HAT
A Handling-qualities Analysis Toolbox for Rotorcraft and Aircraft

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Abstract

This paper describes the salient features of an integrated software package called "HAT" (**H**andling-qualities **A**nalysis **T**oolbox) developed for the evaluation of the handling qualities of rotorcraft and fixed-wing aircraft. The quantitative handling qualities criteria for military rotorcraft specified in ADS-33E, and the handling qualities and APC (Aircraft-Pilot Coupling) prediction criteria for fixed-wing aircraft specified in MIL-STD-1797A, and several new criteria published in open literature, are incorporated in the software package. The software package can also be used for the analysis of the handling qualities of tilt-rotor aircraft operating in pure rotorcraft mode or in pure aeroplane mode.

HAT is a fully GUI based software package, configured as a MATLAB Toolbox, and modular in structure. A comprehensive demonstration programme and several on-screen help messages are included in the software to help a new user. The rotorcraft part of the software was validated using BO 105 helicopter handling qualities database generated by DLR, Germany, and the fixed-wing part of the software was validated using several HQ and APC databases available in the open literature. Throughout this paper emphasis is placed on rotorcraft handling qualities.

Notation

A	Amplitude
ADS	Aeronautical Design Standard
APC	Aircraft-Pilot Coupling
DLR	German Aerospace Center
FHS	Flying Helicopter Simulator
GUI	Graphic User Interface
$\dot{h}$	Height rate [m/sec]
HADS	Helicopter Air Data System
HAT	Handling-qualities Analysis Toolbox
HHQ	Helicopter handling qualities
HQ	Handling qualities
Hz	Hertz
K	Gain of height rate transfer function
MTE	Mission Task Element
NAL	National Aerospace Laboratories
P	Period [sec]
p	Roll rate [rad/sec]
r^2	Correlation coefficient
s	Laplace variable/complex frequency
t	Time [sec]
$T_{1/2}$	Time to halve the amplitude [sec]
$T_{\dot{h}}$	Equivalent time constant [sec]
δ	Logarithmic decrement
δ_y	Lateral cyclic input [%]
ε^2	Square-error
τ	Equivalent time delay [sec]
τ_p	Phase delay [sec]
ζ	Damping ratio
ω_n	Natural frequency [rad/sec]
ω_{BW}	Bandwidth [rad/sec]

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1. Introduction

The main objective of the design and development of a flight vehicle and its control system is to provide a means to the human pilot to control the aircraft safely and effectively throughout the flight envelope, that is, to provide good handling qualities. Handling qualities by definition are "those qualities or characteristics of an aircraft that govern the ease and precision with which the pilot is able to perform the tasks required in support of an aircraft role." [1].

The assessment of the handling qualities (HQ) of an aircraft is difficult because it involves the quantification of the task performance of the vehicle and the pilot's mental and physical workloads involved in performing the given task. The handling qualities assessment process is further complicated in the case of rotorcraft because of strong interactions between the pilot, rotorcraft, operating environment and the flying task. Besides, rotorcraft are complex machines with substantial coupling between all the control axes.

Because of the complex nature of handling qualities assessment, a multitude of criteria have been developed, based on decades of flight test experience, for the prediction of the handling qualities and Aircraft-Pilot Coupling (APC) tendencies of aircraft.

In the case of fixed-wing aircraft the current HQ and APC prediction criteria are compiled in the form of MIL-STD-1797A [2], and several new criteria have been developed since the publication of the Military Standard. The fixed-wing HQ criteria have evolved rather randomly than in a systematic manner. On the other hand, the HQ criteria for military rotorcraft, currently compiled in the form of Aeronautical Design Standard ADS-33E [3], have evolved in a systematic manner based on mission-oriented approach. Following the example of ADS-33, the fixed-wing community is trying to adopt the mission-oriented approach to HQ evaluation [4].

The HQ requirements of an aircraft should be considered early in the design and development process to avoid future surprises and modifications, which could be quite expensive, complex and time consuming.

The assessment of the HQ of a flight vehicle is done in two phases – analytical assessment during the control law design phase using mathematical models (state space or transfer function models) of aircraft, and ultimately the HQ are evaluated through flight tests by experienced test pilots. In between, the HQ of the aircraft are also evaluated using ground-based or in-flight simulators. Further, multiple HQ criteria have to be applied to several flight conditions and configurations of the aircraft, since there is no single universal criterion which can correctly predict the HQ of a flight vehicle.

Thus, the HQ evaluation activity generates a large amount of data which must be analysed meticulously. Therefore, there is a strong need for software which can be used to analyse the database for an efficient, comprehensive, and quick assessment of the HQ of aircraft. DLR, Germany and NAL, India, have long realised the importance of HQ research work, and is being pursued under collaboration programme between DLR and NAL.

2. HQ Activities at DLR and NAL

DLR has a long tradition in rotorcraft and fixed-wing aircraft HQ testing. For lack of space, only the rotorcraft activities of DLR are mentioned here. Using the standard BO 105 helicopter, DLR has conducted a comprehensive evaluation of the quantitative and qualitative HQ criteria for military rotorcraft specified in ADS-33 [5-8].

By the sheer length of the project and by the volume of data generated, the BO 105 evaluation is the most elaborate ADS-33 HQ evaluation performed so far. Several software tools, like the HHQ Toolbox [9], were also developed by DLR for the analysis the huge database generated by them and the results were published in DLR Reports [8], or in journal and conference papers [10].

DLR has generated a comprehensive database for the definition of rotorcraft flight maneuvers and the specification of quantitative evaluation requirements. They include the roll bandwidth criterion for highly aggressive tracking tasks and a redefinition of the roll-to-pitch coupling requirement [11]. Most of the rotorcraft HQ research work at DLR has been carried out through international collaborations, and the Institute has reached as internationally accepted competence.

