UH-60 EXTERNAL LOAD HANDLING QUALITIES EVALUATION

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Abstract

The dynamic motions of external loads are known to have a negative impact on the handling qualities of helicopter/external load systems during hover/low-speed operations. Although criteria have been proposed, currently there are no external load quantitative requirements in the U.S. Army Aeronautical Design Standard for rotorcraft handling qualities, ADS-33. To collect data to support the development of quantitative criteria to address this need, the U.S. Army Aeroflightdynamics directorate has conducted a series of external load flight tests with an EH-60L helicopter at Moffett Field. Four experimental test pilots performed evaluations of three Mission Task Elements from ADS-33E-PRF. These were flown without an external load, and with eight external load configurations (two load weights and four sling lengths). Frequency sweeps of each configuration were also conducted to provide quantitative data. Pilot comments and assigned handling qualities ratings (HQRs) from testing indicate that the effects of external loads on handling qualities are most pronounced with the combination of long sling lengths and large external load weights. Based on the qualitative results, the attitude frequency responses obtained from the frequency sweeps were analyzed and parameters identified that correlate well with the assigned HQRs. Using these parameters, a quantitative criteria has been developed that can be used to predict the hover and low-speed handling qualities of helicopters with external load

1. INTRODUCTION

The U.S. Army's handling qualities specification for military rotorcraft, ADS-33, was originally developed in the 1980s as a specification for the RAH-66 Comanche helicopter program and did not address operations with external loads [1]. Since that time, ADS-33 has been updated several times and in 1996 ADS-33D-PRF was released, remaining primarily focused on the Scout/Attack class of helicopters [2]. Although flight tests had been conducted by the U.S. Army's Airworthiness Qualification Test Directorate (AQTD) in 1994-95 with a CH-47D Chinook helicopter with and without external loads [3], this testing was in progress when ADS-33D-PRF was being released and therefore no requirements for Cargo/Utility class of helicopters were added to the design standard at that time. During the testing at AQTD, handling qualities evaluations were conducted in both Good Visual Environment (GVE) and Degraded Visual Environment (DVE) with night vision goggles both with and without external loads. The results of this test program suggested more than a dozen flight test maneuvers for cargo helicopters for incorporation into the next update of ADS-33.

To provide data to develop performance standards for utility helicopters, a flight test program was undertaken at the U.S. Army Aeroflightdynamics Directorate (AFDD) at Moffett Field, CA in the late 1990s using a UH-60 [4], the U.S. Army's primary utility helicopter. Flight tests were conducted to assess the existing standards in ADS-33D using a UH-60, considering the lessons learned and experience from the AQTD testing of the CH-47D cargo helicopter. The existing flight test maneuvers were tailored for the utility class of helicopter and additional tasks were developed to evaluate the handling qualities of utility helicopters with and without external loads in a good visual environment. The results of these test programs were the development of a set of Mission Task Elements (MTEs) for the Cargo and Utility classes of helicopters with and without external loads.

Also during the 1990s, a series of handling qualities simulation experiments were conducted in the NASA-Ames Vertical Motion Simulator (VMS). These experiments were intended to compliment the flight test programs for expanding the handling qualities specifications for cargo helicopters with external loads in the update of ADS-33D to ADS-33E [5]. Of special interest are two simulation experiments that focused primarily on the effects of external loads on handling qualities [6]. While the simulations were conducted in a simulated day scene, the measured Useable Cue Environment (UCE) was equal to 2, which corresponds to a degraded visual environment. The aircraft used for this study was based on the CH-47D. In order to meet the ADS-33D/E requirements to obtain Level 1 handling qualities in UCE > 1, a generic Attitude Command, Attitude Hold response type with height hold was implemented. A matrix of parameters was varied including load weight, sling length and hook to c.g. distance. Several important findings were reported from these simulation experiments, including the following:

- The effect of the external load on handling qualities was found to be significant when the load-mass

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Presented at the 35th European Rotorcraft Forum, Hamburg Germany, Sep 22-25, 2009.

ratio (LMR, the ratio of the mass of the load to the mass of the helicopter plus load) was greater than or equal to 0.33.

- When the LMR ≤ 0.25, the effects of the external load on handling qualities were not found to be significant.
- The pilot ratings and commentary were not highly sensitive to sling length.
- Attempts to correlate attitude bandwidth with pilot-rating data were unsuccessful; however, good correlation was identified between characteristics of translational velocity and pilot ratings and commentary. Based on these results, a quantitative handling qualities criteria was proposed for cargo helicopters carrying external loads in DVE (ACAH plus HH) when LMR ≥ 0.33.
- Due to the degraded visual environment in the VMS, development of quantitative criteria for external loads with rate response types was not possible.

The report also noted that the proposed criteria were based solely on piloted simulations in a degraded visual environment, and that flight-test verification was recommended before any proposed criteria be considered for inclusion in future updates to ADS-33.

The knowledge gained from these test programs resulted in many of the updates in ADS-33E-PRF, including a set of MTEs tailored for evaluations of Cargo and Utility aircraft with external loads. However, no requirements for operations with external loads based on quantitative criteria were adopted. In order to assess the proposed criteria of [6], or develop a criteria to predict hover low-speed handling qualities of utility rotorcraft with external loads, the U.S. Army AFDD has conducted a series of flight tests using an EH-60L helicopter and a limited matrix of external load weights and sling configurations. This paper describes the flight testing that was conducted and an analysis of the data collected to address this need.

