualities Metrics for Agility Design

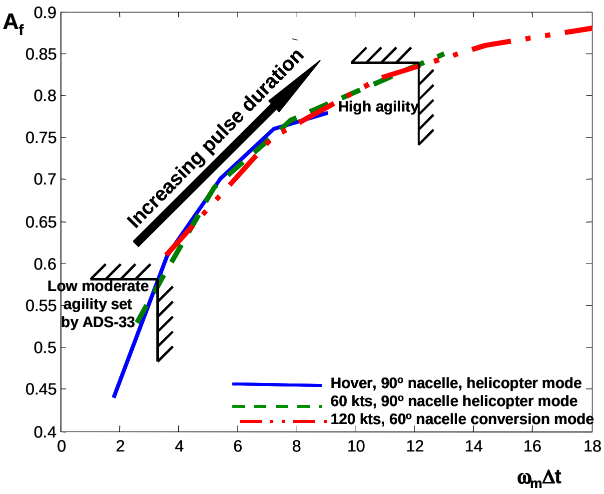
Linking agility to flying qualities raises up a new question: is agility limited by pilot handling qualities or, in other words, are there upper limits for agility imposed by flying qualities considerations? Padfield [9] discussed the fact that flying qualities considerations do limit agility. In this sense, in a series of flight and simulation trials research conducted at DERA (now Qinetics) in the 90’s the pilots were asked to fly manoeuvres 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 the safety.

3.1 Agility factor

A new metric introduced to measure the performance margin and discussed by Padfield and Hodkinson in ref. [10] was the so-called agility factor A_f. Agility factor is defined as the ratio of used to usable performance. For the simple case of the pull-up manoeuvre, agility factor can be easily calculated as the ratio of ideal task time T_i to actual task time T_a and can be expressed as a function of the fundamental first-order break frequency ω_m and the control pulse duration (see ref. [10]):

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

where $T_i = \Delta t$ is the control pulse duration (1 to 5 sec), T_a is the time to reduce pitch angle to 10% of the peak value achieved and ω_m is the natural aircraft bandwidth or pitch damping. Figure 8 illustrates the variation of A_f with $\omega_m\Delta t$. For the pull up manoeuvre ω_m represents actually the maximum achievable value of quickness and thus Figure 8 shows the agility factor as a function of maximum achievable quickness.



‘Fig. 8 Agility factor as a function of quickness’

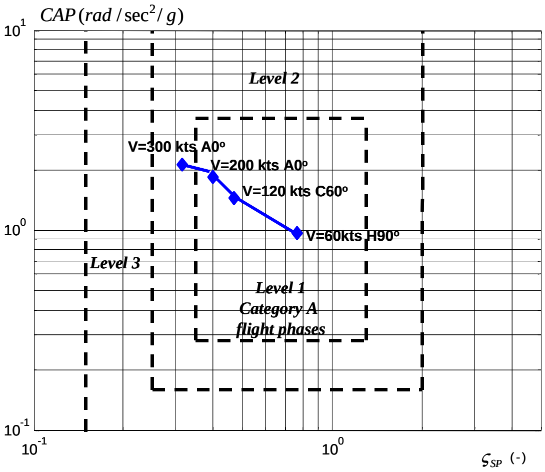
The values considered for ω_m in the simulations with the FXV-15 model are: ω_m=1.81 rad/s in hover, helicopter mode; ω_m=2.6 rad/s at 60 kts, helicopter mode; ω_m=3.6 rad/s at 120kts, 60° conversion mode. Looking at Fig. 8 one can see that increasing the pulse duration results in high agility factors, especially when flying in airplane mode. Figure 8 underlines an important aspect concerning the link between handling qualities and agility. The higher the quickness, the higher the agility but looking also at Fig. 7 one may see that the higher the quickness (thus agility) the poorer the handling qualities. In fact, looking at Fig. 7 one can see that at 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 manoeuvre and thus the higher the agility the worse the HQs. In conclusion, handling qualities considerations do limit the agility.

3.2 Control anticipation parameter

The discussion on the experimental metrics in section 2.2 suggests that the best metrics for measuring both the agility and flight path bending are peak pitch acceleration and peak load factor. In order to capture both these metrics, MIL STD standard on fixed-wing aircraft [11] introduced the so-called "control anticipation parameter CAP" metric. CAP is defined as the ratio of the initial pitch acceleration $\dot{q}(0)$ to the steady state load factor n_z^{qs} after a step-type control input:

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

MIL STD defines CAP boundaries for fixed-wing aircraft. Fig. 9 presents the CAP metric for FXV-15 model as a function of speed (60 kts, 120 kts and 200 kts) in the MIL boundaries. Looking at this figure one can see that FXV-15 meets Level 1 MIL performance with some degradation to Level 2 when flying at high speeds in airplane mode.



