EVALUATION OF AERONAUTICAL DESIGN STANDARD-33E CARGO MISSION REQUIREMENTS
- FLIGHT TESTS WITH A CH-53G -

Marc T. Höfinger[1], Chris L. Blanken[2], Gerhard Strecker[3]

[1] Deutsches Zentrum für Luft- und Raumfahrt e.V., DLR
Lilienthalplatz 7, 38108 Braunschweig, Germany
e-mail: marc.hoefinger@dlr.de

[2] Aeroflightdynamics Directorate (AMRDEC)
U.S. Army Research, Development, and Engineering Command
Moffett Field, California, USA
e-mail: cblanken@mail.arc.nasa.gov

[3] Wehrtechnische Dienststelle (WTD) 61
German Armed Forces Technical and Airworthiness Test Center
for Aircraft and Aeronautical Equipment
Manching, Germany
e-mail: gerhardstrecker@bwb.org

Key words: ADS-33, Handing Qualities, Cargo helicopter

Abstract. Flight tests with a Sikorsky CH-53G cargo helicopter of the German Army were performed in Germany to evaluate the applicability and repeatability of the Aeronautical Design Standard (ADS)-33E-PRF cargo helicopter mission handling qualities requirements. These requirements were developed from flight tests with a CH-47D, a tandem-rotor cargo helicopter. The objective of the CH-53G tests was not to check the helicopter against ADS-33, but to use it as a testbed to corroborate the findings of the CH-47D tests and identify any fundamental differences or tandem rotor biases. The tests were carried out by the Wehrtechnische Dienststelle (WTD) 61, the German Aerospace Center (DLR), and the U.S. Army Aeroflighdynamics Directorate (AMRDEC). Quantitative data were gathered in hover and 100 knots forward flight for all axes. Five test pilots returned Cooper-Harper Handling Quality Ratings (HQRs) for 13 Mission Task Elements (MTEs), flown in Good Visual Environment (GVE), including four with an externally slung load. This paper describes the CH-53G quantitative criteria results and the comparisons with the qualitative results.

1 ABBREVIATIONS

AC	Attitude Command	HAT	Handling qualities Analysis Toolbox
ADS	Aeronautical Design Standard	HQRs	Handling Qualities Ratings
AFCS	Automatic Flight Control System	LMR	Load-Mass-Ratio
APC	Aircraft Pilot Coupling	MTEs	Mission Task Elements
DH	Direction Hold	SAS	Stability Augmentation System
DVE	Degraded Visual Environment	UCE	Usable Cue Environment
GVE	Good Visual Environment		

2 INTRODUCTION

The Aeronautical Design Standard (ADS)-33 is the current U.S. Army handling qualities specification for military rotorcraft. Its development started at the U.S. Army Aeroflightdynamics Directorate (AFDD) in the early 1980´s, when the extension of military helicopter missions made a review of the then applied MIL-H-8501 necessary. Several international organizations supported the development process with piloted simulations and flight tests (see e.g. [1]-[11]). AFDD and DLR, e.g., collaborated on pitch-roll coupling research, the results of which now form the coupling requirements in ADS-33 for target acquisition and tracking. Several new approaches and criteria were developed to cover the increased scenarios and environments of modern helicopter missions. ADS-33 includes requirements for aircraft response characteristics dependant on the visible cues, quantitative criteria in the frequency and time domain as well as qualitative criteria that are based on pilot ratings [12]. It is accepted internationally as a valuable contribution to the definition of requirements for military helicopter handling qualities (e.g. [13], [14], [15]). ADS-33E-PRF [16], the latest version, was released in March 2000.

Cargo mission requirements, including operations with external slung loads, were not addressed in the first versions of ADS-33. As a consequence, beginning in the 1990's the U.S. Army Airworthiness Qualification Test Directorate (AQTD) was tasked by the Aviation and Troop Command to conduct flight tests with a Boeing CH-47D, a tandem-rotor cargo helicopter. The objective was to develop handling qualities requirements for cargo transport missions to be included in ADS-33. The tests were performed from 1993 to 1995 with the helicopter internally loaded up to 46,800 lb gross weight (94 % of maximum) and to 48,000 lb gross weight (96 % of maximum) with an external load. The results ([17], [18], [19]) were incorporated in ADS-33E. In addition, it was explicitly proposed to undertake a comparable evaluation with a single main rotor production cargo helicopter to corroborate the findings of the CH-47D tests. The flight tests with the German Army CH-53G, a transport helicopter with a conventional main and tail rotor configuration, filled this gap.

Test preparation began mid 2004, with the general set-up of the test aircraft and the data gathering systems. In parallel, the ground courses for the maneuvers to be flown, the Mission Task Elements (MTEs), were set up according to ADS-33E. The first flight test phase, conducted at the end of 2004, led to modifications and the final set-up of the ground courses. This was the first time the MTEs were flown with the CH-53G and the pilots returned initial general feedback. The quantitative data were collected May-April 2005, with an additional flight at the end of 2005 to gather missing attitude quickness data. The pilot handling qualities ratings were gathered in July and August 2005. Five test pilots flew the MTEs and provided Cooper-Harper Handling Quality Ratings (HQRs). A total of 27 data gathering flights in 40.5 flight-hours were flown between the end of 2004 and end of 2005. For more detailed information on the qualitative criteria results and lessons learned with respect to the MTEs, refer to reference [20].

This paper focuses on the quantitative criteria and the comparison of quantitative and qualitative results, summarizing the latter ones briefly.

3 TEST AIRCRAFT

In the 1970's, 110 Sikorsky CH-53G were build in Germany under license for the German Army. The two aircraft used for the ADS-33E-PRF evaluation were the first two delivered to the German Army. The aircraft used for the final evaluation and data gathering, call sign 84+02, is equipped with a data acquisition system including a nose boom with air data sensors and is shown in *Figure 1*. The second aircraft was used for the first phase and for MTE pilot training. It is not equipped with a data acquisition system.

The CH-53G is flown by two pilots in a side by side cockpit. It features conventional mechanical helicopter controls that are augmented by two parallel and independent hydraulic servo systems. Collective control is cross fed to both the lateral cyclic and tail rotor controls to offset roll and yaw moments produced by collective pitch changes. The electronic Automatic Flight Control System (AFCS) includes command augmentation of longitudinal cyclic control, rate damping about all axes, attitude and heading stabilization, and turn coordination at indicated airspeeds above 60 knots. The landing gear, front and main, is retractable and the main landing gear has brakes. Some basic aircraft data are given in *Table 1*.

4 TEST SITE

The flight tests were performed at the WTD 61 airfield near Manching, in the south of Germany. All of the MTE courses were set up in parallel on the cargo dropping area of the WTD 61, a plane area of about 2500 m x 1000 m, covered mainly with grass. Several straight concrete roads with circles at the intersections allow driving onto the area, see *Figure 2*.

These roads and circles provided very useful references for setting up the ground courses and were even used as visual references for the MTEs [20]. The WTD 61 cargo dropping area provides an excellent means to have all relevant MTE courses available in parallel throughout the complete period of flight testing.

5 QUANTITATIVE CRITERIA

Quantitative data were gathered in hover and 100 knots forward flight for all axes with an engine-start weight of 33,400 lb (80 % of maximum) and mid c.g. *Table 2* and *Table 3* summarize the flights. Because specific data regarding structural modes and frequencies of the helicopter were not available prior to flight testing, for safety reasons frequency sweeps were only flown in hover for the pitch and roll axes and quantitative data flight tests were not performed with an externally slung load. Pulses, steps and doublets of 10 to 20% control position excursions around trim were generated in every control axis in both flight conditions. All control inputs were considered within the range of normal operation. Four flights resulting in a total of 5h 05 min flight time were needed to collect the data, including an additional flight that was made end of 2005 to collect missing data for attitude quickness analysis. This was necessary because the pitch AFCS function includes a longitudinal control shaping feed-forward element, resulting in an aircraft response in pitch that is not a rate response type. Control inputs different than pulses were therefore necessary to achieve a pitch angle change suitable for quickness analysis. Pitch attitude changes up to 20 degrees from trim, roll attitude changes up to 50 degrees, and heading changes from 10 up to 60 degrees in both directions were performed in hover. Since the attitude quickness criteria for forward flight is only defined for the roll axis, exclusively roll attitude changes from 10 to 50 degrees were performed at 100 knots.