2. TEST OBJECTIVES

The objectives of this test were to: 1) collect flight test data with external loads to develop a database of quantitative data (frequency sweeps) and qualitative data (handling qualities ratings and pilot comments) for a matrix of external load weights and sling lengths, 2) use the database to either validate the proposed external load criteria from [6], or develop new criteria to predict handling qualities with external loads. The remainder of this paper describes the testing that was performed and the analysis of the data obtained from the testing to achieve these objectives.

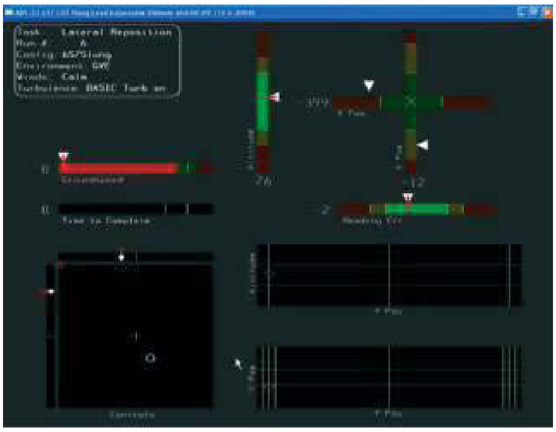
3. TEST AIRCRAFT

The flight tests were carried out by the Aeroflightdynamics Directorate (AFDD) at Ames Research Center, Moffett Field, California. The test aircraft was AFDD's EH-60L Blackhawk helicopter shown in Fig. 1. Two instrumentation racks and an Aircraft Data System (ADS) have been installed in the cabin. Research sensors have been installed on the boom and throughout the control system, and antennas for the research Differential GPS unit and telemetry have been mounted externally on the aircraft. Data are acquired and stored through the PC-based ADS installed in the aircraft, operating with Windows 2000 and LabView™ data acquisition software. The ADS records 130 aircraft data parameters, which are divided into groups corresponding to the analog signals, 1553-formatted data messages from the ship's INU/GPS and the research DGPS. A GPS time stamp is added to each group of data as it is sampled. All the data from each group are then stored on an internal hard drive at 100 Hz regardless of the actual data rates (continual for analog, 50 and 200 Hz for the INU, and 10 Hz for the DGPS).

For this test program, a subset of the aircraft data was telemetered to the ground station at 50 Hz via radio modems. Data were displayed in the ground station, both on video displays and paper stripcharts (Fig. 2), and on ADS-33 performance displays (Fig. 3). This allowed engineers in the ground station to monitor critical aircraft parameters and provide real time feedback to the aircrew about their performance during flight testing.

Figure 1. EH-60L helicopter.

Figure 2. Telemetry stripchart.



Task: Lateral Reposition
Run #: 6
Config: 657Sling
Environment: GVE
Winds: Calm
Turbulence: BASIC Turb on

Figure 3. ADS-33 Lateral Reposition performance display.

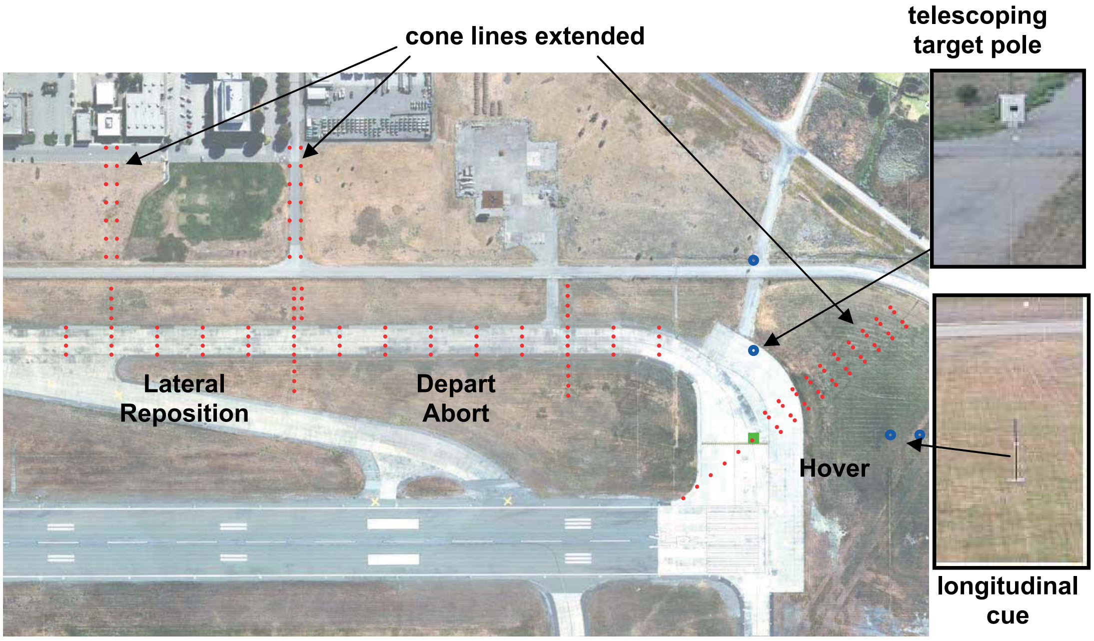


Figure 4. ADS-33 course at Moffett Field modified for external load testing.

