CALCULATION OF ADS-33 QUICKNESS PARAMETERS WITH APPLICATION TO DESIGN OPTIMIZATION

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Abstract

An inverse simulation-based methodology is developed to construct quickness maneuvers with preassigned values of the attitude change. The inverse simulation is based on an optimization procedure, and generates both the final trajectory and the required pilot controls. A variety of constraints can be enforced, ranging from reduced off-axis response to reduced lateral and yaw motions, and to pitch input reversal from trim. Comparisons with flight test data show good agreement for the prediction of the pitch quickness. The roll quickness is overpredicted by about 20%, possibly because the simulation does not include structural load limits, and therefore is free to generate maneuvers that would perhaps be too aggressive for the real aircraft. The methodology can generate quickness maneuvers with desired characteristics, e.g., families of trajectories with the same pitch or roll attitude changes and varying quickness. This permits the rigorous calculation of sensitivities of the quickness with respect to rotor or fuselage design parameters. They also permit the derivation of Taylor series expansions of the quickness in terms of the same design parameters. Both the sensitivities and the Taylor series expansions are important ingredients for the inclusion of quickness-based constraints in broader design optimization problems. Besides the applications to design optimization, the methodology presented in the paper can be useful for fundamental theoretical studies because it generates families of trajectories in which one or more specific parameters can be systematically changed one at a time. It can also be useful for preliminary planning of flight tests to assess compliance with the ADS-33 quickness specifications.

Notation

GJ	Torsional stiffness of the blade
$M_q, M_{\delta_{lon}}$	Stability and control derivatives
p, q	Roll and pitch rates
Q	Quickness, $= p_{qk}/\Delta\phi$ or $= q_{qk}/\Delta\theta$
T	Duration of the maneuver
V	Helicopter speed during the maneuver
y, z	Lateral and vertical displacement of the helicopter
δ_{col}	Collective stick input
δ_{lat}	Lateral stick input
δ_{lon}	Longitudinal stick input
δ_{ped}	Pedal input
$\Delta\phi, \Delta\theta$	Roll and pitch attitude changes from trim
ϕ, θ, ψ	Roll, pitch, and yaw attitudes

Subscripts

act	Actual value reached during the maneuver
des	Desired value
pk	Peak value reached during the attitude change maneuver
$trim$	Trim value
0	Baseline value

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Introduction

The "quickness" of a helicopter is a measure of how quickly the helicopter can move from one steady value of pitch, roll, or yaw attitude, to another steady value. The ADS-33 Handling Qualities specification [1] essentially defines quickness as the ratio of the peak pitch (or roll, or yaw) rate generated during the maneuver, to the magnitude of the attitude change. A more precise definition and two sample specification charts are shown in Fig. 1. The ranges of attitude changes covered by specification are from 5 to 30 degrees for pitch maneuvers, and from 10 to 60 degrees for roll and yaw maneuvers. These attitude changes extend beyond the range of small perturbations for which linearized flight dynamics models are assumed to be valid. Therefore, although linearized models can often provide useful results, the prediction of quickness through simulation is more appropriately carried out by using the full nonlinear equations of motion of the helicopter.

Several studies have addressed this specific handling qualities characteristic, either in isolation, or as part of more comprehensive handling qualities studies. Selected references will be briefly mentioned here. The basic rationale for the specification, including supporting material, is provided in Ref. [2]. Additional pioneering work, especially concerning the roll degree of freedom, was carried out by Heffley *et al.* [3].

The effects of flight control system architecture and design on several handling qualities characteristics of the Sikorsky UH-60, including quickness, have been described by Takahashi [4, 5]. Kothmann and Armbrust describe the development of the flight control system of the RAH-66 Comanche in Ref. [6], and discuss extensively the impact on quickness and many other handling qualities characteristics.

The quickness characteristics of specific helicopters have been described by several Authors, such as Ockier [7] for the Eurocopter BO-105, and Cappetta and

Johns [8], Blanken *et al.* [9], and Bischoff *et al.* [10] for several versions of the Sikorsky UH-60. All these references also include other ADS-33-type handling qualities evaluations. Finally, a detailed discussion of many issues associated with quickness definition and evaluation, plus many additional references, can be found in the textbook by Padfield [11].

Extracting the quickness parameters corresponding to a certain maneuver is not particularly difficult. In some cases, one does not even need to perform a real or simulated attitude change maneuver. In fact, Heffley *et al.* [3] show how to extract the appropriate parameters from generic maneuvers. On the other hand, there are situations, especially when performing basic theoretical studies, which may require special types of "quickness maneuver" (this shorthand definition will be used in the paper for maneuvers from one steady attitude value to another). In this case some subtle issues may arise.

One such situation can occur when we wish to study the changes in quickness caused by the change of a design parameter of the helicopter. In Ref. [12] the quickness calculations were part of a broader design optimization study, the objective of which was the maximization of the in-plane rotor damping, subject to aeroelastic stability, hub loads, and ADS-33 -based handling qualities constraints. The design variables were: blade torsion stiffness, cross-sectional CG position, and chord, area of the horizontal tail; and the gains of pitch attitude and rate feedback to longitudinal cyclic, and of roll attitude and rate feedback to lateral cyclic. One of the handling qualities constraints expressed the requirement that the helicopter achieve Level 1 quickness in pitch. The study confirmed the multidisciplinary nature of the problem, because the improvements in rotor in-plane damping were constrained precisely by the quickness constraint.

Figure 2, taken from Ref. [12], shows the points representative of the baseline and the optimized design on the ADS-33 specification chart for quickness. As the optimization progresses the quickness decreases, and once it reaches the Level 1 boundary, the quickness constraint prevents further improvements. In Ref. [12] several simplifying assumptions were made. In particular, the pilot inputs required for the attitude change maneuver were held constant throughout the optimization. These inputs, which were initially obtained by trial and error, produced appropriate quickness maneuvers only for the baseline design. As the design changed, the final attitude also changed, and it drifted, often considerably, to the point that the final attitude was arbitrarily defined as that reached after a given time, whether it was steady or not. Figure 2 clearly shows that the attitude change $\Delta\theta_{min}$ changed from the baseline to the optimum design, and therefore the quickness was calculated for maneuvers that were not exactly the same.

Maintaining a constant $\Delta\theta_{min}$ during the optimization was not a trivial task, and it was not attempted in that study. Also, there was no guarantee that the fixed pilot input used in the optimization would produce the best possible value of quickness. Therefore, the primary motivation of the present study was to seek ways to remove these two limitations.

In light of the preceding discussion, the main objectives of the present paper are the following:

1. To describe a new methodology to simulate quickness maneuvers with prescribed attitude changes (e.g., with prescribed $\Delta\theta_{min}$), and with a guarantee that the quickness achieved is indeed the maximum possible;

2. To use the methodology to calculate the sensitivity of the quickness with respect to a given design parameters, and to extract Taylor series expansions of the quickness in terms of that design parameters, in a form suitable for design optimization studies; and,

3. To discuss the dependency of quickness on selected flight condition, configuration, and maneuver parameters.

The ability to simulate quickness maneuvers with prescribed attitude changes is important to introduce these maneuvers, in a rigorous theoretical way, in formal design optimization procedures. Also, the methodology can be easily extended to prescribe not only attitude changes, but other characteristics or constraints for the maneuver, such as limits on control rates or structural loads. This can be useful for fundamental research studies, in which the influence of parameters of the maneuver or of design parameters of the helicopter can be studied systematically by changing them one at a time. Finally, the methodology could be useful for the preliminary planning of flight tests. In fact, the procedure not only generates the trajectories of the maneuvers, but also the time histories of the controls that produce those maneuvers, and the time histories of many quantities of interest of the helicopter, such as rotor blade motions, and hub loads in the fixed or rotating frame.