The Flight Mechanics and Control Division of NAL, has more than a decade's experience in designing control law and evaluation of HQ and PIO tendencies of modern high performance aircraft. Based on this experience, NAL has developed a MATLAB GUI based software package, called HQPACK [12], for a comprehensive analysis of HQ and PIO tendencies of fixed-wing aircraft. Further, NAL has recently extended its activity to rotorcraft system identification [13], and as a natural sequence a software package for rotorcraft HQ evaluation, called HELI-HQPACK [14], was developed and validated using data available in the open literature.

DLR has extended its activity to civil tiltrotor aircraft and Flying Helicopter Simulator (FHS). Both these projects would generate huge HQ databases which need efficient software for analysis.

Based on the mutual needs and the lessons learned from each other, an integrated, fully MATLAB GUI based software package called HAT was developed and validated at DLR under a collaboration programme between DLR and NAL [15].

The software package HAT can be used for HQ analysis of fixed-wing aircraft, rotorcraft and tilt-rotor aircraft operating either in pure fixed-wing mode or in pure rotory-wing mode. There are still no well defined HQ criteria for tilt-rotor aircraft, especially for the conversion mode.

The HAT software package accepts processed flight test data for rotorcraft HQ analysis. The data processing and data reduction techniques involved in HQ assessment are discussed in the following section to highlight the multi-disciplinary nature of the HQ evaluation process.

3. Data Processing and Reduction

Evaluation of HQ of rotorcraft through flight testing generates a large amount of data. The quality of measured flight test data is critically important for an accurate HQ assessment. Inaccurate or kinematically inconsistent data can lead to wrong conclusions. Therefore, sophisticated data processing and data reduction techniques are used in HQ analysis work. These techniques are briefly described below. Instrumentation aspects are discussed.

On-board Data Processing

HQ analysis using flight test data is done off-line. Therefore, no specific on-board data processing is required except for standard signal conditioning steps like amplification, filtering, multiplexing, digitization and finally recording the data.

Off-line Data Processing

The off-line data processing [7] mainly includes:

- Conversion to SI units
- Digital low-pass filtering of linear acceleration, angular rates, control inputs and rate of climb
- Unwrapping of angular signals that cross the 360 degree boundary, and subtracting the initial value
- Calculation of the velocity components along the rotorcraft axes from the HADS data
- Correction of velocity components and linear accelerations for center of gravity offset
- Digital differentiation of angular rates to obtain angular accelerations, followed by suitable filtering to reduce noise
- Averaging of torque data
- Frequency domain differentiation of rotor azimuth to obtain rotor speed
- Reduction of all data to 100 Hz
- Reconstruction of bank angle where bank angle signal was saturated
- Reconstruction of angular rates for those cases where saturation occurred
- Reconstruction of the rate of climb from vertical acceleration and pressure altitude or radio altitude when the average airspeed was below 10 knots

The HHQ Toolbox [9] developed by DLR was used to do the necessary data processing mentioned above.

Data Reduction

Once the flight test data is processed properly, simple data reduction methods – some as trivial as reading maximum and minimum values - are enough to extract the HQ parameters in the case of most of the quantitative HQ criteria. A few criteria require substantial data reduction, which is done both in the frequency domain and the time domain. The data reduction methods used in the software package are briefly described below.

Data Reduction in Frequency Domain

Data reduction in the frequency domain mainly involves computation of frequency response [ω , mag, phase] from input/output time histories.

The short-term, small amplitude attitude response to control input criterion (Bandwidth criterion) is formulated in the frequency domain, using the parameters Bandwidth (ω_{BW}) and phase delay (τ_p). These parameters are computed from a frequency response plot of the rotorcraft attitude response to control inputs. Usually the attitude (ϕ) frequency response is derived from the angular-rate (p) frequency response by performing an integration in the frequency domain, as shown:

$$\frac{\phi}{\delta_y} = \frac{1}{s}\frac{p}{\delta_y}$$

Usually three consecutive frequency sweeps are used to excite the angular-rate frequency response. The MULTICZT function in the HHQ Toolbox [9] was used to extract the frequency response from the time histories. This function uses chirp-Z transform, composite windowing, and weighted frequency response averaging techniques.

Data Reduction in Time Domain

1. First Order Model of Height Response

The ADS-33 specification requires the identification of a first-order model for the height response ($\dot{h}$) to collective input (δ_o):

$$\frac{\dot{h}}{\delta_o} = \frac{Ke^{-\tau s}}{T_{\dot{h}} s + 1}$$

It is assumed that the input is a pure step, and this yields the simple closed-form solution for the height rate response:

$$\dot{h}_{est}(t) = K\left[1 - \exp\left(-\frac{t-\tau}{T_{\dot{h}}}\right)\right] \qquad \text{for } t > \tau$$

$$\dot{h}_{est}(t) = 0 \qquad \text{for } t \le \tau$$

The first order transfer function parameters are obtained by a nonlinear optimization search to minimize the square-error (ε^2) between the estimated output ($\dot{h}_{est}$) and the flight test data ($\dot{h}$):

$$\varepsilon^2 = (\dot{h}_{est} - \dot{h})^2$$

The correlation coefficient r^2 is used to measure the goodness of fit:

$$r^2 = \sum_{i=1}^{n}\left(\dot{h}_{est} - \dot{h}\right)^2 \Big/ \sum_{i=1}^{n}\left(\dot{h} - \bar{\dot{h}}\right)^2$$

where $\bar{\dot{h}}$ is the mean value of measured height rate. If $0.97 < r^2 < 1.03$, the fit is deemed good. The software package uses the MATLAB function FMINSEARCH for minimizing ε^2.