'Fig. 9 CAP boundaries for the tiltrotor'

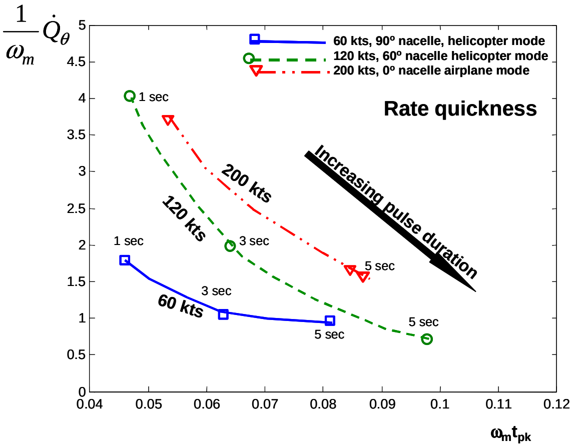
For a further investigation of CAP relation to other flying qualities parameters the reader is referred to ref. [14].

3.3 Rate pitch quickness

For helicopters, a similar metric to CAP was introduced by Padfield and Hodkinson [10]. This metric was called "rate pitch quickness" and was defined as the ratio of pitch acceleration $\dot{q}_{pk}$ to the pitch angle change Δθ:

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

Fig. 10 plotted the rate quickness (non-dimensionalized with the natural aircraft bandwidth ω_m) as a function of the acceleration time constant $\omega_m t_{pk}$ (t_{pk} is the time to peak acceleration).



'Fig. 10 Rate quickness as a function of time peak acceleration'

One can see that as the rate quickness increases, its time to peak decreases, thus causing the agility to increase. However, simply increasing the agility in terms of acceleration rates would lead to over-responsiveness and thus decrease in operational capability since an over-responsive vehicle would not be controllable. In this sense, rate quickness metric and also CAP can be seen as metrics defining over-responsiveness. Unfortunately, the usefulness of rate quickness as metric setting upper limits to agility was not further investigated, more flight and simulation data being needed to be gathered in order to define the upper and lower bounds for this metric.

4 A Rational Development of a Multi-Disciplinary Approach to Agility

Combining equations (3) and (4) results in the following relation:

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

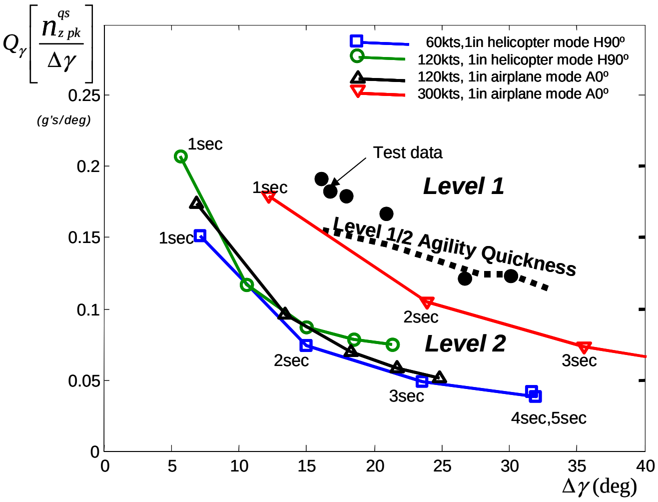
Equation (5) gives the idea that rate quickness and CAP can be related to each other through a new metric. This metric will be investigated in the next paragraph.

4.1 Agility Quickness Metric as a Measurement of Agility and Performance

As a potential useful metric for agility Pavel and Padfield [12] proposed a new metric for characterizing agility, the so-called "agility quickness" metric defined as the ratio of peak quasi-steady normal acceleration $n_{z\,pk}^{qs}$ in g units to a step change in flight path angle Δγ:

$$Q_{\gamma} \overset{def}{=} \frac{n_{z\,pk}^{qs}}{\Delta\gamma} \left(\frac{g's}{\deg}\right) \tag{6}$$

Observe that the pitch angle Δθ from (5) was substituted by the flight path angle, this has been done because actually during vertical axis manoeuvring agility is more related to how quickly the flight path can be changed (the pilot is in reality more interested in the flight path angle change than in the pitch change). Furthermore Pavel and Padfield [13] defined the Level 1/2 performance boundary for agility quickness by flying yo-yo manoeuvres in the full motion simulator at the University of Liverpool the helicopter model of UH-60A. Fig. 11 presents the example of tiltrotor from this paper on the agility quickness charts determined in [13].