Helicopter simulation model

The simulation model used in this study is a blade element-type, coupled-rotor fuselage model. The blades are modeled individually, as flexible beams undergoing coupled flap-lag-torsion deformations. The rotor equations of motion are discretized using finite elements, and a modal coordinate transformation is used to reduce the number of rotor degrees of freedom. Three modes are retained in the present study, namely, the rigid body flap and lag modes, and the first elastic torsion mode. The extended momentum theory of Keller and Curtiss is used to model the main rotor inflow. A one-state dynamic inflow model is used for the tail rotor. Quasi-steady stall and compressibility effects are introduced through look-up tables of airfoil aerodynamic coefficients. The rigid body motion of the fuselage is described through nonlinear Euler equations. The aerodynamic characteristics of the fuselage and of the empennage are described by look-up tables of aerodynamic coefficients. The trim procedure simulates free flight, and simultaneously enforces overall force and moment equilibrium on the aircraft, and the periodicity of the steady state motion of the rotor. The response to pilot inputs is computed by direct numerical integration of the 37 equations of motion that make up the model.

Methodology for quickness calculations

Computing quickness maneuvers with specified attitude changes, and guaranteeing that a certain quickness maneuver is the best possible, are not trivial problems because not only the details of the trajectories, but also the time histories of the pilot inputs are unknown and must be appropriately determined.

The two problems can be solved through a nested loop procedure. In the inner loop of the procedure, a representative trajectory with preassigned quickness is determined, and the controls required to fly this trajectory are computed using optimization-based inverse simulation [13]. In the outer loop, the desired quickness is progressively increased until the simulated actual maneuver can no longer achieve this desired quickness: the maximum value of the actual quickness achieved is taken as the quickness of the helicopter for that speed and attitude change.

For the pitch maneuvers, the desired trajectory is obtained from a simple linear, 1-DOF model of pitch dynamics:

$$\dot{q} - M_q q = M_{\delta_{lon}} \delta_{lon} \tag{1}$$

For this model, the attitude change following a rectangular step input of longitudinal cyclic of magnitude δ and duration Δt is

$$\theta_{des}(t) = -\frac{M_{\delta_{lon}}}{M_q}\delta \left\{ \Delta t + \frac{1}{M_q}\left[e^{M_q(t-\Delta t)} - e^{M_q t} \right] \right\} \tag{2}$$

and its asymptotic value is

$$\begin{aligned} \Delta\theta &= \lim_{t\to\infty} \theta(t) \\ &= \lim_{t\to\infty} -\frac{M_{\delta_{lon}}}{M_q}\delta \Big\{ \Delta t + \\ &\qquad + \frac{1}{M_q}\left[e^{M_q(t-\Delta t)} - e^{M_q t} \right] \Big\} \\ &= -\frac{M_{\delta_{lon}}}{M_q}\delta \Delta t \end{aligned} \tag{3}$$

The maximum pitch rate q_{pk} for this trajectory is the pitch rate at time $t = \Delta t$, that is:

$$q_{pk} = q(t)|_{t=\Delta t} = -\frac{M_{\delta_{lon}}}{M_q}\delta \left(1 - e^{M_q \Delta t} \right) \tag{4}$$

Because Eq. (2) only needs to generate a representative family of trajectories, it is not necessary that the values of the stability and control derivatives be exactly those of the aircraft under consideration. However, the absolute value of M_q should be larger than the expected maximum quickness. In fact, it can be shown [11, pp. 348-350], that the maximum quickness associated with Eq. (4) is equal to $-M_q$. The equations used for the roll attitude change maneuvers are the same as those for pitch, with the obvious changes in notation and stability and control derivatives.

The inverse simulation procedure is described in detail in Ref. [13]. The procedure is formulated as an unconstrained optimization problem. The design variables are the values of the four pitch controls, collective δ_{col}, longitudinal cyclic δ_{lon}, lateral cyclic δ_{lat}, and pedal δ_{ped} at specific time points, with linear variations in between, as shown in Fig. 3. Therefore, the vector of design variables is given by:

$$\begin{aligned} \mathbf{X} &= [\delta_{col}(t_1) \ldots \delta_{col}(t_N)\ \delta_{lat}(t_1) \ldots \delta_{lat}(t_N)\ \ldots \\ &\quad \ldots \delta_{lon}(t_1) \ldots \delta_{lon}(t_N)\ \ldots \\ &\quad \ldots \delta_{ped}(t_1) \ldots \delta_{ped}(t_N)]^T \end{aligned} \tag{5}$$

The objective function to be minimized is the square of the difference between the desired and the actual trajectory. A penalty function is added to enforce constraints on the roll and yaw angles, and on the speed changes from the nominal value, during the attitude change maneuver. The augmented objective functions for the pitch and roll maneuvers are, respectively:

$$\begin{aligned} F(\mathbf{X}) &= \int_0^T \left[\Delta\theta(t) - \Delta\theta_{des}(t)\right]^2 \, dt + \\ &+ k \int_0^T \Big\{ \left[V(t) - V_{trim}\right]^2 + \left[\phi(t) - \phi_{trim}\right]^2 + \\ &\quad + y^2(t) + \psi^2(t) \Big\} \, dt \end{aligned} \tag{6}$$

$$\begin{aligned} F(\mathbf{X}) &= \int_0^T \left[\Delta\phi(t) - \Delta\phi_{des}(t)\right]^2 \, dt + \\ &+ k \int_0^T \Big\{ \left[V(t) - V_{trim}\right]^2 + \left[\theta(t) - \theta_{trim}\right]^2 \\ &\quad + z^2(t) + \psi^2(t) \Big\} \, dt \end{aligned} \tag{7}$$

where $\Delta\theta_{des}(t) = \theta_{des}(t) - \theta_{trim}$ and $\Delta\phi_{des}(t) = \phi_{des}(t) - \phi_{trim}$ are, respectively, the desired pitch and roll attitude changes from the trim values θ_{trim} and ϕ_{trim}, V is the flight speed, y and z are the lateral and vertical displacements from trim, and $\psi(t)$ is the yaw angle, the trim value of which is assumed to be zero. The factor k determines the weight of the constraints relative to the trajectory-matching objective. For all of the calculations of this paper, $k = 0.2$.

Any unconstrained optimization method can be used to minimize Eqs. (6) and (7). The BFGS method [14] as implemented in DOT [15] was used in the present study.

Results

All the results presented in this section refer to an articulated rotor helicopter configuration very similar to the Sikorsky UH-60, and flying at a weight of 16,000 lbs. The flight control system is assumed to be turned off. In this configuration, the helicopter exhibits a rate command response type [1].

Figure 4 shows pitch attitudes, rates, and corresponding quickness for the desired maneuvers, for a final pitch attitude change $\Delta\theta = 10^o$. The maneuvers start at time $t_1 = 1$ sec. The curves correspond to values of the desired quickness $Q_{des} = q_{pk}/\Delta\theta$ going from 0.25 to 2.25 in 0.25 increments. The overall duration of the maneuver, including the initial second, is of 12 rotor revolutions, corresponding to about $T = 2.8$ sec. Each of the four controls is updated every 2 rotor revolutions, or slightly less than 0.5 sec, and varies linearly between consecutive updates (see Fig. 3).