2. Phugoid Oscillation in Forward Flight

The natural frequency (ω_n) and damping ratio (ζ) of the phugoid oscillation in forward flight were obtained by matching the pitch response to an exponentially decreasing sinusoidal pitch rate form [8].

$$q_{ph} = A\, e^{-\zeta\omega_n(t-t_o)} \cos\left(\omega_n\sqrt{1-\zeta^2}\,(t-t_o)\right)$$

where the parameters A, t_o, ζ and ω_n have to be identified. Usually a maximum likelihood parameter estimation program is used for time history matching [8], but the HAT software package uses the MATLAB function FMINSEARCH for this purpose.

3. Dutch Roll Oscillations in Forward Flight

There are several methods that can be used to compute the frequency and damping of an oscillatory response from its time history.

The natural frequency, ω_n, and damping ratio, ζ, of the Dutch roll oscillations are calculated using the logarithmic decrement method [8] as shown below:

$$\xi_i = \omega_n\sqrt{1-\zeta^2} = \frac{2\pi}{P}$$

$$\xi_r = \zeta\omega_n = \frac{\delta}{P} = \frac{\ln(1/2)}{T_{1/2}}$$

$$\omega_n = \sqrt{\xi_i^2 + \xi_r^2} \quad \text{and} \quad \zeta = \xi_r/\omega_n$$

The δ can also be calculated using the successive peaks (maxima and minima) of oscillations , A_1 , A_2 , ... A_{n-1} and A_n as shown below:

$$\delta = \frac{2}{n-2} \ln\left(\frac{|A_1|+|A_2|}{|A_{n-1}|+|A_n|}\right)$$

State Space Model Identification

Evaluating the ADS-33 dynamic stability criteria in hover is a complex task because it is difficult to extract the natural frequency and damping ratio parameters from the strongly coupled motion using simple techniques. Therefore, these eigenvalues have to be determined from six degree of freedom state-space models identified using advanced parameter estimation techniques. Thus, system identification is an indispensable part of rotorcraft HQ evaluation process.

MATLAB and GUI

MATLAB was used for data processing, data reduction and overall software development because it offers several advantages. MATLAB is most suitable for HQ evaluations because of the support provided by its Signal Processing, Control and Optimization Toolboxes, besides powerful graphic tools.

A GUI approach, instead of a Command Line Interface (CLI) approach, is used because it makes the learning and HQ criteria execution process easier and faster. The user need not know the source code involved. Multiple GUI windows allow different information to be displayed simultaneously on the user's screen. Switching from one task to another is possible without losing sight of the first task.

4. HAT: Handling-qualities Analysis Toolbox

The salient features of the software package such as the organisation or structure, the GUI Tools available to the User, the formats of input and output data, and the operating procedure are discussed below.

Organization

The software package HAT is configured as a MATLAB Toolbox and is modular in structure. New criteria can be easily added, and any obsolete criteria can be easily removed from the software package. The software is divided into seven sections or modules comprising of:

1. Helicopter Hover/Low-speed HQ Criteria
2. Helicopter Forward Flight HQ Criteria
3. Demo of Helicopter HQ Criteria
4. Helicopter MTEs Data Analysis
5. Data Processing Tools
6. Fixed-wing Aircraft HQ/APC Criteria
7. Demo of Fixed-wing HQ/APC Criteria

Each of these sections are further divided into sub-sections comprising of several individual HQ criteria. The individual HQ criterion can be selected and executed or demonstrated with the help of GUI Tools or Windows of HAT. The helicopter MTEs section and the Data Processing Tools section are not yet fully developed.

GUI Windows

The software package HAT uses three layers of GUI Windows for the evaluation or demonstration of HQ criteria. Standard MATLAB dialog boxes like the question dialog, the input dialog and the warn dialog appear as the fourth layer in the GUI structure. The GUI Windows which are used for the execution of the software are described below.

Main GUI Window

The Main GUI Window, shown in Figure 1, appears on the computer screen when the software package is invoked. Individual sections of the software package can be opened by clicking on the appropriate push button on the Main GUI Window.

Criteria Selection Window

When a push button on the Main GUI Window, say the "Hover HQ" button, is clicked upon, a second GUI window, which can be called as Criteria Selection Window, appears as shown in Figure 2.

As can be seen from Figure 2, the helicopter hover/low-speed requirements are divided into five sub-groups labelled:

1. Pitch Axis Response Criteria
2. Roll Axis Response Criteria
3. Yaw Axis Response Criteria
4. Heave Axis Response Criteria
5. Inter-axis Coupling Criteria

Each of these five sub-groups comprise of several individual criteria which can be accessed through popup menus shown on Figure 2.

Info Window

Information about a set of HQ criteria, say Pitch Axis Response Criteria for helicopters, can be read by clicking on the push buttons at the top of the popup menus (Figure 2) and opening an Info Window.

A typical "Info Window", shown in Figure 3, comprises of several "pages" of information which can be opened by clicking on the page buttons P1, P2, etc., on the Info Window.

Criteria Evaluation Window

Clicking on a criterion name in a popup menu in the Criteria Selection Window opens a Criteria Evaluation Window which is a simple figure window for plots, and an Input Dialog Box also appears simultaneously.

Input Dialog Box

The Input Dialog Box of HAT is a standard input dialog box of MATLAB. Using the Input Dialog Box, an user can enter numerical values or options for:

- Number of Flight Conditions to be evaluated
- Format of input data – State Space, Transfer Function, Time Histories, Frequency Response Data
- Mode of loading input data – automatic loading or manual loading
- Properties of markers for plots etc.,

In addition, there are many default options such as the Meta file option for saving the plots etc., incorporated in the Input Dialog of HAT.