To a large extent the analysis of the quantitative criteria was made utilizing the software tool “HAT”, a joint development of the Indian National Aerospace Laboratories (NAL) and DLR [21]. This allowed time effective processing of the flight data and generation of results on the criteria boundaries. Nevertheless, prior to using HAT pre-selection of appropriate time history flight test data is necessary, requiring engineering experience with regard to the ADS-33 criteria and rotorcraft handling qualities in general. The results are categorized according to the aircraft role, i.e., the CH-53G as being a cargo helicopter does not need to fulfill the “Target Acquisition and Tracking” ADS-33E requirements. In addition, primarily moderate or limited agility is required, and the requirements for aggressive agility, although not required, are only mentioned to a certain extent.

Figure 1: WTD 61 Sikorsky CH-53G testbed.

Table 1: Sikorsky CH-53G data

WEIGHTS		**PERFORMANCE**	
Max. gross weight	42,000 lb (19,050 kg)	Engines	2 x T-64-GE-7
Max. load	16,645 lb (7,550 kg)	Cont. power	2 x 2,409 kW
		Max. speed @ SL	170 kt (315 km/h)
MAIN ROTOR		Cruise speed @ SL	150 kt (278 km/h)
Number of blades	6	Max. sideward speed	±35 kt (65 km/h)
Type	articulated	Max. backward speed	30 kt (56 km/h)
Diameter	72 ft (22.02 m)	Min. / Max. load factor	-0.5 g / 2.38 g
Normal rpm	185 rpm (19.4 rad/s)	Max. slope	10 deg
TAIL ROTOR			
Number of blades	4		
Diameter	16 ft (4.88 m)		
Normal rpm	788 rpm (82.8 rad/s)		

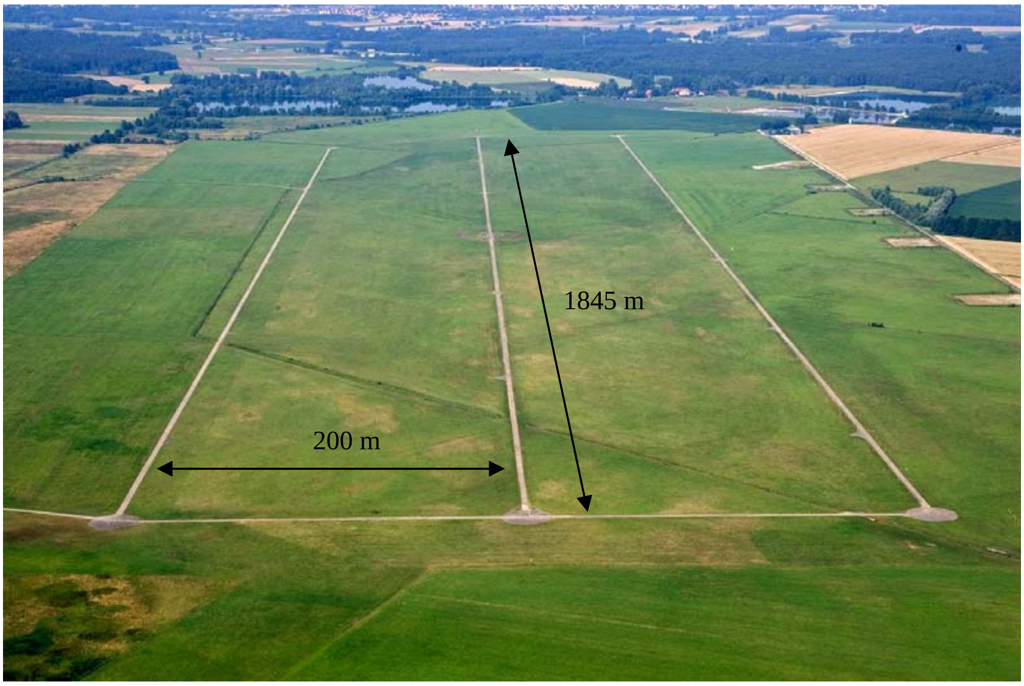


Figure 2: WTD 61 cargo dropping area.

Table 2: Hover tests performed.

Test Techniques	Axis	Requirement	ADS-33E-PRF paragraph
Trim	all	Equilibrium	3.3.1
Frequency Sweeps	Roll Pitch	Bandwidth, Coupling	3.3.2.1 3.3.9.3
Pulse inputs	Roll Pitch Yaw	Mid-term resp., Att. quickness	3.3.2.3 3.3.3 3.3.5.2 3.3.6
Step inputs	Roll Pitch Yaw Col.	Max. rate, Coupling, Response to coll. controller	3.3.4 3.3.8 3.3.9 3.3.10
Attitude capture	Pitch Roll Yaw	Max. attitude, Att. quickness	3.3.4 3.3.3

Table 3: Forward flight tests performed.

Test Techniques	Axis	Requirement	ADS-33E-PRF paragraph
Pulse inputs	Roll Pitch	Mid-term resp., Att. quickness, Oscillations, Spiral stability	3.4.1.2 3.4.6.2 3.4.7.1-2 3.4.9.2
Step inputs	Roll Pitch Yaw Col.	Coupling, Max. rate, Heading	3.4.4 3.4.5.1-2 3.4.6.3 3.4.8.2
Doublet inputs	Yaw	Lateral-direct. stability	3.4.9
Steady Sideslip	Roll Yaw	Lateral-direct. characteristics	3.4.10
Attitude capture	Roll	Att. quickness	3.4.6.2

5.1 Hover and low speed requirements

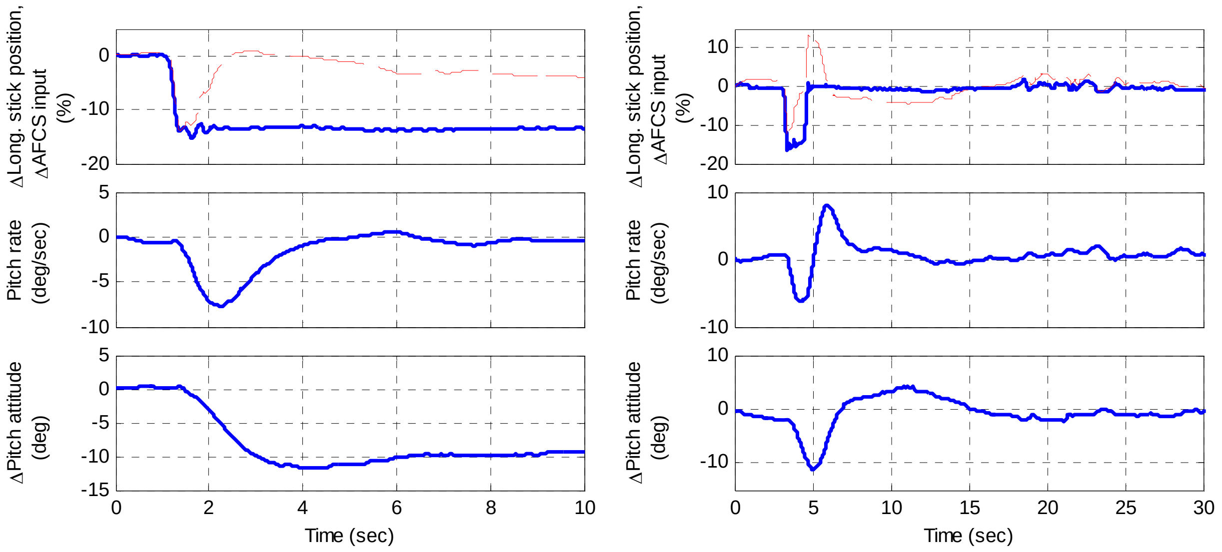
Pitch axis

The aircraft pitch axis response to a longitudinal step and pulse input is given in *Figure 3*. It fulfils the ADS-33E requirements for Attitude Command (AC), requiring a proportional pitch attitude change 6 seconds after a step cockpit pitch controller input. The attitude shall then remain essentially constant for 6 to 12 seconds. As *Figure 3* shows, this is the case for the CH-53G pitch attitude response. A feed-forward part in the AFCS longitudinal control path results in the command input being taken back, see the red dashed line in *Figure 3,* representing the measured control input after the AFCS, i.e., the longitudinal actuator command input. As a consequence the pitch rate is washed out. This response type is not selectable and is present throughout the flight envelope.