4. ADS-33 COURSE MODIFICATIONS FOR EXTERNAL LOAD TESTING

To perform testing with external loads and long slings, the height above ground level (AGL) at which the MTEs are evaluated must be high enough to provide sufficient clearance between the external load and the ground. To provide cueing at the greater aircraft height, the ADS-33 course at Moffett Field was modified as follows. For the lateral reposition and precision hover MTEs, the cone lines were extended to allow the pilot to see the cones at the higher altitudes as shown in Fig. 4. To provide lateral and vertical cueing for the hover maneuver, a truck-mounted pneumatically-operated telescoping pole was used to hold the target. This pole could be adjusted by the ground crew to accommodate changes in hover height from 20 ft AGL (for unloaded testing) to 110 ft AGL (for loaded testing) during the flights. To provide longitudinal cueing, a sight pole and hover board were positioned as shown in Fig. 4 to provide desired and adequate longitudinal cues to the pilot.

5. EFFECTS OF HEIGHT ABOVE THE GROUND ON HANDLING QUALITIES

As the height above the ground increases, the usable cues available to the pilot degrade, which can impact the handling qualities ratings obtained for a given MTE. To quantify the effect of increasing height above the ground on handling qualities, the Hover, Lateral Reposition and Depart/Abort MTEs were evaluated at three altitudes. For the Hover maneuver, evaluations were conducted at altitudes of 20 ft, 75 ft and 100 ft AGL, and for the Lateral Reposition and Depart/Abort at 35 ft, 75 ft and 110 ft AGL.

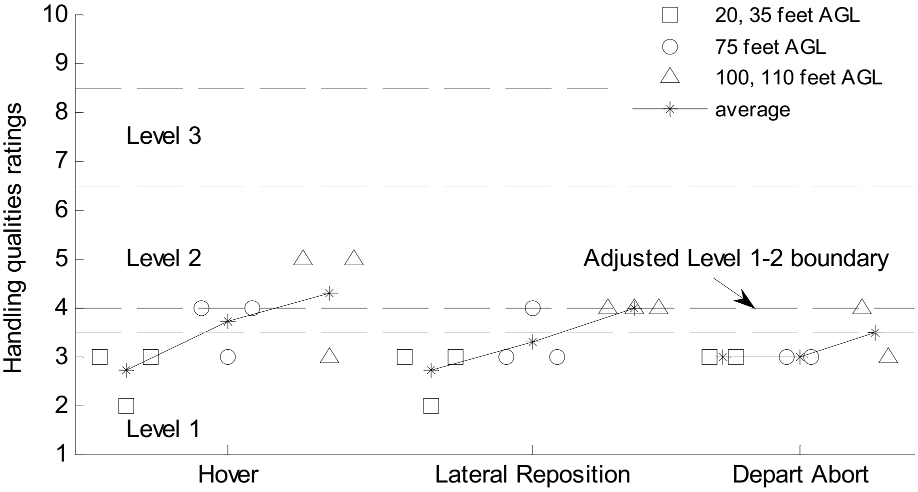


Figure 5. Effects of increasing altitude above the ground on handling qualities ratings, no external load.

Three pilots conducted evaluations at these altitudes, without an external load but to external load standards, and provided handling qualities ratings which are presented in Fig. 5. These ratings show that for all three maneuvers, increasing the altitude above the ground and the associated reduction in the quality of the cueing resulted in a degradation in handling qualities. The change in altitude had the largest effect on the Hover maneuver where increasing the altitude from 20 ft to 100 ft resulted in a degradation of 1.6 HQRs, and the least effect on the Depart/Abort maneuver where increasing the altitude from 35 ft to 110 ft resulted in a degradation 0.5 HQRs. These results indicate that independent of the effects of the external load, handling qualities of a given aircraft will degrade with increasing altitude above the ground due to the associated reduction in the quality of the cues available to the pilot. Based on these results, the Level 1-2 boundary for the external load testing at or above 75 feet AGL presented in this paper has been adjusted to a HQR of 4.0 as shown in Fig. 5.

6. TEST MATRIX

Of the Mission Task Elements designated for testing with external loads in ADS-33, the Lateral Reposition, Depart/Abort and Hover maneuvers were selected for evaluation. This provided one predominantly lateral maneuver, one predominantly longitudinal maneuver, and one both lateral and longitudinal maneuver. Testing with external loads was conducted at two weights to provide data at two load-mass ratios (LMRs). The lighter weight was 5100 lb which resulted in a LMR of about 0.25, and the heavier weight of 7150 which resulted in a LMR of about 0.33. These LMRs were selected based on the results of [6] which found that the effects of external loads on handling qualities were significant for LMR greater than or equal to 0.33 and were not significant for LMRs less than 0.25. It was not practical to conduct testing with LMRs greater than 0.33 because when carrying a 7150 lb external load, the UH-60 was limited to about 40 minutes of usable fuel. Four sling lengths were selected that resulted in hook to load c.g. distances of approximately 13, 31, 51, and 78 feet.

Four experimental test pilots conducted evaluations of the eight configurations providing handling qualities ratings and pilot comments for each configuration evaluated. All of the evaluations were conducted at 75 ft above ground level (AGL) except the 78 ft sling cases, which were conducted at 100 ft AGL for the Hover maneuver, and at 110 ft for the Lateral Reposition and Depart/Abort maneuvers. The pilots were allowed to practice each maneuver until they were comfortable with their control strategy, and then conduct a minimum of three additional evaluations for the record. After completing the evaluations for the maneuver, the pilots answered a short questionnaire and then proceeded through the Cooper-Harper rating scale providing a verbal record of each step in the decision process ending with the assignment of the HQR. Not all configurations were evaluated by every pilot and due to time constraints the Depart/Abort maneuver was not evaluated with the 31 ft sling configuration.