Finally, clicking on the "OK" button on the Input Dialog Box starts the evaluation of the HQ criterion chosen. During the evaluation of a criterion, standard MATLAB dialog boxes like the question dialog, input dialog and warn dialog box appear as a fourth layer in the GUI structure.

Demo Selection Window

A "Demo Selection Window" appears on the computer screen when the "HC HQ Demo" or the "FW HQ Demo" pushbutton on the Main GUI Window is pressed. The Demo Selection Window is similar to the Criterion Selection Window. The User can select a criterion for demonstration using the popup menus in the Demo Selection Window.

Criteria Demo window

When the User clicks on a criterion name in a popup menu on the Demo Selection Window, a "Criteria Demo Window" appears as shown in Figure 4. This window is split into two sections, a graphical window to show plots and a text window to show numerical values of HQ parameters and comments. The Demo can be started, stopped, reset, made to run either in steps or continuously using the push buttons and the check box on the Criteria demo Window.

Input Data Format

Fixed-wing Aircraft Input Data

The input data can be either in the form of state-space models or transfer function models in MATLAB format. In the case of a few criteria, the input can be in the form of frequency response data (Bandwidth criterion) or time histories. More details can be found in Reference 12.

Rotorcraft Input Data

At present, the software package accepts fully processed time histories for rotorcraft HQ analysis. To save computer memory, the time histories are entered as individual variables rather than a huge data matrix, using a specially developed data interface tool. The names and units of the variables used for HQ analysis are shown below:

Variable	Description
1. t	Time vector [sec]
2. dt	Time increment [sec]
3. P	Roll rate [rad/sec]
4. Q	Pitch rate [rad/sec]
5. R	Yaw rate [rad/sec]
6. ax	Longitudinal accln. [m/sec]
7. ay	Lateral acceleration [m/sec]

8. az Normal acceleration [m/sec]
9. Phi Roll attitude [rad]
10. Theta Pitch attitude [rad]
11. hdg Heading angle [rad]
12. Beta Sideslip angle [rad]
13. trq2 Right engine torque [nm]
14. trq1 Left engine torque [nm]
15. trqavg Average torque [nm]
16. DeltaX Longitudinal cyclic input [%]
17. DeltaY Lateral cyclic input [%]
18. DeltaHR Pedal input [%]
19. DeltaO Collective input [%]
20. U Longitudinal velocity [m/sec]
21. V Lateral velocity [m/sec]
22. W Vertical velocity [m/sec]
23. Hbar Barometric altitude [m]
24. Hrate Height rate [m/sec]
25. hRadio Radio altitude [m]

For evaluating HQ criteria only the relevant variables need be loaded into the workspace.

Rotorcraft Input Data Interface

Since different data files (CDF files) use different names and units for the variables, a macro \hat\VAR_SEPARATE.M is incorporated in the software package for extracting the variables from data matrices, or re-naming the variables and converting the units if necessary.

Loading Input Data

The input data can be loaded into the MATLAB workspace either through user interaction ("Manual" mode) or automatically ("Auto" mode). In the Manual mode input data is loaded using the MATLAB macro "UIGETFILE". In the Automatic mode, input data is automatically loaded by the software itself. For automatic loading the user should save the names of the data files and their path in specific .m files, before starting the software, as shown by an example below:

```
% pitch_bw_hover_files.m
pathname = 'c:\bo105data\HQ95_96\';
mdlnames = char('HQ950301',...
                'HQ950401',...
                'HQ950402');
```

Multiple flight conditions can be evaluated in terms of a chosen criterion.

Output Data Format

The analytical evaluation of HQ criteria yields a large amount of output data both in the numerical form as well as graphical form. The numerical output comprises of the numerical values of HQ metrics like Bandwidth, Phase Delay etc. The graphical output comprises of plots of HQ Level boundaries, Bode plots and time history plots. Both the forms of output data are stored automatically under specific file names in specific subdirectories. Options are provided in the software package either to delete the previous numerical and graphical output stores or to append new outputs to the earlier outputs.

Numerical Output

The numerical outputs are stored in two formats - in the form of ASCII files and in the form of .MAT files, under specific file names in specific subdirectories of HAT.

ASCII File Format

The numerical values of HQ parameters are automatically saved in the form of ASCII files with specific names and with the extension ".out". These files can be readily converted to tables when preparing documents. For example, the numerical output from the analysis of pitch-axis bandwidth criterion for rotorcraft is saved in the file *\hat\hc_opdata\pitchbw.out* as shown below:

Pitch Bandwidth Criterion

Module: PITCHBW.M
Flight Phase: Hover
Date: 27. 9.2002
Time: 9.23.21

FC, Data File,	W180,	BWph,	BWg,	BW,	Tp
No, ,	(rad/s),	(rad/s),	(rad/s),	(rad/s),	(sec)
1, HQ950301 ,	6.2980,	2.8002,	4.1157,	2.8002,	0.0778
2, HQ950401 ,	5.9223,	2.9027,	3.7825,	2.9027,	0.0750
3, HQ950402 ,	5.7270,	2.9595,	3.6856,	2.9595,	0.0733

MAT File Format

The numerical values of HQ parameters, along with the name of the associated input data file, are stored in the form of .MAT files also. These .MAT files can be used for re-plotting HQ Level boundaries off-line later, if required.

Graphical Output

The graphical output can be saved as a MATLAB PostScript (.ps) file or a Meta file (.emf) under specific file names in specific subdirectories of

HAT. The Meta files can be used to insert HQ Level plots, as figures, into word documents.

Demo of HQ Criteria

The software package HAT incorporates full fledged demonstration programmes both for the fixed-wing and rotorcraft HQ criteria, to help a new user. The user can select the required demonstration through the GUI Tools provided in the software package. The Demo runs automatically without the intervention of the user.