The pitch axis bandwidth, determined from two manually flown frequency sweeps in the longitudinal axis, is Level 1 (see *Figure 4 a)*) for operations in good visual environment (ADS-33: “Usable Cue Environment (UCE) = 1”) and fully attended operations, i.e., when pilots are fully concentrating on the stability and control of the aircraft while flying a maneuver rather than doing side tasks. For operations in degraded visual environment or when the pilots are distracted from the primary flight task, the requirements are more stringent so the bandwidth falls into the Level 2 region, see *Figure 4 b).* The pitch attitude quickness in hover is borderline Level 1-2, see *Figure 5.*

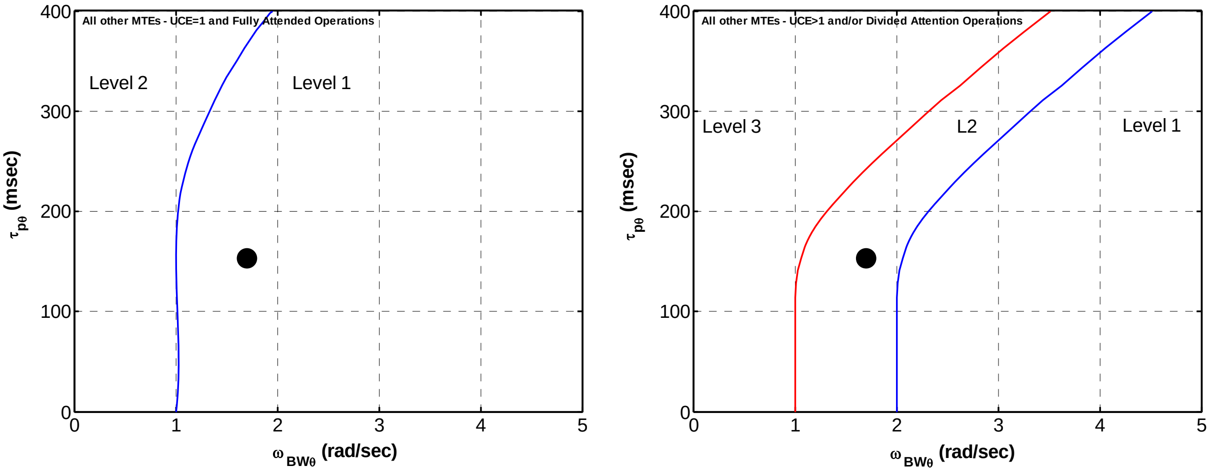
Pitch attitudes of +27 deg (pitch up) and -38 deg (pitch down) were achieved in flight test, thus meeting the ADS-33E large-amplitude moderate agility requirements of +20/-30 deg. Since the corresponding longitudinal cockpit controller deflections were not the maximum possible, even higher attitudes are possible. A linear approximation of pitch attitude with stick deflection from flight test data results in predicted achievable attitudes of ±53 deg at maximum stick deflections, thus even fulfilling the requirement for aggressive agility (±30 deg).

The mid-term response criteria, requiring certain limits on frequency and damping for pitch oscillations, have not been evaluated in detail, but the aircraft did not show any potential to disturbing oscillations in the longitudinal axis in hover, see *Figure 3 b).* It is therefore regarded Level 1.



a) Longitudinal step input *b) Longitudinal pulse input*

Figure 3: CH-53G hover pitch axis response-type (solid: stick input; dashed: input after AFCS).



a) UCE = 1, Fully Attended Operations *b) UCE > 1, Divided Attention Operations*

Figure 4: Hover pitch bandwidth results (data from 2 frequency sweeps processed).

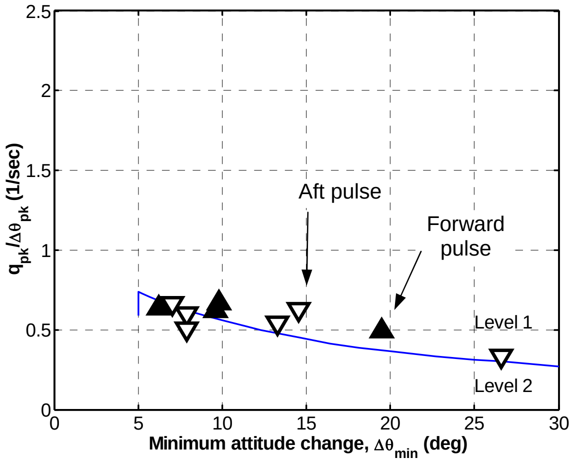


Figure 5: Hover pitch attitude quickness.

Roll axis

The roll axis meets the ADS-33 criteria for a rate response-type, see *Figure 6*.

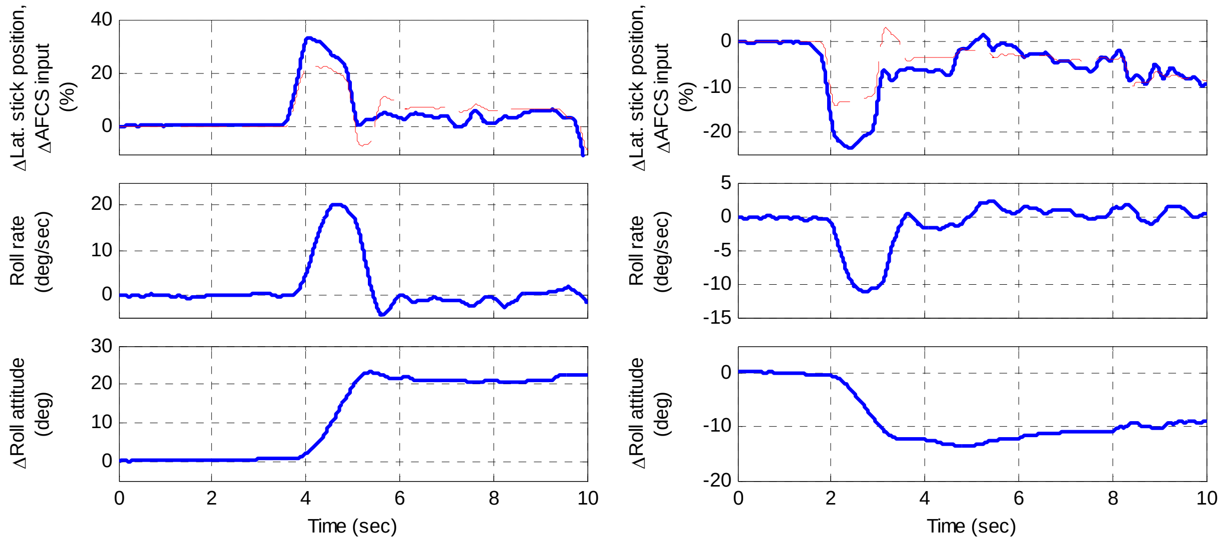
The bandwidth, again determined from manually flown frequency sweeps, is Level 1 for both UCE = 1 and fully attended operations and UCE > 1 and divided attention operations, see *Figure 7*.

The attitude quickness is Level 2 and for larger attitude changes even further degrades to borderline Level 2-3, see *Figure 8*. This was not expected as the bandwidth of 3 rad/sec is clearly Level 1. Experience with the ADS-33 attitude quickness parameter, peak rate divided by attitude change, has shown its high sensitivity to variations of the input used during the corresponding flight tests. Short and sharp pulse inputs are required. To cross check for any variations in the shape of the input used during the CH-53G quantitative data gathering flights, additional analysis using the Lateral Reposition MTE data was made. The corresponding result is again Level 2, see *Figure 9*, where equal symbols represent the three runs made by one pilot.

During the flight tests a roll rate of 31.5 deg/sec was obtained in hover. The corresponding cockpit controller deflection was 46 % to the right, i.e., nearly a maximum input, see *Figure 10*. As a consequence only the large-amplitude requirement for limited agility (±21 deg/sec) is Level 1, whereas the large-amplitude requirement for moderate agility does not meet Level 1 (±50 deg/sec), but is only Level 2-3.