To provide quantitative data to correlate with the handling qualities ratings, one experimental test pilot conducted lateral and longitudinal frequency sweeps of all eight configurations (two load weights and four sling lengths). The frequency sweeps were conducted in winds of less than 5 kt as reported by the control tower to minimize contamination from atmospheric turbulence. A minimum of two frequency sweeps were performed in each axis. The frequency sweep data were processed in CIFER® to generate lateral and longitudinal attitude and translational rate responses to pilot controls. When using frequency domain analysis software to analyze frequency sweep data where the characteristics of the lightly damped load mode are of interest, great care must be taken to ensure that the windows are sized correctly, or the effects of the load mode on the response can appear overly damped. Guidance for setting minimum window sizes for identifying modes can be found in [7]. The CIFER® frequency responses generated utilizing properly sized windows were used to extract the quantitative parameters presented in the remainder of the paper.

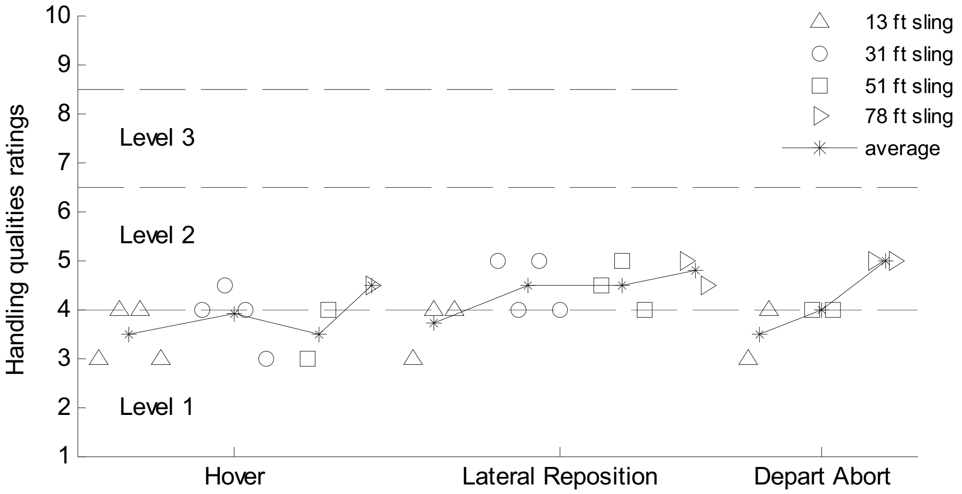


Figure 6. HQRs from MTE evaluations with a 5100 lb external load for increasing sling length.

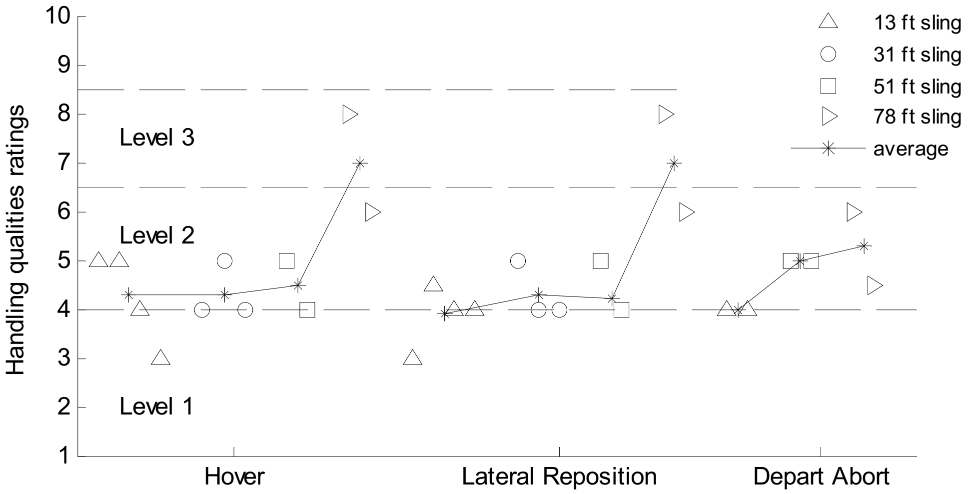


Figure 7. HQRs from MTE evaluations with a 7150 lb external load for increasing sling length.

7. RESULTS

7.1. Qualitative Results

The handling qualities ratings from all of the pilots for the 5100 lb external load cases are shown in Fig. 6 with the Level 1-2 boundary adjusted to HQR=4 for ratings with external loads at or above 75 feet AGL. Each symbol represents a rating from one pilot for the corresponding sling length. The average of all the pilots' ratings for each sling length is shown as an asterisk connected between configurations by a solid line. The ratings show that in general, there is an increase of about one HQR as the sling length increased from 13 ft to 78 ft, for all three maneuvers with a 5100 lb external load (LMR ~ 0.25). For the primarily lateral maneuver (lateral reposition), the ratings cross into the Level 2 region when the sling length is 30 ft or longer. For the primarily longitudinal maneuver (Depart/Abort), the ratings exceed HQR=4 only for the longest sling length (78 ft).