Hardware/Software Requirements

- Pentium 3/4 PC
- Windows 98 or higher operating system
- MATLAB 6.0 or higher version, with its associated Signal Processing, Control and Optimization Toolboxes
- About 9 MB hard disc memory, including the storage required for numerical and graphical output

Software Execution Procedure

Adding HAT to MATLAB Path

The software package is organized as a main directory \hat\ and several sub-directories. These directories must be added to MATLAB path, preferably at the top to avoid clash with standard MATLAB names, before starting the software. This addition to MATLAB path can last for a single session of HQ evaluations or it can be saved for future use. A macro *'hqpath.m'* incorporated in the software package does the job as shown below:

>> chdir c:\hat $\langle CR \rangle$

% Change directory to HAT

>> hqpath $\langle CR \rangle$

% Append HAT and its subdirectories to MATLAB path

>> hat $\langle CR \rangle$

% Invoke HAT software package

Criteria Evaluation/Demo Procedure

1) Add HAT and its subdirectories to MATLAB path.
2) Start HAT: >> hat $\langle CR \rangle$
3) Select a sub-section of HAT by clicking on the appropriate push button on the Main GUI Window (Figure 1).
4) Read Info/Help (Figure 3), if required, using the Info push buttons on the Criteria Selection Window (Figure 2).
5) Open a popup menu and select the required criterion. When the User clicks on a name in the popup menu, Criteria Evaluation Window and the Input Dialog Box appear simultaneously.
6) Enter/Select proper values/options for the parameters displayed in the Input Dialog Box.
7) Click on the OK button in the Input Dialog Box to start criterion evaluation.
8) During the execution of HQ criteria several standard MATLAB dialog boxes appear for entering numerical values (say, starting values for optimization) or to query about options, and will disappear when answered.
9) The numerical output and the graphical output are automatically saved in specific output files
10) The user can print out the numerical and graphical output after the HQ evaluation session.
11) Using 'Demo Selection Window' and 'Criteria Demo Window' (Figure 4), the user can view a demo of chosen criteria.

The validation of the software package using standard fixed-wing and rotorcraft HQ data bases is discussed in the following sections.

5. Rotorcraft Criteria Validation

The quantitative HQ criteria for rotorcraft, incorporated in the software package, were validated using the BO 105 helicopter flight test database. A complete list of criteria incorporated in HAT and validation results are given in this Section. Flight test techniques, the rationale behind each criteria, and the merits and demerits of criteria are not discussed. These aspects are elaborately described in several DLR publications [10].

The quantitative HQ criteria for rotorcraft are lumped into two groups Hover/Low-speed Requirements and the Forward Flight Requirements following the ADS-33E convention. For each flight regime, the criteria are grouped axis-wise. For some criteria popular names like Bandwidth, Dynamic Stability, Attitude Quickness are used instead of elaborate descriptive names given in ADS-33E. A list of HQ criteria incorporated in HAT are given below.

List of Rotorcraft HQ Criteria

Hover / Low Speed Requirements

A. Pitch Axis Response Criteria
1. Bandwidth Criterion
(Small-amplitude short-term response)
2. Dynamic Stability Criterion
(Small-amplitude mid-term response)
3. Attitude Quickness Criterion
(Moderate-amplitude attitude changes)
4. Large-amplitude pitch attitude changes

B. Roll Axis Response Criteria
1. Bandwidth Criterion
2. Dynamic Stability Criterion
3. Attitude Quickness Criterion
4. Large-amplitude roll attitude changes

C. Yaw Axis Response Criteria
1. Bandwidth Criterion
2. Dynamic Stability Criterion
3. Attitude Quickness Criterion
4. Large-amplitude heading changes

D. Heave Axis Response Criteria
1. Height response characteristics
2. Torque response

E. Inter-axis Coupling Criteria
1. Pitch due to roll coupling for Aggressive agility (time domain criterion)
2. Roll due to pitch coupling for Aggressive agility (time domain criterion)
3. Pitch due to roll and roll due to pitch coupling for Target Acquisition and Tracking (frequency domain criterion)
4.Yaw due to collective for Aggressive agility

Forward Flight Requirements

A. Pitch Axis Response Criteria
1. Bandwidth Criterion
2. Dynamic Stability Criterion
3. Pitch control power

B. Roll Axis Response Criteria
1. Bandwidth Criterion
2. Dynamic Stability Criterion
(Lateral-directional oscillations)
3. Spiral Stability
4. Attitude quickness Criterion
5. Large-amplitude roll attitude changes

C. Yaw Axis Response Criteria
1. Bandwidth Criterion
(for Target Acquisition and Tracking)
2. Large-amplitude heading changes for Aggressive agility

D. Flight Path Control
1.Flight path response to collective controller (backside operation)
(Height response characteristics)

E. Inter-axis Coupling Criteria
1. Pitch due to roll coupling for Aggressive agility (*qualitative* criterion)
2. Roll due to pitch coupling for Aggressive agility
3. Pitch due to roll and roll due to pitch coupling for Target Acquisition and Tracking (frequency domain criterion)
4. Pitch attitude due to collective control

HQ Criteria Validation Results

Typical results obtained from an evaluation of the rotorcraft quantitative HQ criteria using the BO 105 helicopter database are shown in Figures 5–9. These results are comparable to similar results published in DLR reports [8] earlier. More details can be found in Reference 15.

6. Fixed-Wing Criteria Validation

The fixed-wing section of the software package, HAT, comprises of an updated version of HQPACK [12] which has been validated comprehensively using standard databases like the Neal-Smith, LAHOS, LATHOS, HAVE PIO databases available in the open literature.