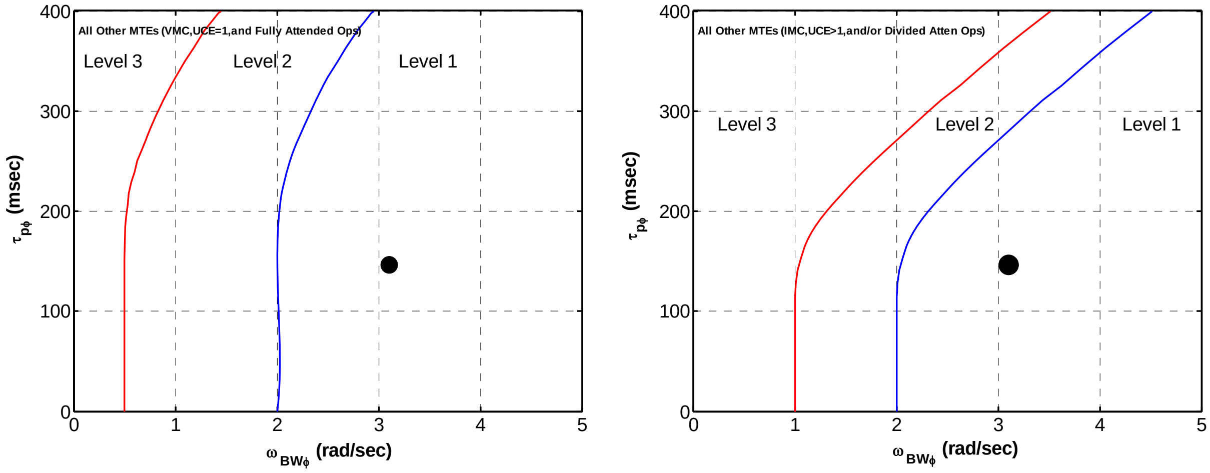
To evaluate the theoretically possible maximum roll rate, the flight test data was analyzed with respect to roll rate over lateral stick deflection. As can be seen in *Figure 11*, a slight non-linearity is present. Using a 3rd-order approximation results in theoretical maximum achievable rates of +35.6 at +50% and -30.1 deg/sec at -50 % stick deflection. A pure linear approximation would result in ±28.5 deg/sec, thus even lower values than the flight tests revealed.

The mid-term response criteria for the roll axis require certain limits on frequency and damping for roll oscillations. Comparable to the pitch axis, these have not been evaluated in detail. But no disturbing oscillations were observed. It is therefore regarded Level 1.



a) Right pulse input *b) Left pulse input*

Figure 6: CH-53G hover roll axis response-type (solid: stick input; dashed: input after AFCS).



a) UCE = 1, Fully Attended Operations
b) UCE > 1, Divided Attention Operations

Figure 7: Hover roll bandwidth results (data from 4 frequency sweeps processed).

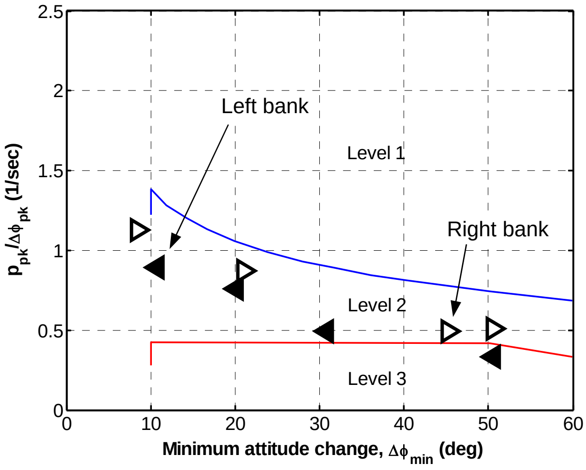


Figure 8: Hover roll attitude quickness from pulse inputs.

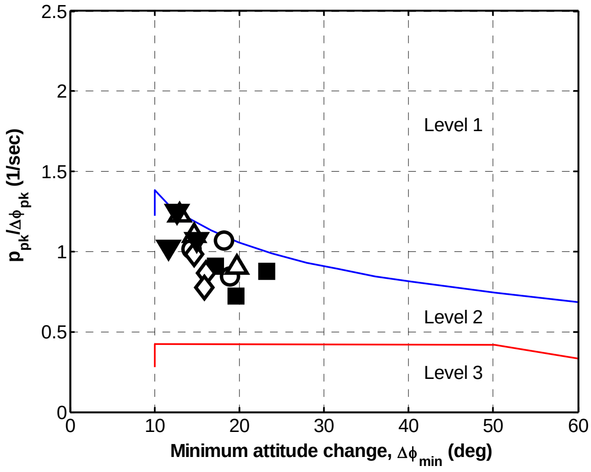


Figure 9: Hover roll attitude quickness from Lateral Reposition MTE data. (5 pilots, 3 runs each)

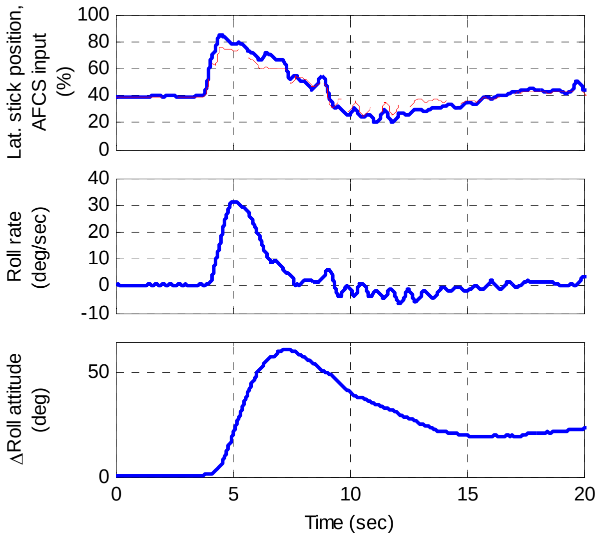


Figure 10: Roll response to large lateral input (hover).

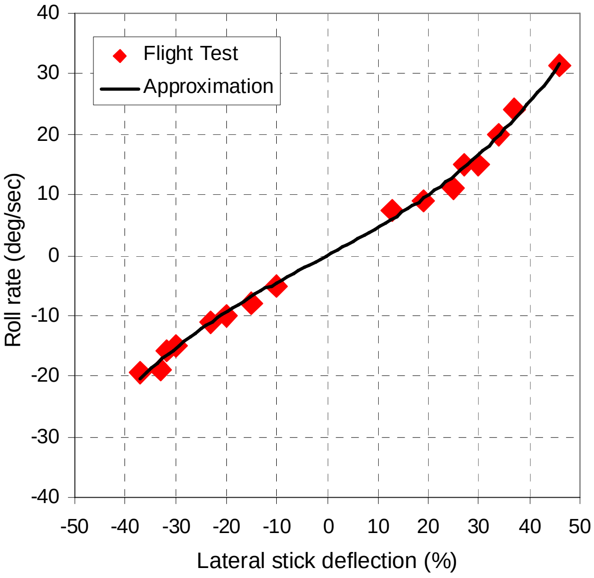


Figure 11: Roll rate over lateral stick deflection (hover).