For the lower values of Q_{des} the maneuver cannot be completed in the time T, but even in those cases the attitude change $\Delta\theta_{min}$ was assumed to be equal to its final value ($\Delta\theta_{min} = 10^o$ in Fig. 4). The lowest plot in the figure shows the representative points on one portion of an ADS-33 quickness specifications. These points are all aligned on a vertical line, as desired, and are equally spaced.

Pitch change maneuver

Baseline maneuver, $\Delta\theta = 10^o$

Figure 5 shows desired and actual values of pitch attitude change $\Delta\theta$ (top plot), pitch rate q (middle), and quickness $Q = q_{pk}/\Delta\theta$ (bottom). The flight speed is $V = 45$ kts, which is the highest speed of the "low speed" range, as defined in ADS-33. The attitude change is $\Delta\theta = 10^o$. The trajectories generated using inverse simulation match the desired trajectories very well for quicknesses up to about $Q = 1.00$. As the desired quickness increases, the actual pitch attitude cannot rise as quickly as needed, and the pitch rate q can no longer follow the desired value. Note that the computations over the last 0.25-0.5 seconds are not very significant: continuing the inverse simulation for another 2-4 rotor revolutions would have removed some computational artifacts such as the larger negative values of q (q should tend to zero as time goes by, to maintain the final value of $\Delta\theta$ constant). Figure 6 shows the actual quickness as a function of the desired quickness. The maximum value of Q_{act}, obtained using quadratic polynomial interpolation, is $Q_{act} = 1.10$, which is therefore taken as the quickness for this case. This corresponds to Level 2 handling qualities for the Target Acquisition and Tracking (TAT) Mission Task Element (MTE), and Level 1 for other MTE [1].

Figure 7 shows the time histories of the controls (top plots) and of some response quantities (bottom plot), for the three values of the desired quickness that bracket the maximum value of Q_{act}, i.e., $Q_{des} = 1.25, 1.50$, and 1.75. Assuming realistic values of ± 5 in for the control excursions of longitudinal cyclic δ_{lon} and lateral cyclic δ_{lat}, and a maximum achievable rate of 100%/sec, corresponding to 10^o/sec, neither displacement nor rate saturation occur for δ_{lat} and δ_{lon}. Therefore, although rate saturation is often a limiting factor for quickness, it is not in this case. The same is also true for the collective δ_{col} and pedal δ_{ped} inputs. The combination of controls generates a pitch maneuver with very small amounts of roll angle ϕ (always less than $\pm 1^o$) and lateral motion y (always less than 1 ft).

Control reversal

Figure 7 shows that the maximum value of quickness is obtained with some significant longitudinal control reversal. The ADS-33 specification explicitly prohibits this, the rationale being that the maneuver should be an open-loop maneuver, and therefore it should be carried out by simply displacing the pitch control in the appropriate direction. Any control reversal implies that the pilot is providing compensation, and therefore is behaving like a flight control system. This will tend to increase the piloting workload, hence it should be avoided [2].

With this in mind, the quickness calculation was repeated with constraints on the maximum size of the longitudinal cyclic reversal. Selected results are presented in Fig. 8 for the case $Q_{des} = 1.75$. The top plot shows the time history of longitudinal cyclic δ_{lon} for three cases: (i) no limit to the value of δ_{lon}, (ii) δ_{lon} reversal no greater than 0.25 in from trim, and (iii) no reversal allowed at all. The constraint is enforced for all values of δ_{lon} except the last, but in practice it limits only the fourth value of δ_{lon}, that at $t = 1.86$ sec. At the beginning, i.e. $t \le 1$ sec, the three maneuvers are almost identical, as shown by the time history of q (middle plot). The effect of the reversal constraint is felt in the subsequent portion of the maneuver, for $1 \le t \le 2$. As the constraint gets tighter, δ_{lon} must be brought back faster to its trim value, and the maximum value of q becomes correspondingly smaller. The actual quicknesses for all the cases are summarized in the portion of the ADS-33 specification chart at the bottom of the figure. The overall quickness decreases from the baseline $Q_{act} = 1.10$ to $Q_{act} = 1.06$ for $\delta_{lon} \le -0.25$ in, and to $Q_{act} = 0.98$ for $\delta_{lon} \le 0$ in, i.e., no reversal at all. (In the bottom plot of the figure, all the results refer to $\Delta\theta = 10^o$; some of them have been plotted slightly offset from $\Delta\theta = 10^o$ for clarity.) Desired and actual values of Q are shown in Fig. 9.

Figure 10 compares the results just described with flight test data, taken from Ref. [9]. Flight conditions and aircraft configuration are not exactly the same for the computed and the flight test data. In fact, the tests were conducted at hover, rather than at the 45 kts of the simulation, the flight control system was turned on instead of off, the weight was slightly higher (17,300 vs. 16,000 lbs), and the control inputs were not arbitrary, i.e., not limited to updates every about 0.5 sec and piecewise linear in between. However, none of these differences should significantly affect the achievable quickness. The figure shows a good agreement: the predictions are well within the scatter of the flight test data. The same conclusion can be drawn from the flight test data in Figure 11, taken from Ref. [10]. These data were also for hover, and a much higher weight (in excess of 22,000 lbs) than both the simulations of this study and the flight test data of Ref. [10]. The time histories of the pilot inputs were not compared because the flight test data were carried out with the flight control system turned on, whereas the simulations were all in a bare airframe configuration and with a simplified version of the UH-60 mechanical control mixer. Therefore, the comparisons would not be very meaningful.

Sensitivity analysis

Fig. 12 summarizes the calculations required to compute the sensitivity of Q with respect to a design parameter, in this case the torsion stiffness GJ of the blade. The quickness is calculated as shown in the previous examples for the baseline configuration, and for configurations with GJ reduced by 10% and 20%. The values are $Q_{act} = 1.1033$, $Q_{act} = 1.1228$, and $Q_{act} = 1.2048$, respectively. No constraints were placed on the controls to prevent excessive reversal, but clearly such constraints could be easily enforced. Using backward difference approximations for both the first and the second derivative yields:

$$\frac{\partial Q}{\partial (GJ/GJ_0)} \approx 0.195 \tag{8}$$

$$\frac{\partial^2 Q}{\partial (GJ/GJ_0)^2} \approx 5.92 \tag{9}$$

These sensitivities are obtained by comparing identical maneuvers, i.e., maneuvers with the same value of attitude change. On the ADS-33 specification charts, the points representative of the maneuver are aligned on the same vertical axis. Therefore, the inconsistency shown in Fig. 2, and mentioned in the introduction of the present paper, has been eliminated.

Using first and second order sensitivities it is also possible to construct Taylor series approximations, which describe the variation of quickness with the design parameter in a computationally efficient form. For the example shown, the quadratic expansion is

$$\begin{aligned} Q(GJ) &\approx Q(GJ_0) + \frac{\partial Q}{\partial GJ}(GJ - GJ_0) + \\ &\quad + \frac{1}{2}\frac{\partial^2 Q}{\partial GJ^2}(GJ - GJ_0)^2 \\ &= 1.10 + 0.195\left(1 - \frac{GJ}{GJ_0}\right) + \\ &\quad + 2.96\left(1 - \frac{GJ}{GJ_0}\right)^2 \end{aligned} \tag{10}$$

Taylor series expansions like Eq. (13) can improve the computational efficiency of design optimization procedures. In fact, in the neighborhood of a given design, the value of Q can be obtained from a very simple Taylor series expansion, rather than from the far more complex, full quickness calculation procedure described earlier. The determination of the size of the change of the baseline design for which the Taylor series expansions remain sufficiently accurate was not carried out, and will be left for future work.