List of HQ / PIO Criteria

For the sake of information a list of fixed-wing HQ and PIO prediction criteria included in the software package are given below.

A. Longitudinal HQ Criteria
1. Lower Order Equivalent Systems
2. CAP / CAP'
3. Bandwidth Criterion
4. Unified Bandwidth Criterion
5. Neal-Smith Criterion
6. Closed Loop Criterion
7. Pitch Rate Response
8. Gibson's Criteria
9. C* Criterion
10. Turbulence Response
11. Step Input Response

B. Lateral-directional HQ Criteria
1. Lower Order Equivalent Systems
2. Phi/Beta Mode Ratio
3. Lateral/Directional Modes

4. Roll Rate Oscillations
5. Bank Angle Oscillations
6. Roll Performance
7. Sideslip Excursions
8. Turbulence Response
9. Step/Pulse Input Response

C. Longitudinal PIO Criteria
1. Ralph Smith Criteria
2. Smith-Geddes Criteria
3. Bandwidth PIO Criteria
4. Average Phase Rate
5. Loop separation Parameter
6. Unified PIO Criteria
   Unified Bandwidth Criteria
   Time-domain Neal-Smith Criterion

D. Lateral PIO Criteria
1. Ralph Smith Criterion
2. Average Phase Rate
3. Mario Innocenti's Criteria

HQ Criteria Validation Results

Figures 10–11 show the HQ analysis results obtained from an application of the Unified Bandwidth Criterion to a modern high performance aircraft. More details can be found in Reference 12.

7. Outlook

The development of the software package HAT has been undertaken with the main objective of making it a broad based software toolbox which can be used for the analysis of handling qualities of flight vehicles of all sorts.

It is envisaged that the HAT software package would be an useful tool for the following HQ research work:

- Investigation of the applicability of some of the fixed-wing HQ criteria to rotorcraft
- Development of mission-oriented HQ criteria for fixed-wing aircraft
- Development of a comprehensive set of HQ criteria for Tiltrotor aircraft

The RHILP project [16] is aiming to assemble an integrated set of HQ criteria primarily to define the design requirements for a Civil Tiltrotor control systems. The software package HAT may play some useful part in this task.

8. References

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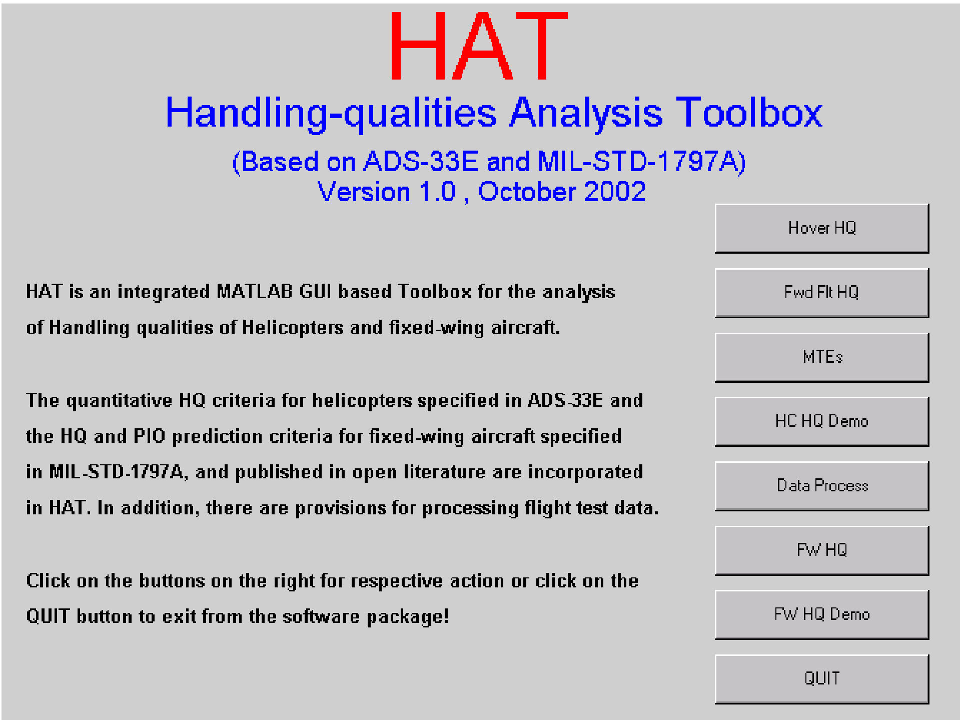