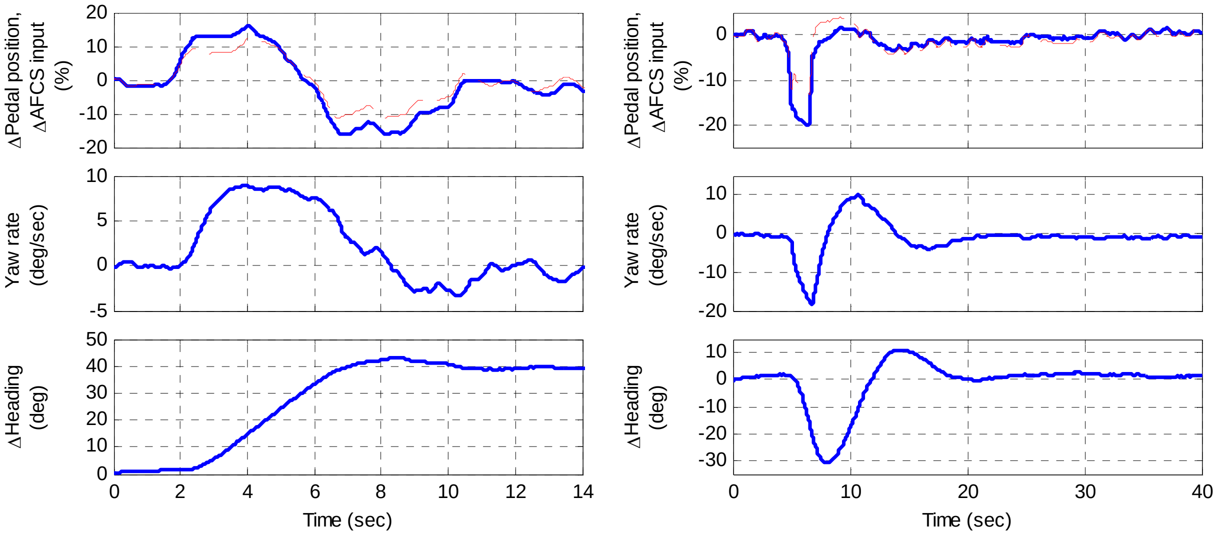
Yaw axis

The aircraft has a rate response-type in yaw, see *Figure 12 a)*. In addition, the AFCS features a heading hold function (ADS-33: Direction Hold, DH), which is engaged as long as the pilot's feet are off pedals. Pressing the pedal switches by putting his feet on the pedals disengages the DH.

The response to a pedal pulse input with DH engaged is given in *Figure 12 b)*. This data was generated by the pilot using the pedals without pressing the switches with his feet.

The yaw axis bandwidth was determined from a first order transfer function model that was fitted to the frequency response of pedal to yaw rate using CIFER® [22]. As a yaw-axis frequency sweep was not performed, flight test data of various pulses and doublets were processed. This yielded better results than using the Hovering Turn MTE data. Outcome of this approach is a Level 2 yaw axis bandwidth, see *Figure 13*.

The heading quickness is borderline Level 2-3, see *Figure 14*. Since the pilots did not use pedal inputs suitable for heading quickness analysis in any of the MTEs, an additional analysis to support the results using MTE data was not possible.



a) Pedal input (DH disengaged)

b) Pedal pulse (DH engaged)

Figure 12: CH-53G hover yaw axis response-type (solid: pedal input; dashed: input after AFCS).

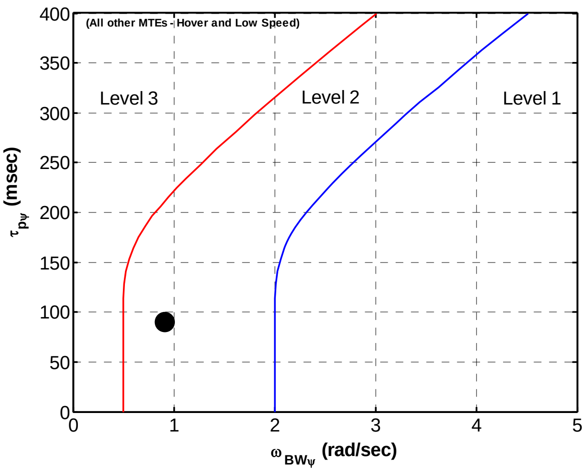


Figure 13: Hover yaw bandwidth results from first order model.

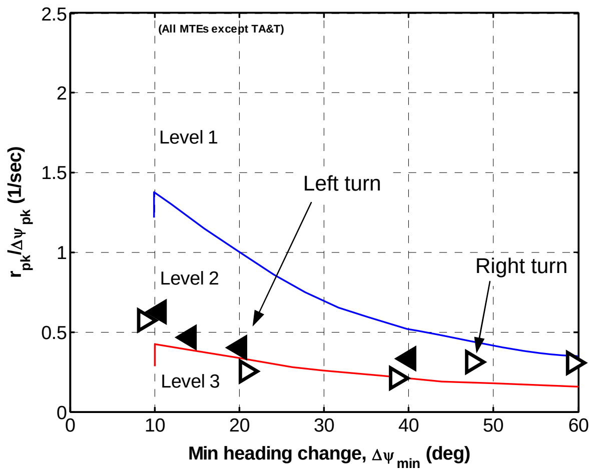


Figure 14: Hover heading quickness from pulse inputs.

The maximum yaw rate achieved during the flight tests was 30.8 deg/sec, which is Level 1 for the large-amplitude moderate agility requirement. This was achieved with a pedal input of 23 %, see *Figure 15*.

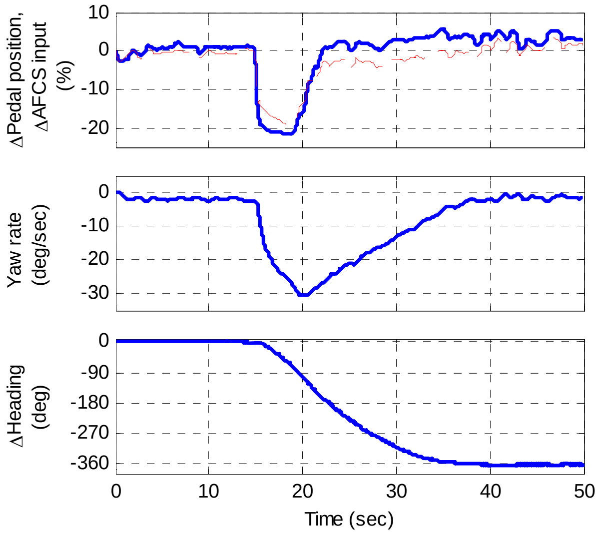


Figure 15: Hover yaw response to left pedal input

Interaxis coupling

The criteria regarding the off-axis coupling reaction of the aircraft in hover are formulated for either aggressive agility or target acquisition and tracking, thus not mandatory for a cargo helicopter. Nevertheless an analysis of the CH-53G data showed that the aircraft is Level 1 or Level 2 for several coupling criteria, see *Figures 16* to *19*. The frequency domain criterion was evaluated from longitudinal and lateral frequency sweeps using CIFER® (*Figure 19*).

Response to collective controller

The height rate response to a collective controller step input is first order. The corresponding height and torque response criteria are both Level 1, see *Figure 20* and *Figure 21*. The vertical axis control power, requiring 160 ft/min 1.5 sec after the collective controller step input, is also Level 1. In general it can be stated that the vertical axis did not show any deficiencies in terms of the ADS-33 height-axis requirements. However, on the Vertical Maneuver, one pilot momentarily got into a vertical-bounce mode. This undamped aircraft-pilot-coupling (APC) cannot be predicted by any existing quantitative criteria.

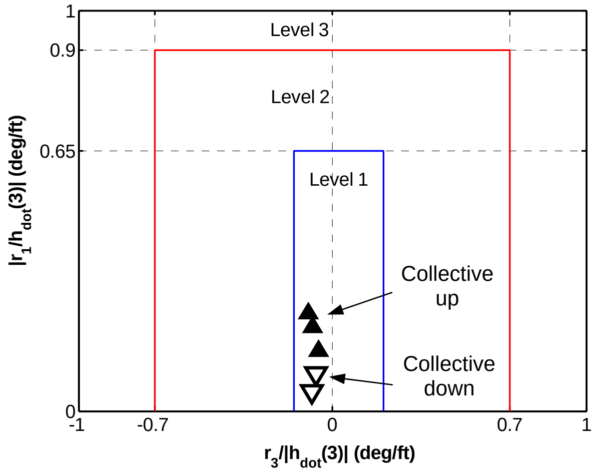


Figure 16: Hover yaw due to collective coupling criteria (Aggressive Agility)

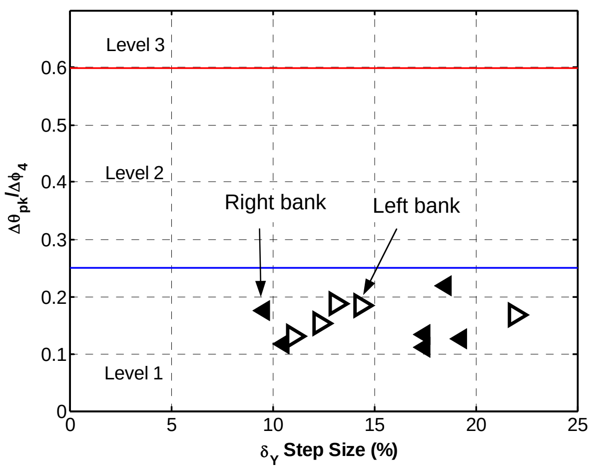


Figure 17: Hover pitch due to roll time domain coupling criteria (Aggressive Agility).