Roll attitude change maneuver

Baseline maneuver, $\Delta\phi = 20^o$

Figure 13 shows results for a roll attitude change maneuver of magnitude $\Delta\phi = 20^o$. The methodology is the same as for the pitch attitude change maneuvers. The top plot of the figure shows the time histories of the roll attitude ϕ and the pitch attitude θ, corresponding to desired values of the quickness ranging from $Q_{des} = 4$ to 4.75 (the actual roll quicknesses are much lower). The desired roll attitude change $\Delta\phi$ is achieved precisely, with a small reversal before the beginning of the desired maneuver, and very small oscillations at the end. The pitch response θ is very small. Roll and pitch rates for the 4 maneuvers are shown in the middle plot. The stick inputs are shown in the bottom plot. The lateral input δ_{lat} has a triangular shape, with a sharp initial input and a more progressive return to trim. Neither displacement nor rate saturation appear to occur, and no reversal is present. The longitudinal stick inputs δ_{lon}, required to reduce the off-axis pitch attitude response, are rather large.

The actual values of quickness Q_{act} achieved for increasing desired quickness Q_{des} are shown in Fig. 14. The maximum value of Q_{act} is obtained from polynomial interpolation, and is equal to approximately 1.83. This result is compared with flight test data in Fig. 15. The same considerations concerning the differences between predictions and flight test data made for Figure 10 also apply here. Under these conditions, the predicted quickness is about 20% higher than the flight test indicates. The same is true for the comparison with the flight test data of Ref. [10], Fig. 16. The reasons for the discrepancies are not clear. Perhaps the actual helicopter cannot change roll attitude more quickly without encountering structural limits, whereas the simulation does not include any such limits, and therefore can accept arbitrarily large hub or blade loads.

Sensitivity analysis

Fig. 17 summarizes the calculations required to compute the sensitivity of the roll quickness Q with respect to the blade torsion stiffness GJ. The quickness is calculated for the baseline configuration, and for configurations with GJ reduced by 10% and 20%. The values are $Q_{act} = 1.8250$, $Q_{act} = 1.9180$, and $Q_{act} = 1.8930$, respectively. Using backward difference approximations for both the first and the second derivative yields:

$$\frac{\partial Q}{\partial (GJ/GJ_0)} \approx -0.93 \tag{11}$$

$$\frac{\partial^2 Q}{\partial (GJ/GJ_0)^2} \approx -11.8 \tag{12}$$

As in the pitch case, using first and second order sensitivities it is also possible to construct Taylor series approximations. For the example shown, the quadratic expansion is

$$Q(GJ) \approx 1.83 - 0.93\left(1 - \frac{GJ}{GJ_0}\right) + -5.9\left(1 - \frac{GJ}{GJ_0}\right)^2 \quad (13)$$

Conclusions

An inverse simulation-based methodology was developed to construct quickness maneuvers with preassigned values of the attitude change. The inverse simulation is based on an optimization procedure, and generates both the final trajectory and the required pilot controls. A variety of constraints can be enforced, ranging from reduced off-axis response to reduced lateral and yaw motions, and to pitch input reversal from trim.

Comparisons with flight test data show good agreement for the prediction of the pitch quickness. The roll quickness is overpredicted by about 20%, possibly because the simulation does not include structural load limits, and therefore is free to generate maneuvers that would perhaps be too aggressive for the real aircraft.

The methodology proves capable of generating quickness maneuvers with desired characteristics, e.g., families of trajectories with the same pitch or roll attitude changes and varying quickness. This permits the rigorous calculation of sensitivities of the quickness with respect to rotor or fuselage design parameters. They also permit the derivation of Taylor series expansions of the quickness in terms of the same design parameters. Both the sensitivities and the Taylor series expansions are important ingredients for the inclusion of quickness-based constraints in broader design optimization problems.

Besides the applications to design optimization, the methodology presented in this paper can be useful for fundamental theoretical studies because it generates families of trajectories in which one or more specific parameters can be systematically changed one at a time. It can also be useful for preliminary planning of flight tests to assess compliance with the ADS-33 quickness specifications.

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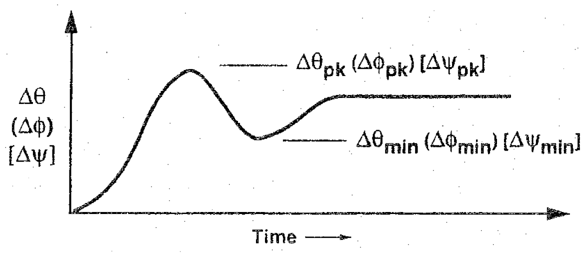
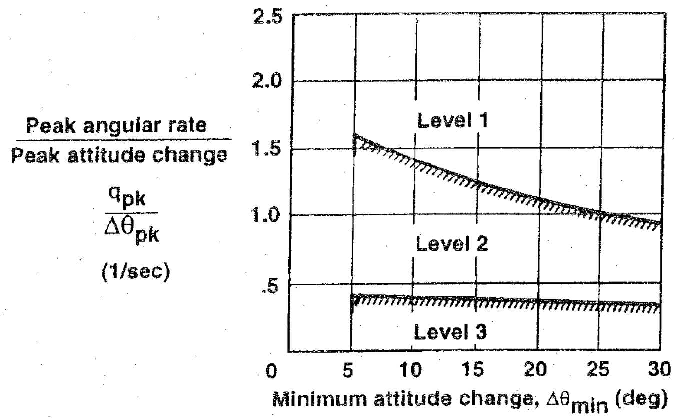
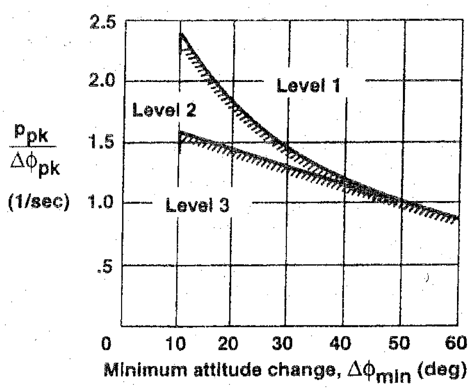




a) Target Acquisition and Tracking (pitch)



b) Target Acquisition and Tracking (roll)

Figure 1: Definition of quickness (from ADS-33, Ref. [1]).

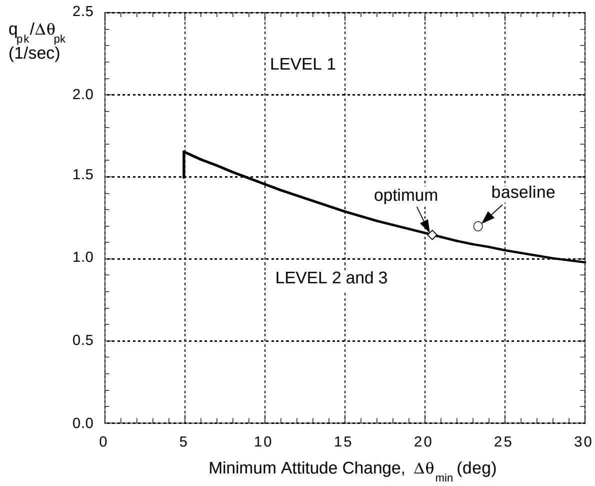


Figure 2: Pitch quickness for baseline and optimized configuration (from Ref. [12]).