'Fig. 11 Tiltrotor on Agility quickness chart

One can see that the FXV-15 tiltrotor is mostly at Level 2 performance both in helicopter and airplane modes. Agility quickness can be related to CAP as demonstrated in ref. [13].

One of the reasons the attitude quickness criterion has gained large acceptance was due to its physical interpretation. It can be demonstrated (see ref. [12]) that agility quickness has also a physical interpretation, at limits, for small-amplitude manoeuvres agility quickness corresponds to heave damping and for large amplitude manoeuvres it signifies the attitude quickness.

4.2 Vibratory Quickness Metric as a Measurement of Vibratory Activity

Another important advantage of the agility quickness metric is the fact that it could be linked to the structural design. In this sense, Pavel and Padfield [12] defined in parallel to the agility quickness a complementary vibratory metric, the so-called “vibratory load quickness”, quantifying the build up of loads in the rotor during manoeuvring flight:

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

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 ($F_{x\ hub}$, $F_{y\ hub}$, $F_{z\ hub}$) and/or moments ($M_{x\ hub}$, $M_{y\ hub}$, $M_{z\ hub}$) for the manoeuvre flown and determining the critical loads (i.e. the loads achieving the highest peaks).

For example, for the pull-up manoeuvre flown with the tiltrotor in this paper 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 in 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. 12 presents the vibratory quickness charts corresponding to the agility charts of Fig. 11 for the critical 2/rev (airplane mode) and 3/rev (helicopter and airplane mode) component of the hub vertical shear when flying respectively at 60, 120 and 300 kts and giving an 1 in input in longitudinal cyclic for 1 to 5 seconds. Looking at Fig. 12 (a) one can see that, for the FXV-15 in helicopter mode, a presumable Level 1/2 vibratory quickness boundary was plotted as derived in ref. [13]. This boundary was determined, as in the case of agility quickness, when flying piloted yo-yo’s in the full-motion simulator at the University of Liverpool. This boundary is a vibratory boundary that the structural designer would aim for reducing the loads in the rotor.

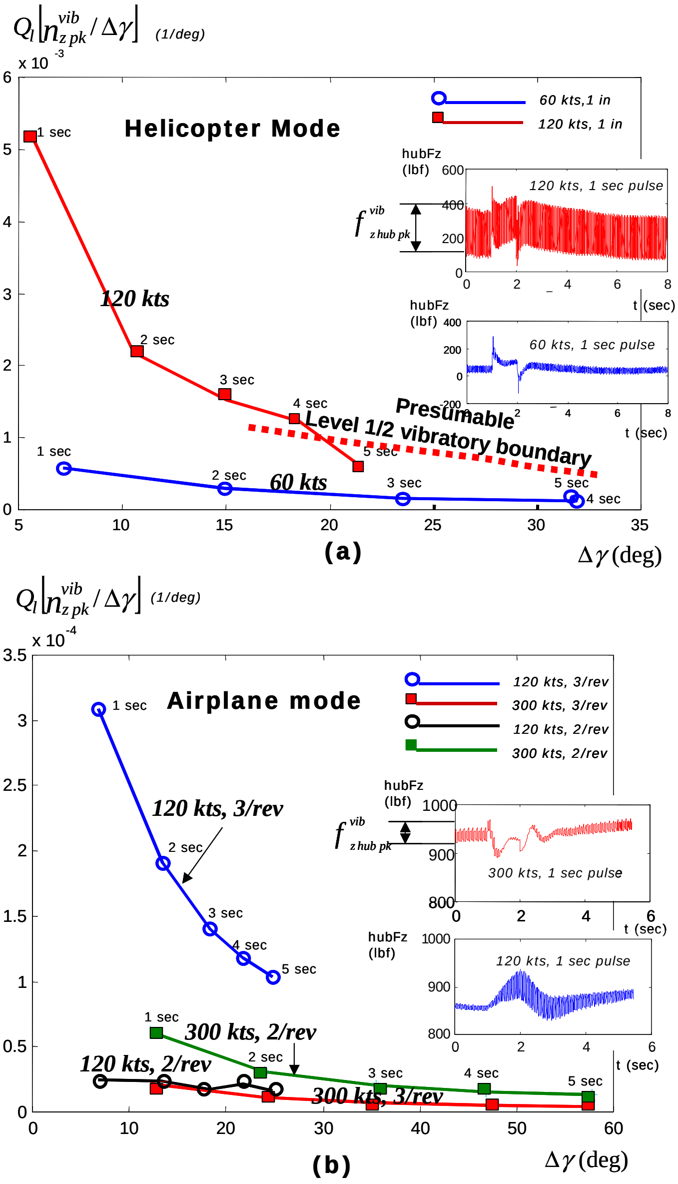
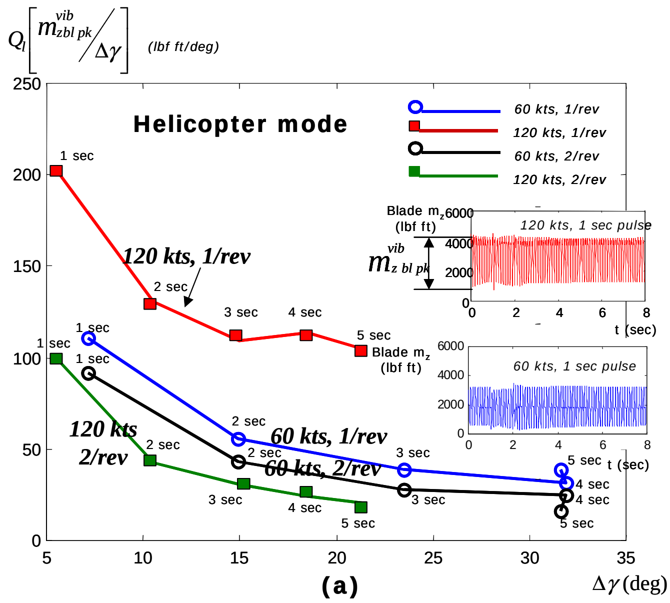