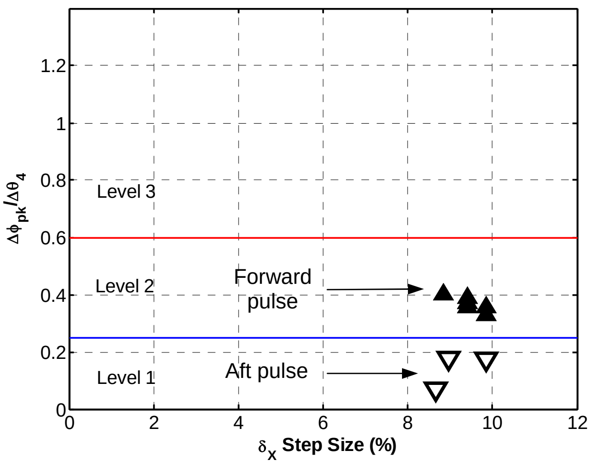


Figure 18: Hover roll due to pitch time domain coupling criteria (Aggressive Agility).

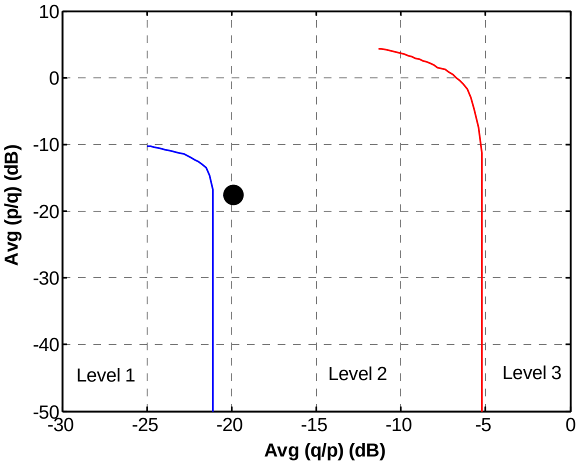


Figure 19: Hover pitch due to roll and roll due to pitch frequency domain coupling criteria (Target Acquisition and Tracking).

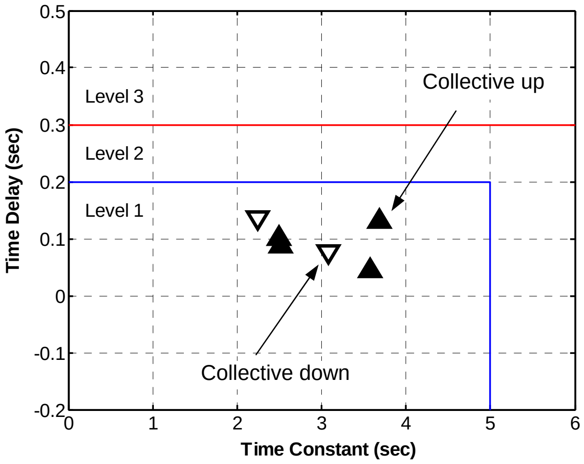


Figure 20: Hover height response criteria.

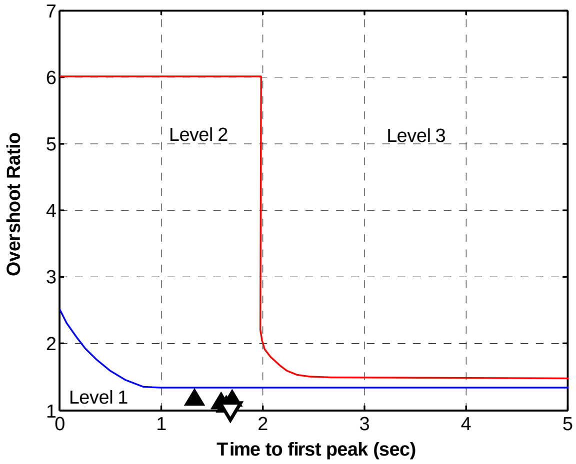


Figure 21: Hover torque response criteria.

5.2 Forward flight requirements

The main focus of this paper is on the comparison of quantitative and qualitative criteria. Limited results regarding the quantitative forward flight requirements shall be presented here, since qualitative forward flight data is only available for the Slalom MTE.

Roll Axis

The roll attitude quickness is Level 2, see *Figure 22*, as it was for the hover criteria. In addition to the analysis of the pulse inputs, the roll attitude quickness used by the pilots during the Slalom MTE was evaluated. All attitude changes above a 2-deg threshold were identified and the peak angular rate and attitude change were determined. The results presented in *Figure 23* are for all runs made by the five pilots. As can be seen, the majority of the data points lie in the Level 2 region. This matches with the quickness analysis from pulse inputs, both in hover and forward flight and indicates that the pilots used the maximum capability of the aircraft when flying the Slalom MTE. It is generally possible for the pilot to improve the attitude quickness results by varying his control strategy using control reversals to stop the rate, thus acting as a Stability Augmentation System (SAS). This increases his workload and is therefore not appropriate. The improved but misleading results can be seen in *Figure 23*, since there are a few Level 1data points.

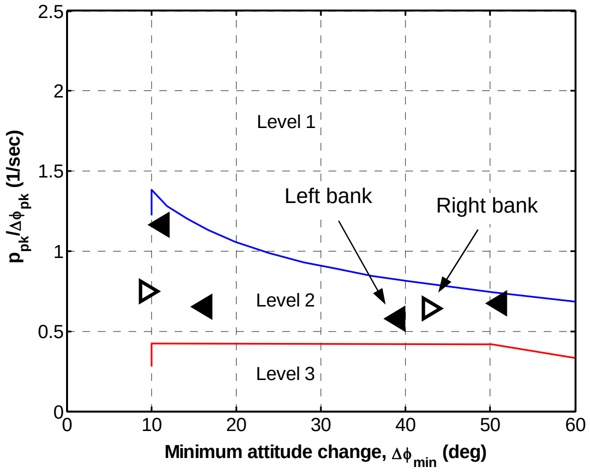


Figure 22: Forward flight roll attitude quickness.

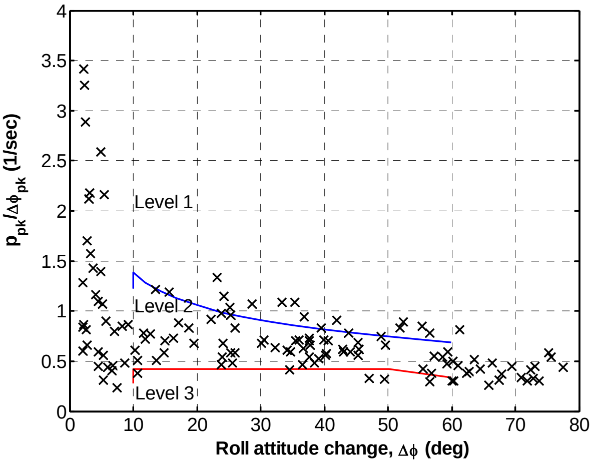


Figure 23: Roll quickness used in Slalom MTE (data of all 15 runs shown)

Roll rates greater than 30 deg/sec in both directions were achieved in flight test, hence fulfilling the large-amplitude moderate agility requirement. The requirements on bank angle oscillation and sideslip excursion are as well Level 1.

Interaxis coupling

In forward flight, off-axis coupling is not an issue with this aircraft. The coupling effects are suppressed satisfactory by the AFCS. As a consequence, the pitch due to collective coupling criteria is Level 1. The other coupling requirements, though only formulated for aggressive agility or target acquisition and tracking, are borderline Level 1-2.