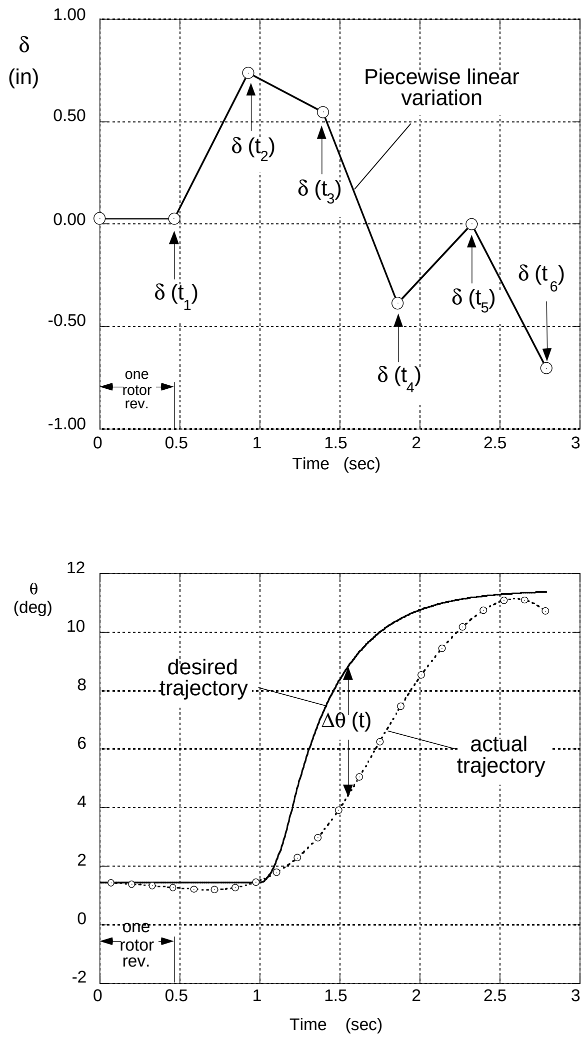


Figure 3: Definition of the optimization-based inverse simulation: example of definition of pilot inputs (top) and of difference between desired and actual trajectory (bottom).

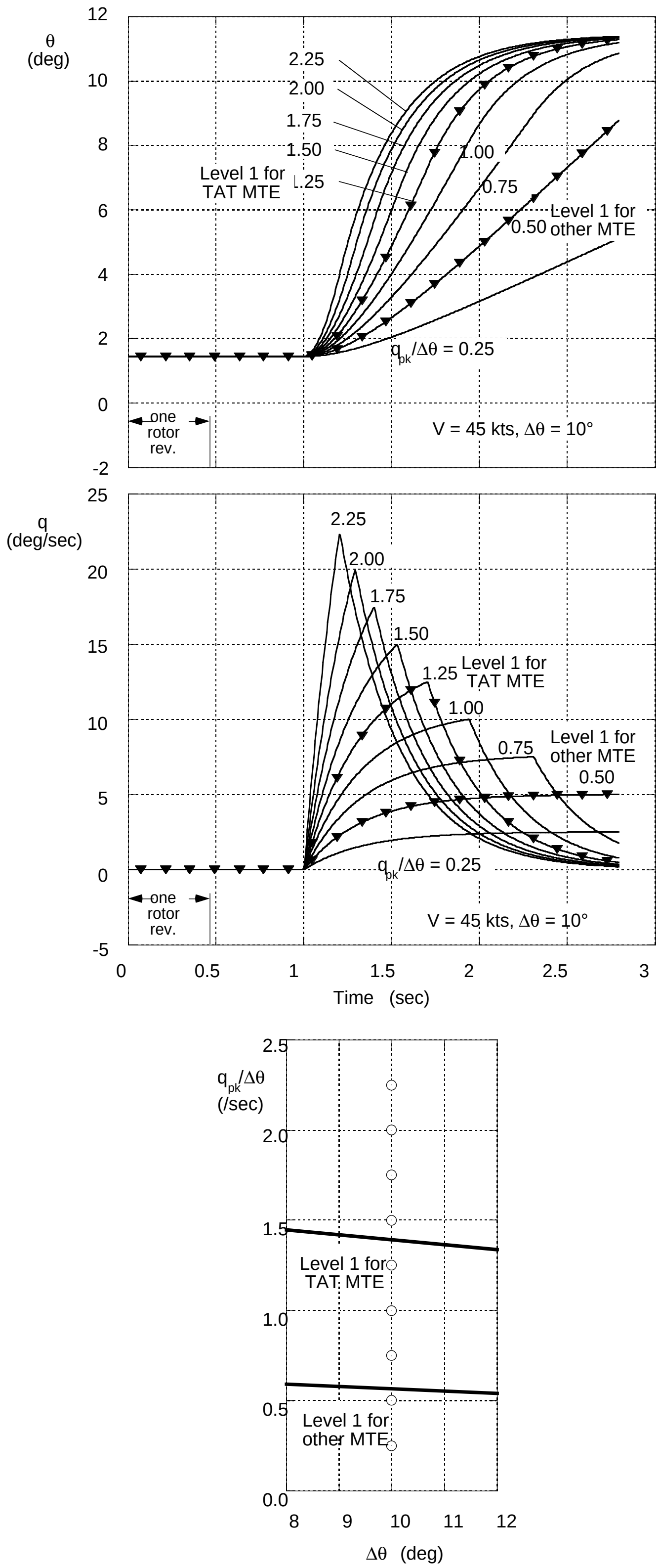


Figure 4: Pitch attitudes, rates, and quickness for desired pitch attitude change maneuvers.