The handling qualities ratings for the 7150 lb external load cases are shown in Fig. 7. For the heavier load weight (LMR ~ 0.33), all of the sling lengths result in an average HQR of 3.9 or greater for all three maneuvers. For the longest sling length (78 ft) at this load weight, the Lateral Reposition average HQR is 7 placing this configuration in the Level 3 region, while the same configuration received an average HQR of 5 for the Depart/Abort. These results indicate that the pilots found that the external load effects on the aircraft lateral axis were stronger than on the longitudinal axis for long sling lengths with heavy external loads.

7.1.1. Pilot Comments

When evaluating each configuration, each pilot answered a short questionnaire and provided commentary on the effect of the configuration on the handling qualities of the externally loaded aircraft. The following is a summary of the pilot comments for four of the configurations.

5100 lb external load, 13 ft sling

For all of the maneuvers, the pilots commented that it was not difficult to meet the desired performance standards. One pilot commented that other than the additional torque required to hover with the external load, the aircraft did not feel any different with the external load

5100 lb external load, 78 ft sling

The pilots were not able to meet the desired performance standards consistently for any of the maneuvers. For the Hover maneuver, it became more difficult to maintain ground speed and more lateral cyclic corrections were required to keep the aircraft within the desired position tolerances. Longitudinal predictability was degraded for the Depart/Abort maneuver, and larger control inputs were required to perform the maneuver. One pilot commented that during the Lateral Reposition maneuver, there was the uncomfortable feeling of the aircraft not providing the expected response for the amount of cyclic input.

7150 lb external load, 13 ft sling

For all maneuvers tested, the pilots commented that it was not difficult to meet desired performance with this configuration. Comments indicated that the main factor that influenced their ratings was the increase in collective workload due to the additional torque required at this weight and constant monitoring of altitude.

7150 lb external load, 78 ft sling

For this configuration, all pilot's agreed that it was not possible to consistently meet desired performance. The collective workload increased even more than with the shorter sling due to the proximity of the load to the ground, and larger torque excursions resulting from the lower pendulum frequency. During the Lateral Reposition maneuver the pilots commented about uncomfortable translation of the aircraft that did not correspond to their control inputs. When attempting to maintain ground speed, larger cyclic inputs were required and the inputs had to be held for a longer period of time. For the Depart/Abort maneuver, it was noted that the initial aircraft response was predictable, but due to the motion of the load the subsequent response was not predictable.

Based on a compilation of all the pilot comments, the effects of external loads on aircraft handling qualities can be summarized as follows. Increasing weight results in an increased pilot workload since as the weight increases the torque required for the maneuvers approaches the transmission limits of the aircraft. Operation near the aircraft torque limits requires the pilot to more carefully monitor torque and to be less aggressive with the collective. Increasing weight also has an increased effect on aircraft motion, but only at the longer sling lengths. Increasing sling length appeared to increase the effect of the load on the motion of the aircraft. This increase in the load induced motion of the aircraft also increased the level of pilot discomfort and added to the pilot workload. In contrast to the findings of [6], these results indicate that the effects of external loads on handling qualities can be significant at LMR = 0.25, especially for longer sling length.

7.2. Quantitative Results

7.2.1. Evaluation of translational rate criteria

Strictly speaking, the quantitative criteria developed in [6] are applicable to LMRs $\geq$ 0.33, and were developed based on data gathered from a simulation experiment using a math-model based on a CH-47 augmented to Attitude Command Attitude Hold with Height Hold flown in a degraded visual environment where the Level 1-2 boundary has been set to a HQR=4. In this study, the criterion will be evaluated against flight test data from a Rate Command aircraft without Height Hold flown in a good visual environment. To evaluate the criteria proposed in [6], the translational rate frequency responses to cyclic were calculated from the piloted frequency sweeps using CIFER®. From these responses, four bandwidth parameters are calculated for each axis, two phase margin bandwidths, one for the basic aircraft and one due to the load, and two gain margin bandwidths, one for the basic aircraft and one due to the load. In addition, a load coupling parameter is calculated based on the frequency range where the phase is greater than –135 degrees due to the load. The graphical calculation of these parameters for one configuration in the longitudinal axis is shown in Fig. 8. Complete details of how the parameters are defined can be found in [6]. Once all of the parameters are obtained from the translational rate responses, the handling qualities are predicted based on the lowest of the four bandwidth parameters plotted against the load coupling parameter.

Figure 9 shows the bandwidth and load coupling parameters plotted against the boundaries from [6] for the 7150 lb configurations for the lateral axis. The handling qualities ratings for the Hover and Lateral Reposition MTEs obtained from flight are also noted on the figure. This data shows that in general as the sling length increases, the bandwidth parameter decreases which correlates with a degradation in handling qualities ratings. The load coupling parameter however does not appear to provide a consistent trend with respect to the ratings. Figure 10 shows the data from the 5100 lb cases plotted against the criteria for the lateral axis. While the criteria does not strictly apply to the 5100 lb configurations (LMR < 0.33), the criteria predicts that all of the smaller load mass ratio configurations would result in degraded handling qualities, which is inconsistent with the ratings obtained from flight tests. The results for the longitudinal axis show similar trends, but are omitted here for the sake of brevity. These results show that the criteria as presented in [6] do not completely correlate with the results from flight testing. However, these results do show that the bandwidth parameters obtained from the translational rate responses can be correlated with the trend of degrading handling qualities with increasing sling length for a given LMR.