Yaw axis

The evaluation of the different forward flight yaw control criteria, including the requirements regarding lateral-directional stability and sideslip, did not reveal any noticeable deficiencies. Although the ADS-33E does not have a forward flight yaw axis attitude quickness requirement, the results of an analysis of the heading quickness used during the Slalom MTE, equal to the roll axis analysis, shall be presented, representing additional information on the yaw axis. Performing the Slalom MTE, all pilots use Level 2 yaw attitude quickness, see *Figure 24*. This supports the yaw axis heading quickness results presented earlier (*Figure 14*), although now for forward flight. As with the roll axis, it can be stated that the pilots use the available yaw axis capability of the aircraft to get through the Slalom course.

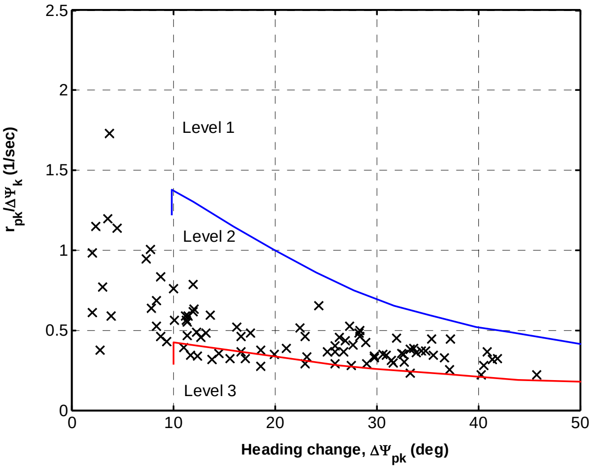


Figure 24: Heading quickness used in Slalom MTE (data of all 15 runs shown)

6 QUALITATIVE CRITERIA

List of MTEs

The following MTEs were performed:

1. Hover
2. Hover Turn *(right and left)*
3. Lateral Reposition *(to right only)*
4. Depart / Abort
5. Vertical Maneuver
6. Slalom *(left turn first only)*
7. Pirouette *(right and left)*
8. Slope Landing *(right, left, and nose upslope)*
9. Landing
10. Hover with External Load
11. Lateral Reposition with External Load *(to right only)*
12. Depart / Abort with External Load
13. Vertical Maneuver with External Load

The MTEs were flown at a take-off weight of 34,000 lb (81 % of maximum) for the internal load configuration. For the external load configuration, an 8,818 lb (4000 kg) concrete block was attached to the single cargo hook of the aircraft, increasing the combined aircraft-external load weight to 38,800 lb (92 % of maximum). The load-mass-ratio (LMR) was 0.23. The MTE performance standards were identical to ADS-33E-PRF, except for the Slalom. The distances between the gates were increased after first pilot feedback indicated that the initial Slalom MTE was too aggressive and could not be performed with desired performance (min. 60 kt) [20]. All evaluation flights were made with a mid c.g. in good visual environment (GVE). Fifteen data gathering flights for 22.5 flight-hours were needed to get the HQRs from all pilots, not counting various training and re-familiarization flights.

Conduct of test

The CH-53G ADS-33E-PRF flight tests started mid 2004 with the preparation of the test aircraft, mainly for reconfiguration of the onboard data gathering system and removing of test equipment of an earlier test program. Designing and building the MTE ground courses took roughly three months. The first four-week phase of MTE flight testing began in November 2004. The objectives of this first phase were to get initial feedback from the pilots regarding the ability to perform the MTEs with the aircraft, check the design and set-up of the ground courses, especially the visibility of the visual cues, and to identify necessary modifications. The HQR flights were performed in July and August 2005. Four pilots from WTD 61 and one U.S. pilot were involved, all of them were experienced test pilots, but with different backgrounds regarding the flight hours on CH-53G. During each flight, the crew consisted of the evaluation pilot and co-pilot, two on-board crew members, and the flight test engineer. For external load operations, additional ground staff was needed. Every evaluation pilot flew a maneuver as often as needed to develop a repeatable control strategy before doing at least three evaluation runs. After performing the evaluation runs, the aircraft was landed on the cargo dropping area and the evaluation pilot filled in the questionnaire and gave his rating while the co-pilot had the controls. For the external load configurations, the co-pilot flew the aircraft while the evaluation pilot completed the questionnaire and HQR. After having completed the questionnaire, the evaluation pilot took the controls again and the next MTE was approached. Averaged over the entire flight time, this procedure resulted in about 20 minutes per pilot per MTE.

Results

One of the overall objectives of this flight test assessment of ADS-33E using the CH-53G was to better generalize the results from the ADS-33C/D assessment using a CH-47D ([18], [19]). Going into the CH-47D test, the ADS-33 requirements were primarily focused on the scout/attack class of rotorcraft. Following the CH-47D test, the results suggested substantial changes to the applicable MTEs, i.e., for the cargo class rotorcraft the aggressive MTEs were dropped, new cargo-class MTEs were developed, and nearly all of the common MTEs were modified to be more appropriate for a cargo rotorcraft.

The CH-53G test was aimed at corroborating these revised MTEs with a single-main rotor cargo class rotorcraft and investigating tandem rotor biases. All of the recommended cargo class MTEs for the good visual environment (GVE) were evaluated with the CH-53G.

Despite detailed changes concerning the performance standards of several MTEs [20], all but one were found to be appropriate. The ADS-33E Slalom MTE was found to be too aggressive. After lengthening the distance between the gates in the Slalom, it was a moderate aggressive task with the CH-53G.

The HQRs from these two flight campaigns are presented in *Figures 25* and *Figure 26*. Shown are the ranges of ratings along with the average. Considering these average values, the overall handling quality ratings are Level 2, with only a few exceptions. In general, there was good agreement between the pilots across the various MTEs as there was a small amount of scatter. However, for a few maneuvers there was a large scatter for the CH-53G, with a maximum of up to 5 HQRs present for the Slope Landing MTE. The primary reasons for this scatter are related to course cueing, different pilot control strategies, and different pilot backgrounds. A detailed description of the CH-53G HQR scatter and reasons for the scatter is presented in reference [20].

The cargo class rotorcraft handling quality requirements evaluation tests were made by the U.S. and German Army. It is recognized that other services, such as the Navy, may have additional missions and performance standards that are not reflected in the current set of MTEs. In addition, for the Slalom MTE, further research is recommended for refinement of the performance standards for future cargo rotorcraft.

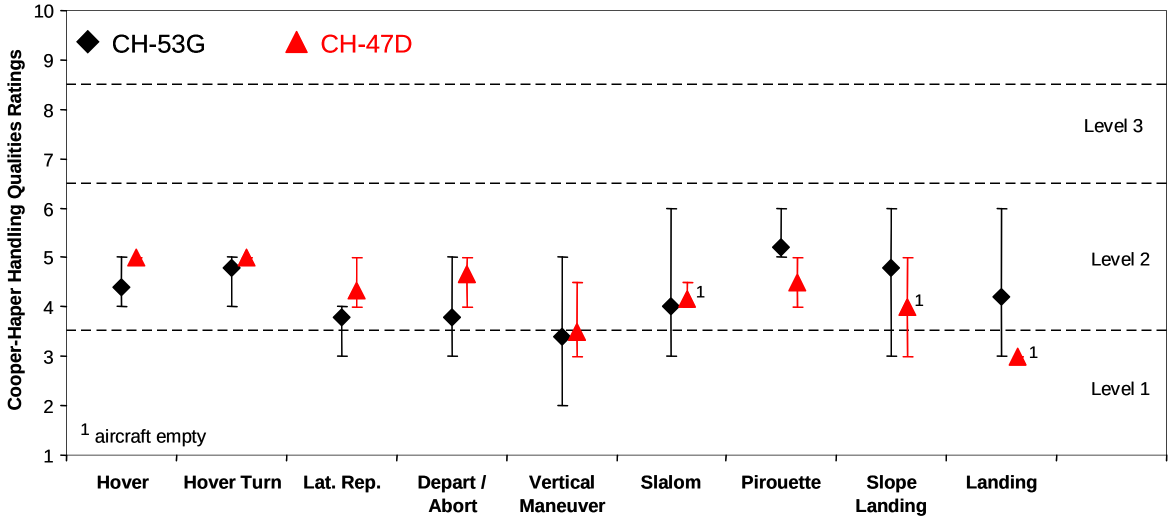


Figure 25: Comparison of Cooper-Harper handling qualities ratings for the CH-47D and CH-53G internal load configurations (max., min., and mean ratings).