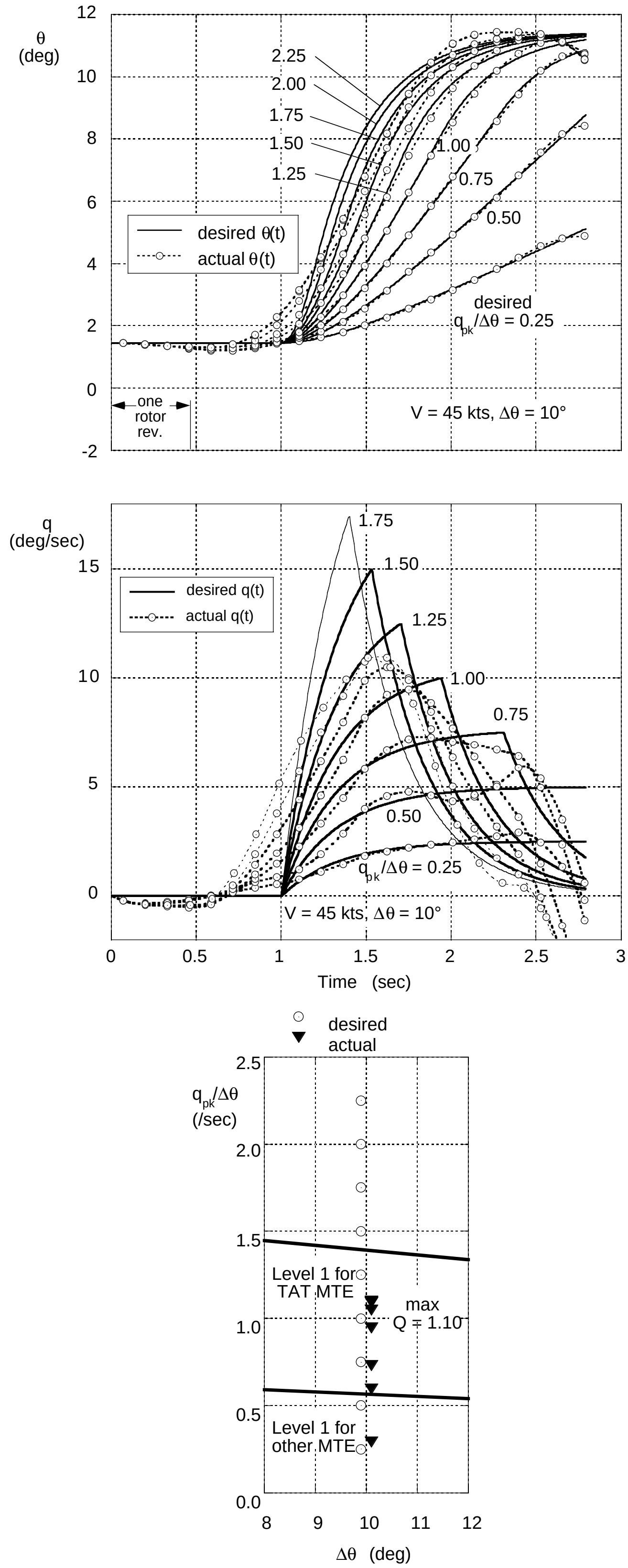


Figure 5: Pitch attitudes, rates, and quickness for desired and actual pitch attitude change maneuvers; $V = 45$ kts, $\Delta\theta = 10^o$.

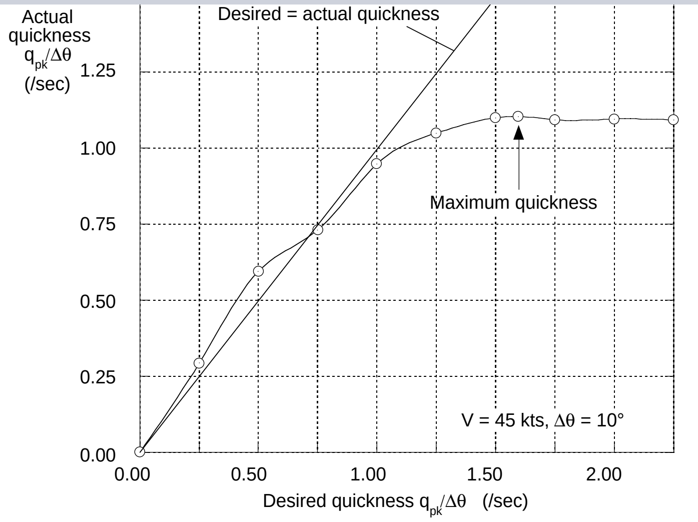


Figure 6: Actual vs. desired quickness in pitch attitude change maneuver.

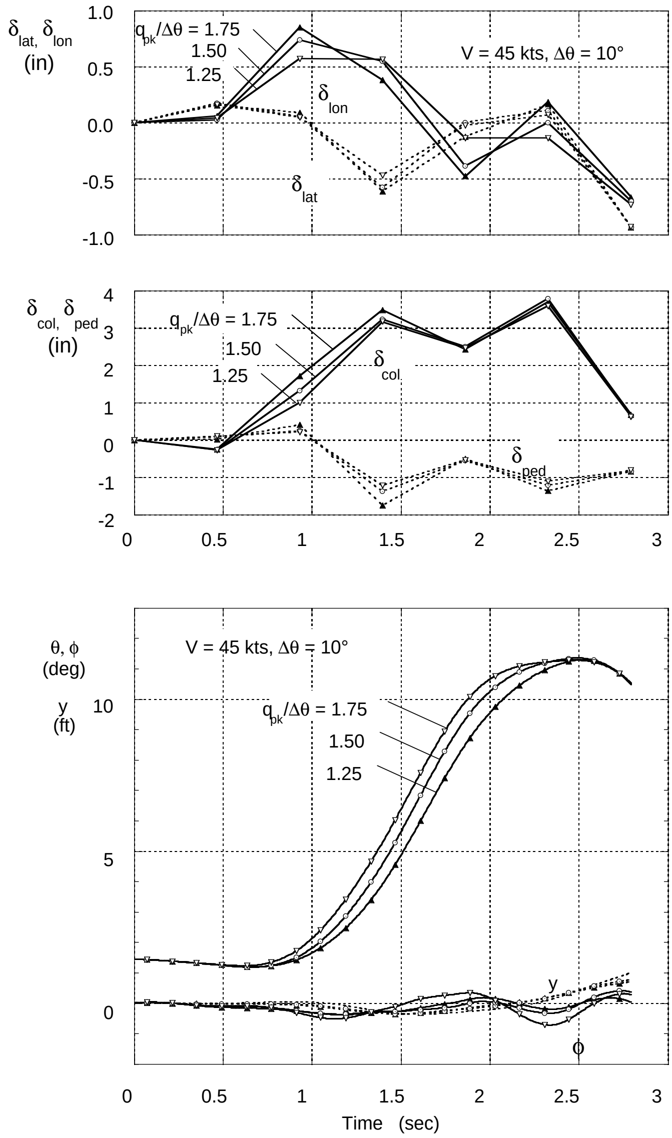


Figure 7: Controls and responses for three actual maneuvers; $q_{pk}/\Delta\theta$ denotes desired quickness.