Fig. 12 Vibratory quickness envelopes for 2/rev and 3/rev components of the hub vertical shear during a pull-up manoeuvre with FXV-15

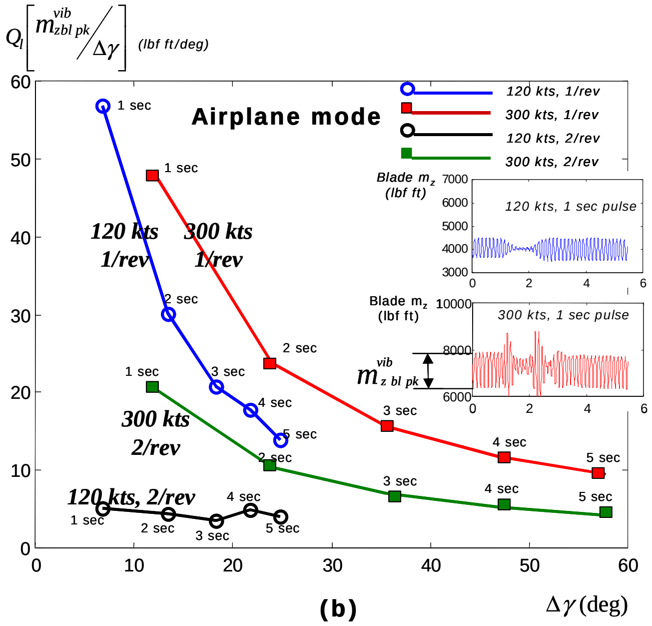
Figure 12 shows that, flying quicker enables the pilot to pull more g’s (thus increase performance) but also increases the vibratory activity in the rotor. The goal of the structural designer would be then to alleviate these high peak loads to lower levels and reduce the sensitivity of the vibratory loads to flight path angle. In this way, the designer can make a proper trade-off in the sense that between agility and vibratory loads.

From Fig. 12 one can see that increasing the pulse duration decreases the vibratory quickness. 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 manoeuvre) and not on the pulse duration.

Furthermore, Fig. 13 presents vibratory quickness charts in the tiltrotor example for another critical load measured during the pull-up manoeuvres, namely 1/rev and 2/rev vibratory components of blade inplane moment for both the helicopter and airplane modes. Looking at Fig. 13 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.



(a)



(b)

Fig. 13 Vibratory quickness envelopes for the blade inplane moment in pull-up manoeuvres with FXV-15

5 Conclusions and Recommendations

The present paper 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 manoeuvres) and taking as case study the unique example of a tiltrotor aircraft, the paper 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. The paper discussed the many correlations existing between the study of agility and the study of flying qualities and emphasized the fact that flying qualities do limit agility. In this sense, providing the pilot with a high level of manoeuvrability, without a high level of controllability, will reduce agility. Especially for the tiltrotor case, higher agility cannot be achieved without increasing the vibratory loads on the rotor, and thus the designer must make a trade-off between maximizing agility and minimizing the vibratory levels. The paper 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 for studying manoeuvres in axial, turning (horizontal-plane manoeuvres) and roll (torsion) axes. It is hoped that in this way a more unified set of design criteria will be developed for the designer enhancing multi-disciplinary design optimization.

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