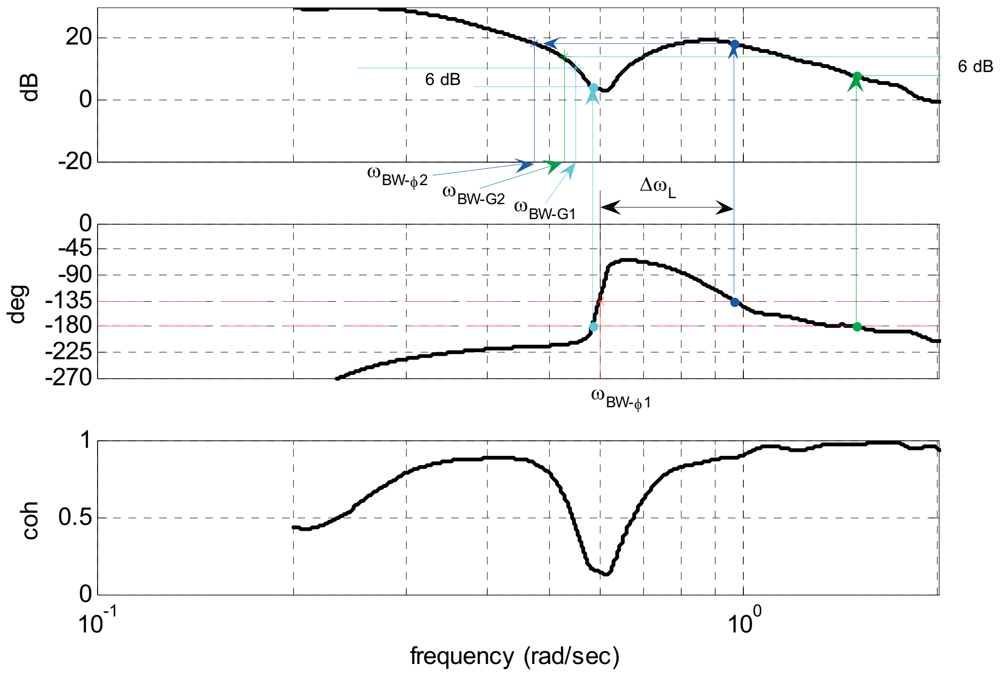


Figure 8. Calculation of external load handling qualities translational rate criteria parameters from [6] for the 7150 lb, 78 foot sling configuration in the longitudinal axis.

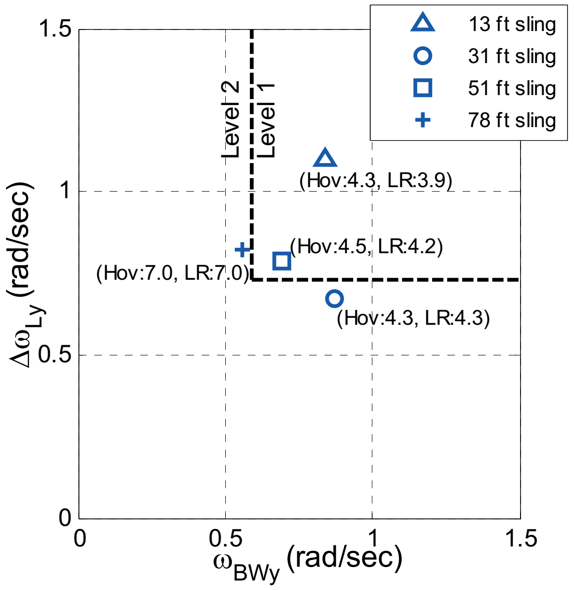


Figure 9. Plot of rate command data from GVE evaluations against criteria from [6], for the 7150 lb configurations in the lateral axis with HQRs from the Hover and Lateral Reposition maneuvers.

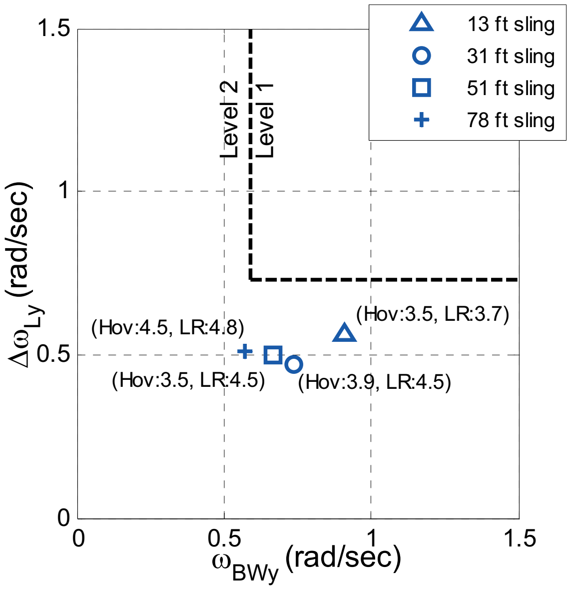


Figure 10. Plot of rate command data from GVE evaluations against criteria from [6], for the 5100 lb configurations in the lateral axis with HQRs from the Hover and Lateral Reposition maneuvers.

Although this correlation is encouraging, it is important to note that the translational rate responses can be difficult to obtain reliably from frequency sweeps. Therefore it would be attractive to study the attitude frequency responses in order to determine if a similar correlation exists between parameters obtained from the attitude responses and the handling qualities ratings obtained from flight.