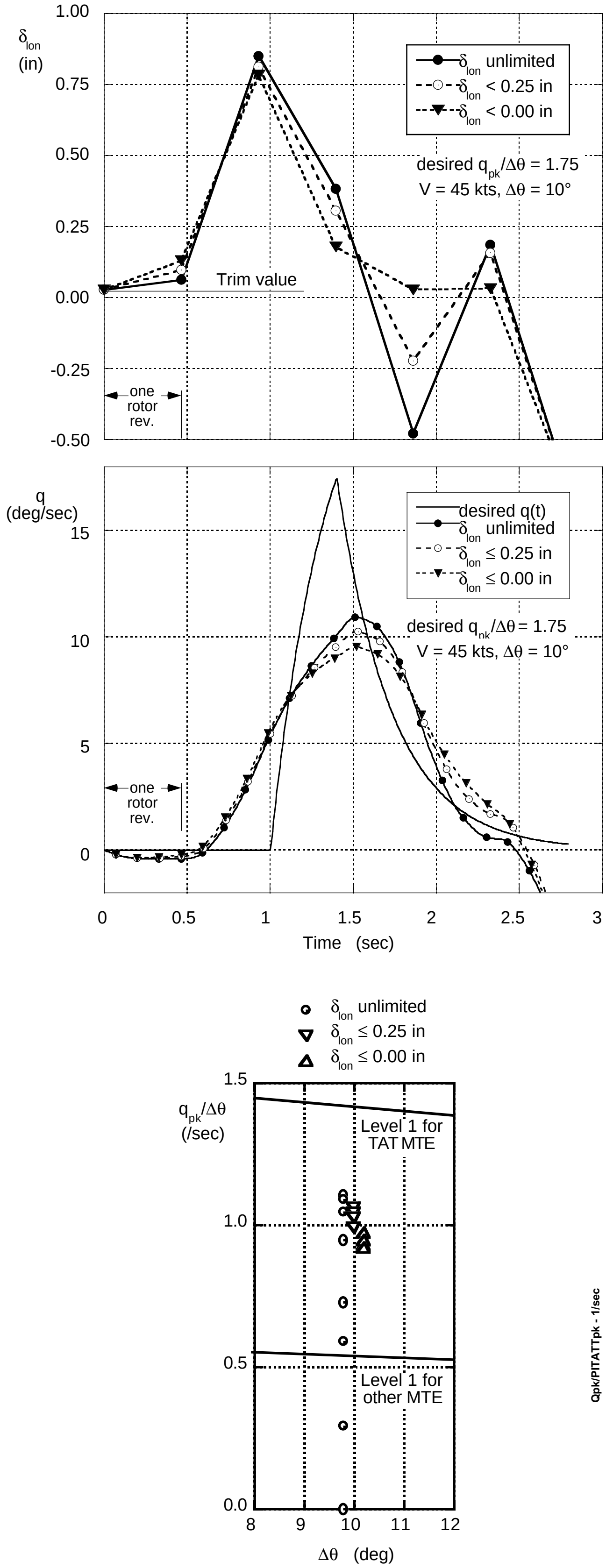


Figure 8: Pilot inputs (top) pitch rates (middle) and quickness (bottom) for various degrees of allowable control reversal; $V = 45$ kts, $\Delta\theta = 10^o, Q_{des} = 1.75$.

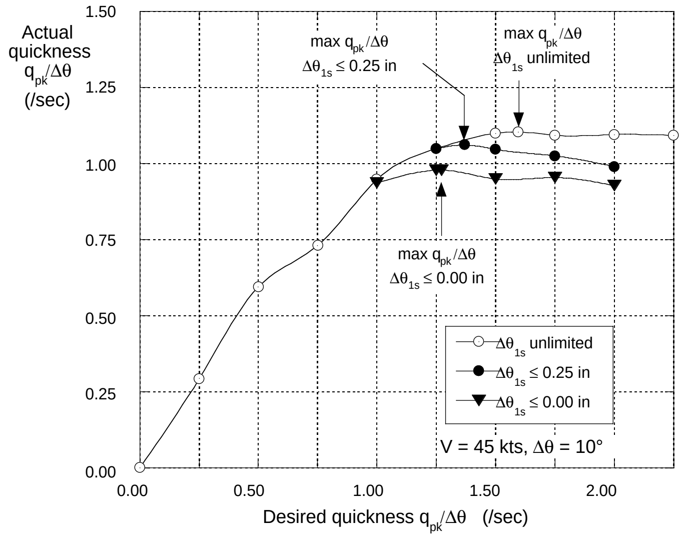


Figure 9: Desired and actual quicknesses for various degrees of allowable control reversal; $V = 45$ kts, $\Delta\theta = 10^o$.

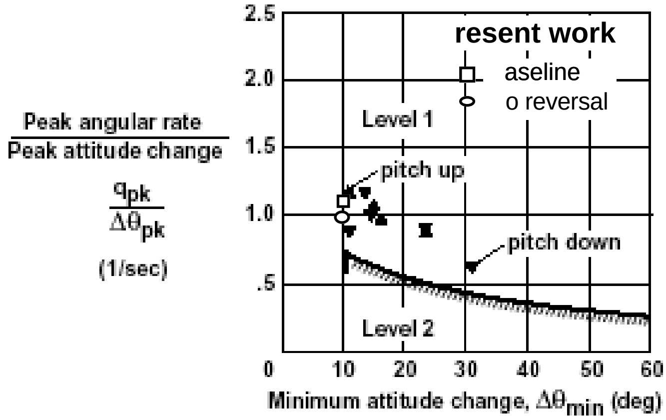


Figure 10: Pitch quickness: comparison with flight test data from Ref. [9].

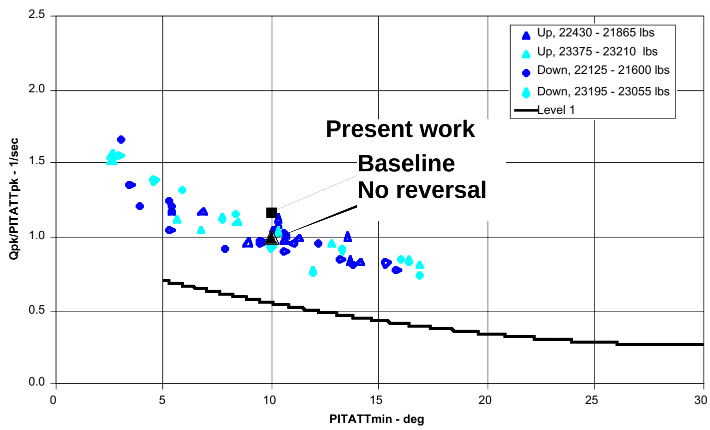
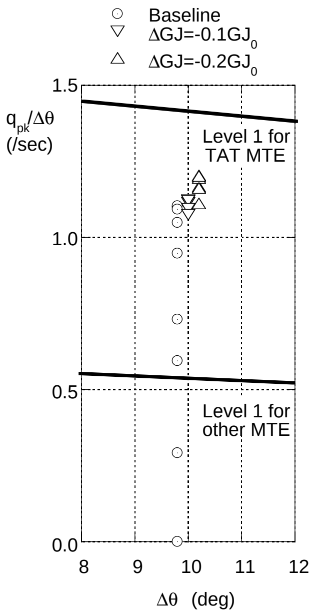


Figure 11: Pitch quickness: comparison with flight test data from Ref. [10].



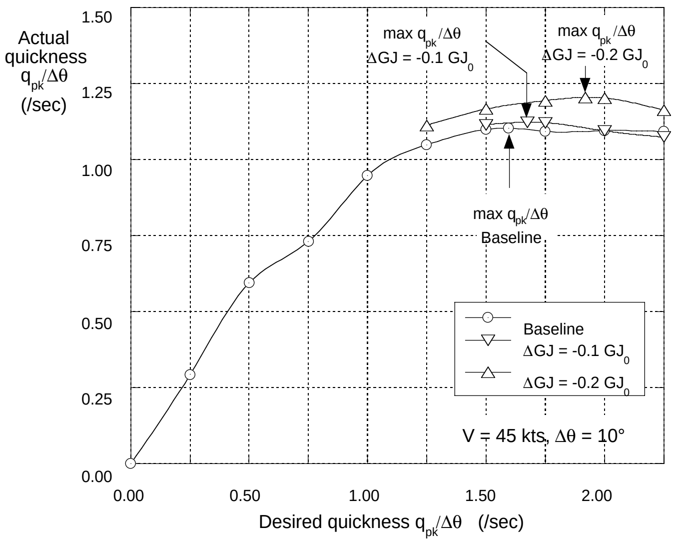


Figure 12: Desired and actual quicknesses for baseline and reduced torsion stiffness blades; $V = 45$ kts, $\Delta\theta = 10^o$.