Figure 1. Main GUI Window

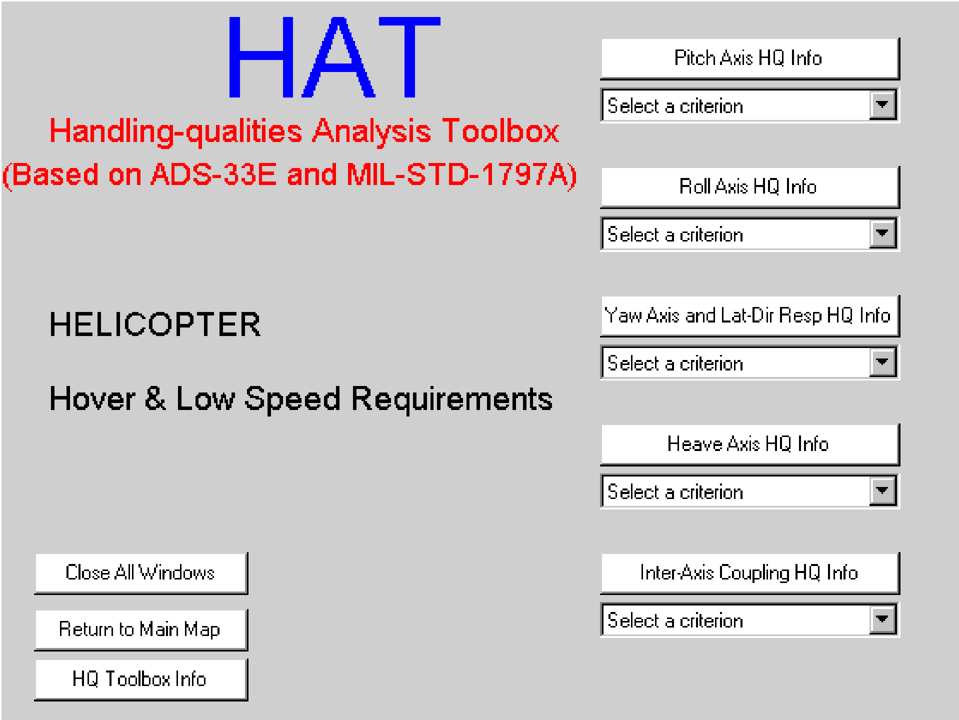


Figure 2. Criteria Selection Window

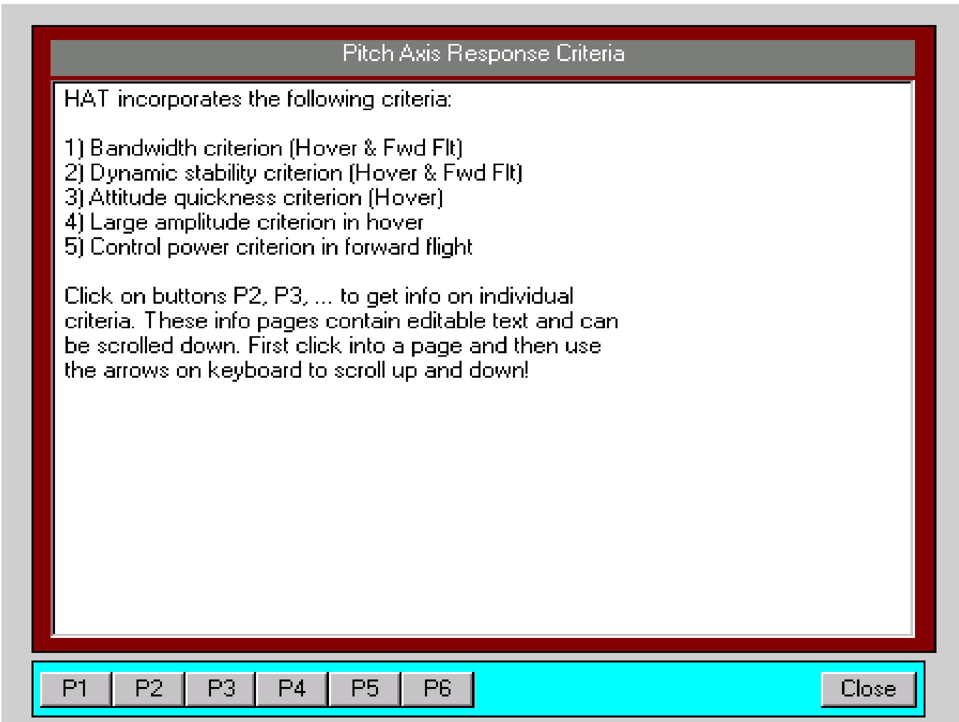


Figure 3. Info Window

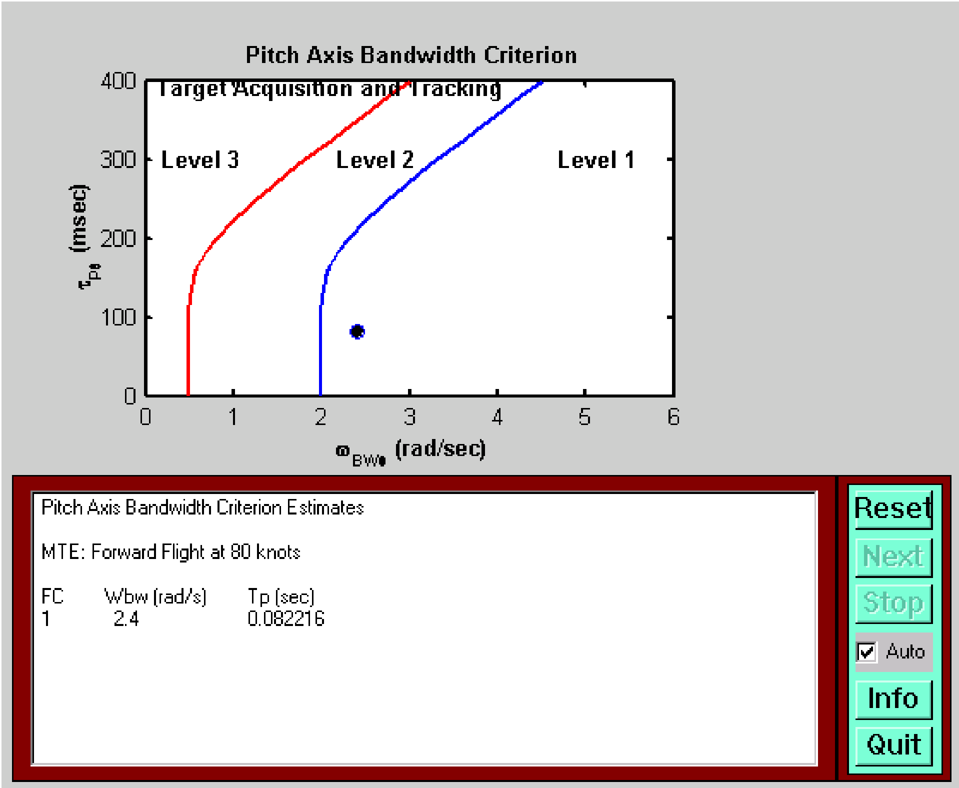


Figure 4. Criteria Demo Window

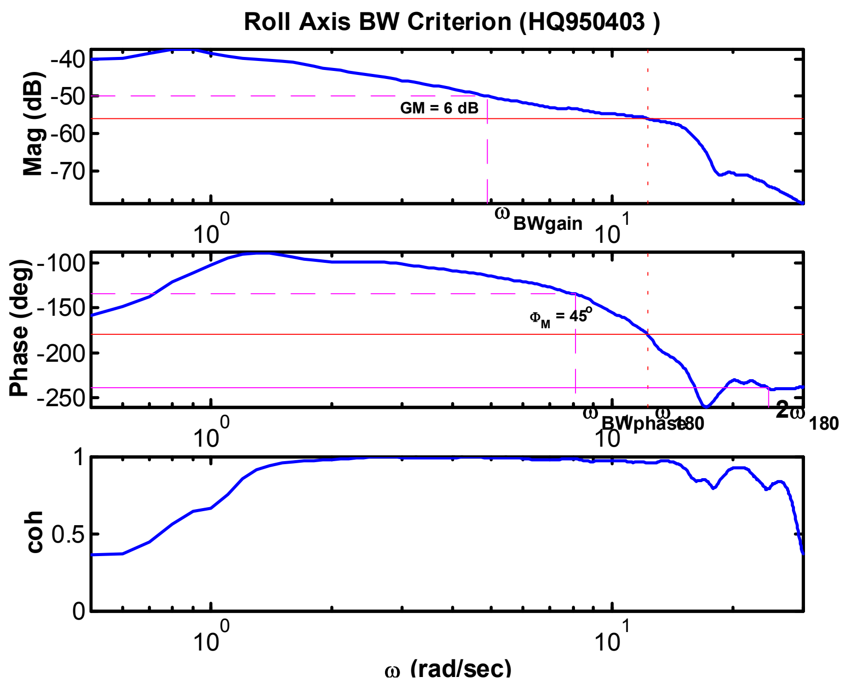


Figure 5. Computation of Bandwidth Criterion Parameters

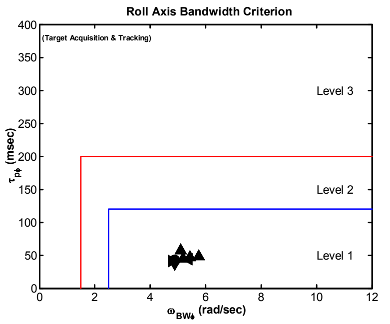


Figure 6. Roll axis BW criterion bounds

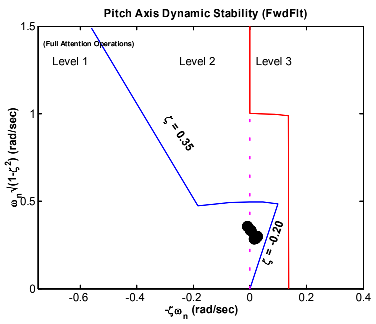