7.2.2. Bandwidth-phase delay criteria

Given that the proposed translational rate criteria from [6] did not completely correlate with the current flight test results, the flight test data set was evaluated against the current attitude bandwidth/phase delay criteria from ADS-33E for helicopters without external loads. Figure 11 shows the bandwidth and phase delay parameters obtained from longitudinal frequency sweeps with 5100 and 7150 lb external loads plotted on the ADS-33 hover low-speed small amplitude pitch attitude change boundaries for fully attended operations, UCE = 1. The bandwidth and phase delay parameters were obtained from the pitch attitude frequency responses shown in Fig. 12 (5100 lb external load) and Fig. 13 (7150 lb external load). The attitude frequency responses were obtained from the corresponding rate responses which were integrated in the frequency domain. For both load weights, the phase delay shows very little change due to the external load. This is because the phase delay is calculated from features of the frequency responses at frequencies well above the load mode and therefore is primarily a function of the aircraft rotor dynamics, sensor delays and filters, and any additional delays introduced in the control laws. The bandwidth parameter however can be affected by the external load dynamics. For a rate command aircraft such as the UH-60L, ADS-33 defines the bandwidth as the lesser of the gain bandwidth and the phase bandwidth [5]. For all the configurations, the phase bandwidth defined the pitch bandwidth. Note that the unloaded case is Level 1 (Depart/Abort HQR=3.0 at 75 ft AGL, 3.5 at 110 ft AGL), and the point on the bandwidth phase delay plot and is very close to the 5100 lb 78 ft sling data point, even though for the Depart/Abort MTE the average handling qualities rating assigned by the pilots for the external load case is degraded by one and one half ratings. The reason for this can be seen in Fig. 12, which shows that the phase for the 78 ft case comes very close, but does not cross –135 degrees due to the load so the phase bandwidth does not reflect the impact of the load dynamics. As a result, the bandwidth is effectively the bandwidth of the unloaded aircraft. The red arrow on the plot points to the location of the bandwidth parameter had the phase crossed -135 degrees due to the load, which is Level 2. Clearly the current bandwidth criteria in ADS-33E is sensitive to the effects of an external load, provided the phase due to the load crosses –135 deg, or the effect of the load mode on the magnitude curve is captured by the gain bandwidth (for a rate command system). If neither of these conditions is met, the effects of the external load mode are not captured and the existing criteria parameters cannot be used to reliably predict the effect of the external load mode on handling qualities. These results indicate that relying solely on a discrete phase crossing can lead to inconsistent results when trying to capture the impact of load mode dynamics on the handling qualities of the aircraft/external load system.

The average pilot longitudinal cutoff frequencies from the Depart/Abort maneuver from one pilot are included in Figs. 12 and 13 as circles. The cutoff frequency is calculated from the autospectra of the pilot control time history, and is defined as the upper end of the frequency range that encompasses one-half of the total area under the curve. This cutoff frequency parameter is a good measure of bandwidth for piloted control and has been shown to be a good estimate of the piloted crossover frequency [7],[8].

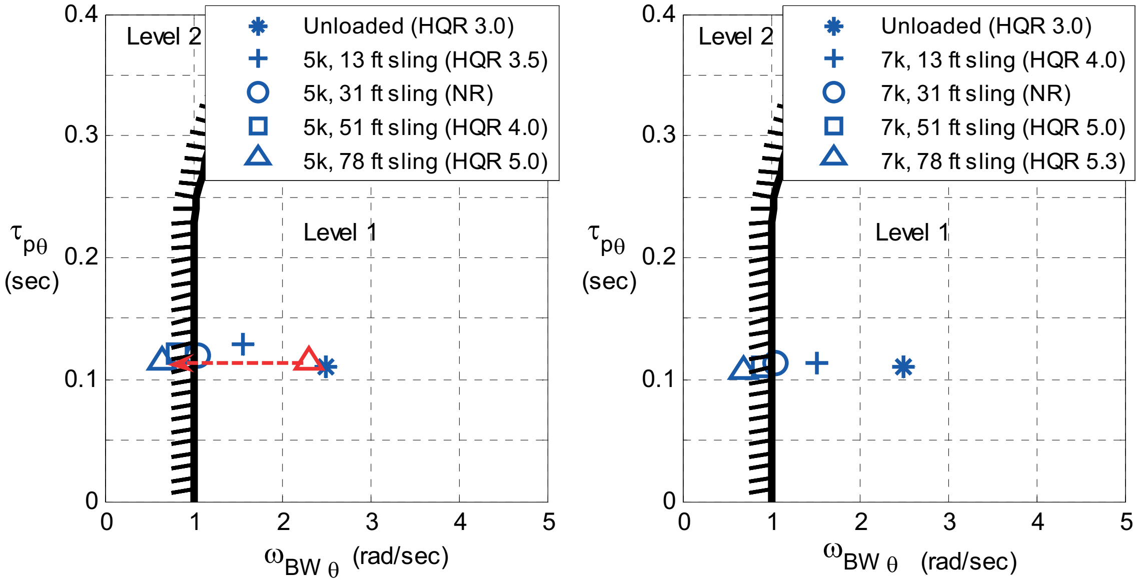


Figure 11. Hover low-speed small amplitude pitch attitude change requirement, 5100 lb and 7150 lb external loads, average HQRs from the Depart/Abort maneuver.