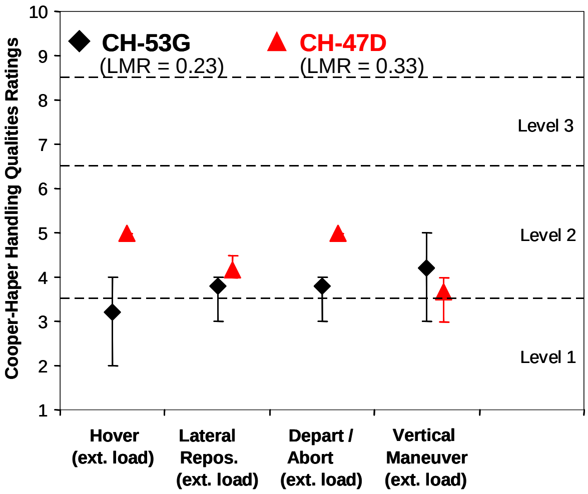


Figure 26: Comparison of Cooper-Harper handling qualities ratings for the CH-47D and CH-53G external load configurations (max., min., and mean ratings).

7 COMPARISON OF QUANTITATIVE AND QUALITATIVE RESULTS

This section will present a comparison or correlation between the results from the quantitative data collected to characterize the dynamics of the aircraft and the qualitative data collected to characterize the ease and precision with which a pilot is able to perform a task. The quantitative requirements in ADS-33E correlate to a Predicted Level of handling qualities. The qualitative requirements in ADS-33E correlate to an Assigned Level of handling qualities. The overall rotorcraft handling qualities Level shall be a combination of both the Predicted and Assigned Levels. In theory, the Predicted and Assigned Levels should align or agree with each other. That is, violation of any one quantitative requirement is expected to degrade the vehicle's handling qualities and, depending upon the task being performed, degrade the qualitative assessment while performing specific maneuvers. Violation of several quantitative requirements (e.g., to Level 2) is expected to have a synergistic effect so that the overall handling qualities may degrade to Level 3, or worse. However, it should be pointed out that the quantitative requirements are necessary but not sufficient. For example, not meeting a Level 1 bandwidth requirement would be expected to degrade the pilot's assessment of an MTE. On the other hand, there may be adverse vehicle dynamics that are not covered by any of the ADS-33E quantitative criteria, but do influence the pilot's ability to perform an MTE. It should be noted that the quantitative data was only collected in the internal load configuration and therefore, direct correlation between this quantitative and qualitative data for the external slung load configurations will not be possible.

All pilots returned comments on the longitudinal positioning as being an issue in several MTEs, because of the weak visual cues provided. This was the main reason for degrading the ratings for several MTEs to Level 2. Besides the weak cues having an influence on the pilots' workload when attempting to keep height and longitudinal position within the constraints, the aircraft features a collective to longitudinal drift coupling effect. It was present especially in the MTEs that focus on the heave axis, such as Vertical Maneuver and Landing MTE. This effect makes compensation in the longitudinal axis necessary to keep horizontal position when introducing collective inputs. It is not covered by any quantitative criteria, which predict Level 1 for the longitudinal axis. Pilot's comments on the Depart/Abort MTE, a task focusing mainly on the longitudinal axis, list the large longitudinal cyclic and collective control inputs necessary to perform the maneuver, and keeping lateral track during initiation and end of the maneuver as main contributions to the workload. The latter effect can be related to the Level 2 result of the frequency domain roll due to pitch coupling criteria.

The roll axis attitude quickness criterion predicts Level 2 HQ (*Figure 8*, *Figure 9*) and the large-amplitude requirements do not meet Level 1 for moderate agility. Referring to the Lateral Reposition MTE as one focusing especially on the roll axis, four of the five pilots return an HQR 4, overall resulting in good Level 2 HQ for this MTE. The pilots mentioned the large lateral control input necessary to achieve the required sideward speed, a hint to the limited large-amplitude criteria results.

According to the ADS-33 quantitative criteria, with a Level 2 result for yaw bandwidth (*Figure 13*) and Level 2-3 for the heading quickness (*Figure 14*, *Figure 24*), the yaw axis has deficiencies. The HQRs and pilots' comments returned for the Hovering Turn MTE, a mainly yaw axis task, match well with these results. The mean HQR is 4.8, so mid Level 2, and all pilots refer to the yaw control as being sluggish and that a considerable amount of lead is required to arrest the turns. Improvements are highly desirable. But there is also a roll due to yaw coupling effect that is not covered by the quantitative criteria. In right hovering turns bank angles of 7-9 deg developed, making precise positioning during the turn difficult.

The heave axis criteria, height and torque response (*Figure 20*, *Figure 21*) and control power, all predict Level 1 HQ for the response to collective controller inputs. Even the corresponding coupling, yaw due to collective (*Figure 16*), is predicted to be Level 1. The pilots detected no heave-axis deficiencies during the flight tests, except for the collective-to-longitudinal drift coupling mentioned above. The mean HQR for the Vertical Maneuver MTE is 3.4, thus borderline Level 1-2. For this MTE, again the weak longitudinal cues and not a deficiency in the heave axis were identified as the main factor for degrading the ratings from good Level 1.

The mean HQR for the Pirouette MTE is 5.2, i.e., mid Level 2. It is a high gain task requiring continuous control activity in all axes to maintain track, height, and heading. The time and track constraints made the task a very aggressive one, felt by the pilots as not being suitable for a helicopter the size of the CH-53G. In general it can be said that no single effect was identified by the pilots as a driving factor for the ratings. This MTE did not reveal any new findings regarding the HQ of the aircraft not already known from previous MTEs and the quantitative criteria results.

From pilots' comments it is known, that the original ADS-33E Slalom MTE was not flyable with the CH-53G, meaning desired performance (min. 60 kt) was not achievable. The distances between the gates were therefore increased. But still pilots commented on the excessive lateral control displacements up to the control limits and the significant pedal inputs necessary that would hardly allow for more aggressiveness. The mean HQR 4 represents Level 2 HQ. These results match well with the results for roll attitude and heading quickness and the roll axis large-amplitude requirement, all predicting Level 2 HQ. However, from these results it is not clear how the Level 2 quantitative results impacted the need to lengthen the distance between the gates. In addition, it is not clear if this Slalom MTE lengthening and/or by how much would be needed for a future cargo helicopter with a substantially larger size than the CH-53G or CH-47D.

8 CONCLUSIONS

In 2004/5 flight tests with a Sikorsky CH-53G helicopter of the German Army were performed to verify the ADS-33E requirements for cargo helicopters, which are solely based on flight tests with a Boeing CH-47D, a tandem rotor design. Quantitative data for hover and 100 kt forward flight as well as qualitative data for 13 MTEs were gathered. The MTE results, as well as lesson's learned on course design and conduct of the tests were presented in detail in a previous paper.

The ADS-33E quantitative criteria predictions and the pilot's comments returned for the various MTEs in general show good agreement. Two effects that are not covered by any quantitative criteria, but which were mentioned by the pilots as having an influence on their ratings, were identified: a collective-to-longitudinal coupling, and a yaw-to-roll coupling during hovering turns. It may be the subject of further research whether quantitative requirements for both effects should be included in ADS-33.

The quantitative criteria predict deficiencies in roll (attitude quickness, large-amplitude) and yaw (bandwidth, heading quickness). The roll axes deficiencies clearly degrade the performance during the forward flight Slalom MTE, but do not degrade the Lateral Reposition MTE, a low-speed maneuver especially focusing on the lateral axis. This indicates that

- either the Lateral Reposition MTE is not demanding enough to expose the predicted roll axis deficiencies, or
- the quantitative criteria for roll attitude quickness and large-amplitude in conjunction with the ADS-33E Slalom MTE design are too demanding for a cargo helicopter.

The predicted yaw axis deficiencies in contrast are clearly identified by the pilots in the Hovering Turn MTE, a hover maneuver focusing especially on the yaw axis.

The results for the CH53G and CH-47D suggest there are no tandem rotor biases built into the ADS-33 cargo-class MTEs. The roll axis results, specifically the lengthening of the Slalom MTE, make additional research necessary to refine the roll axis requirements for future cargo rotorcraft.

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