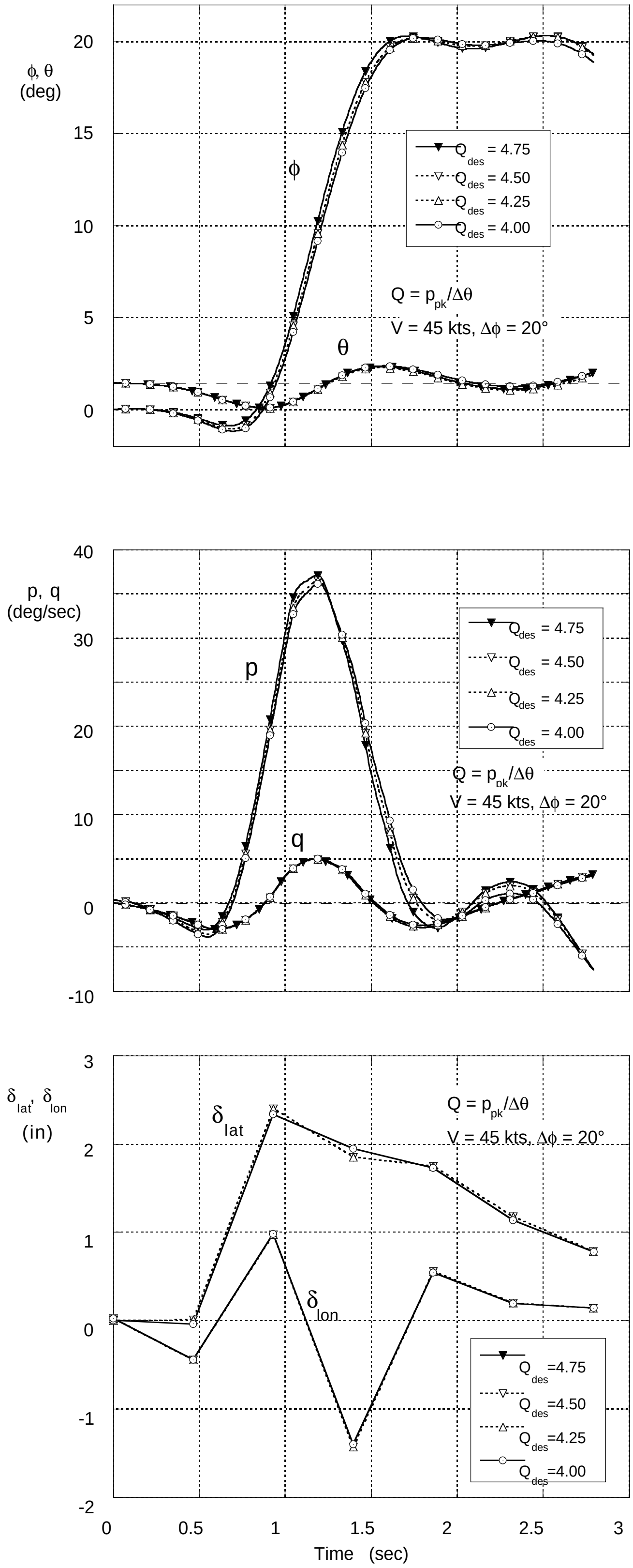


Figure 13: Roll attitudes (top) and rates (middle) and pilot inputs (bottom) for various values of desired quickness; $V = 45$ kts, $\Delta\phi = 20^o$.

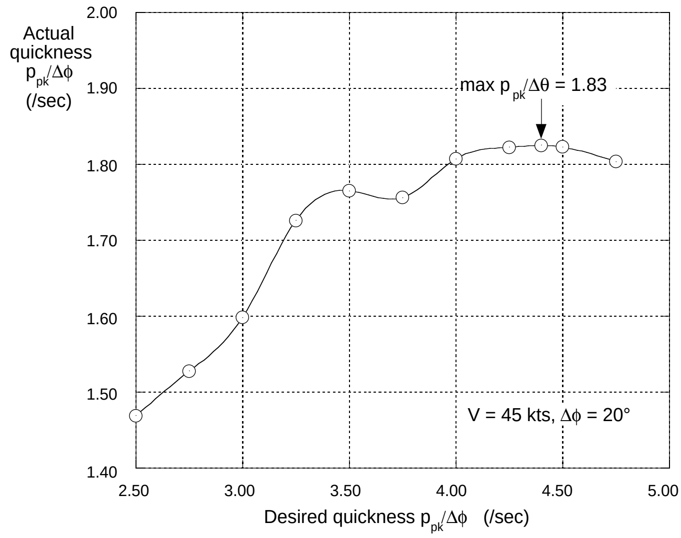


Figure 14: Actual vs. desired quickness in roll attitude change maneuver.

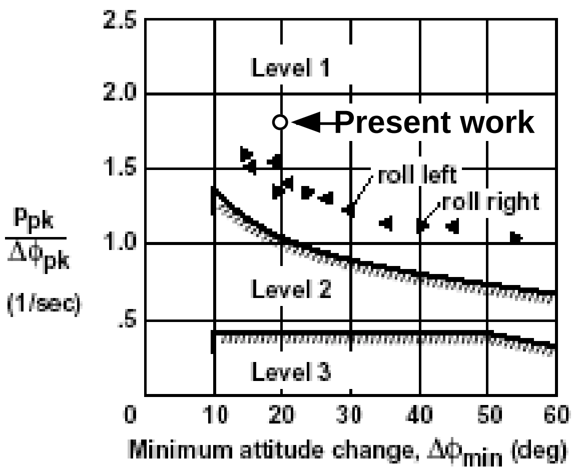


Figure 15: Roll quickness: comparison with flight test data (data from Ref. [9]).

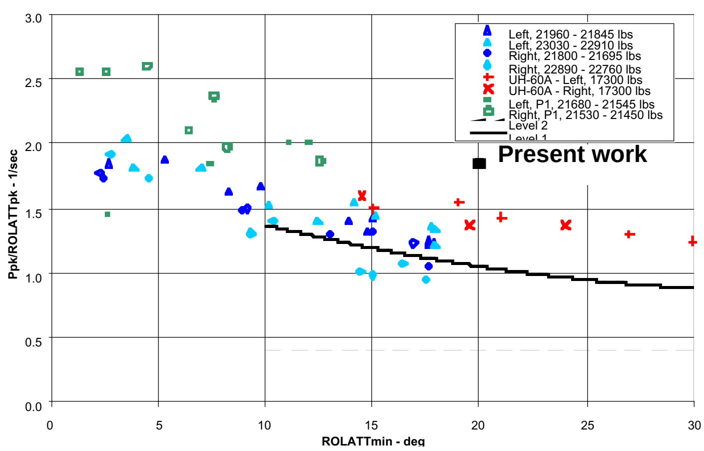


Figure 16: Roll quickness: comparison with flight test data from Ref. [10].

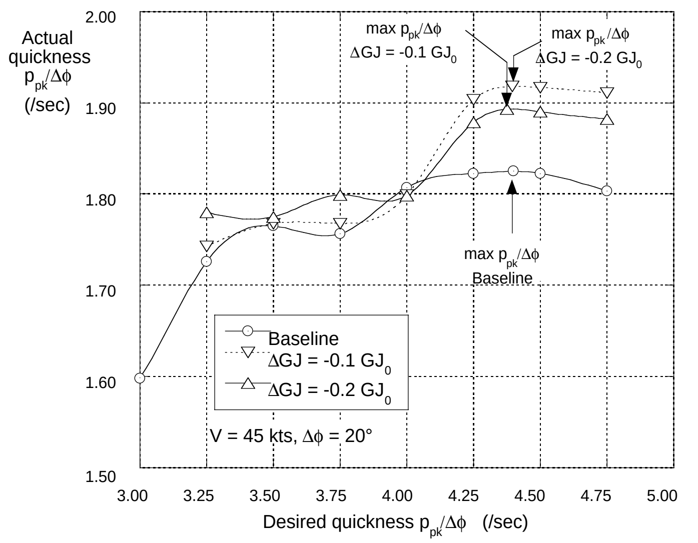


Figure 17: Desired and actual quicknesses for baseline and reduced torsion stiffness blades; $V = 45$ kts, $\Delta\phi = 20^o$.