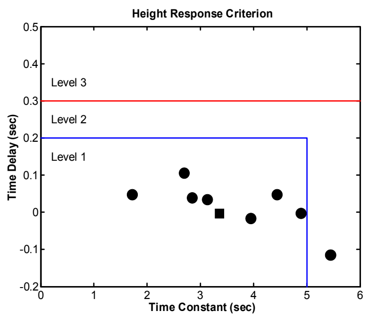


Figure 7. Pitch dynamic stability in forward flight



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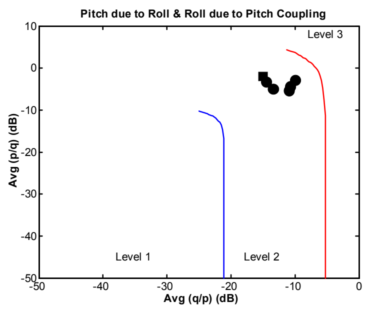

Figure 9. Frequency domain roll/pitch coupling Criteria bounds

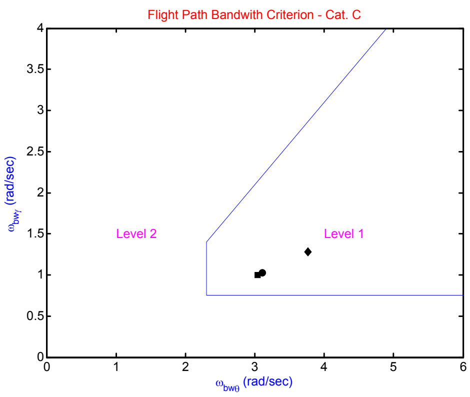

Figure 10. Fixed-wing Unified BW criteria - Prediction of HQ Level

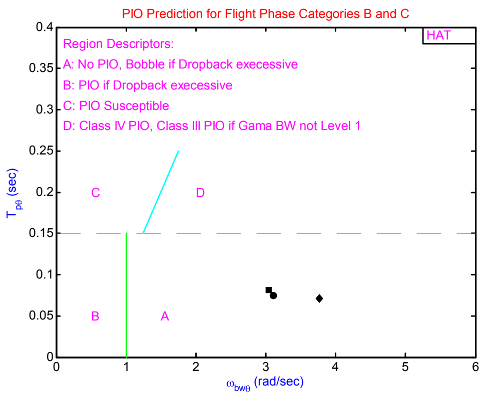

Figure 11. Fixed-wing Unified BW criteria - Prediction of PIO tendency