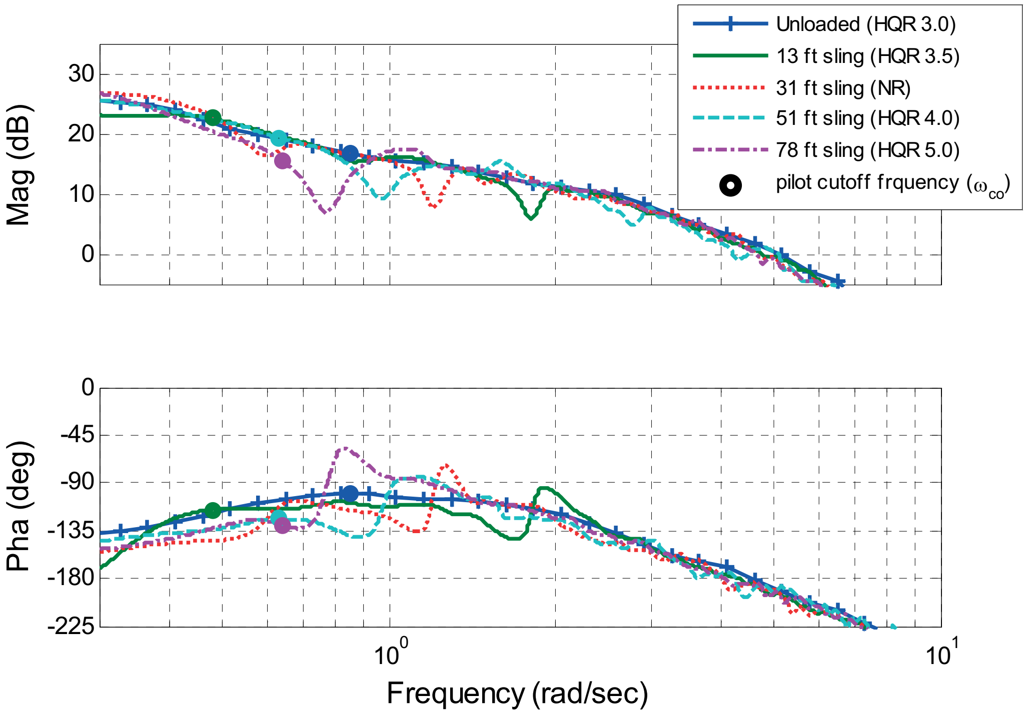


Figure 12. Pitch attitude frequency responses for increasing sling length, 5100 lb external load, average HQRs from the Depart/Abort maneuver.

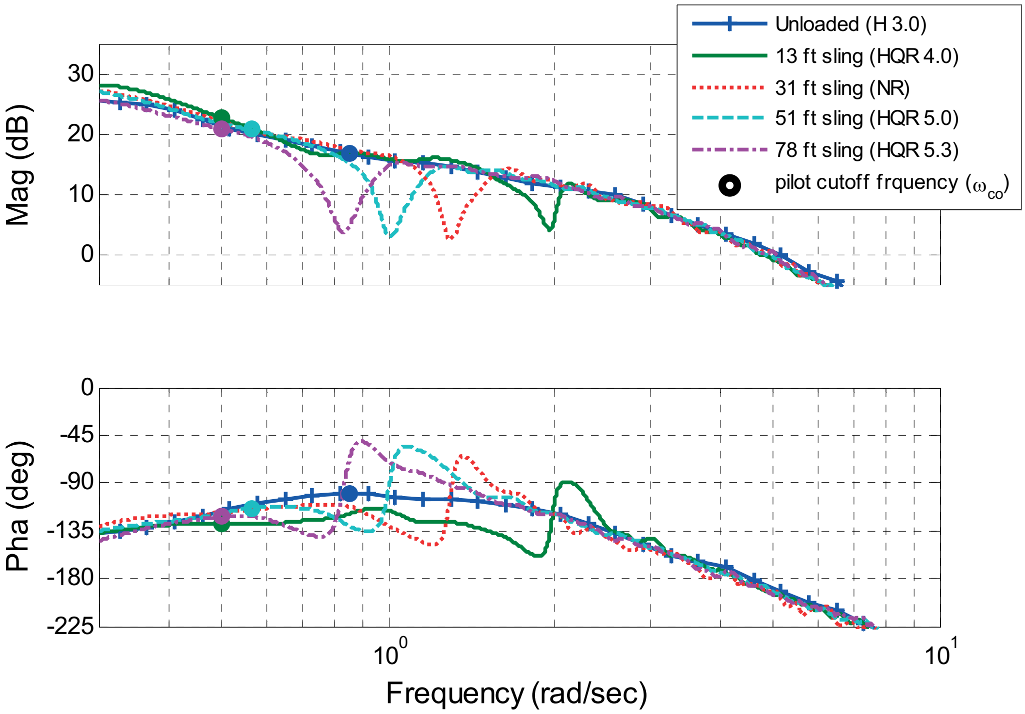


Figure 13. Pitch attitude frequency responses for increasing sling length, 7150 lb external load, average HQRs from the Depart/Abort maneuver.

For the unloaded case, the pilot's cutoff frequency is about 0.85 rad/sec and the average time to complete the Depart/Abort maneuver was 24.9 seconds (desired time 30 seconds, adequate time 35 seconds). When the external load is added, the average time to complete the maneuver was 29.2 seconds, indicating that the pilots were not as aggressive with the external load. This is also reflected in the pilot's cutoff frequency which is reduced to about 0.5 rad/sec with the 13 ft sling and increases slightly to about 0.64 for the 51 ft and 78 ft cases, well below the corresponding load modes. This indicates that the pilot's strategy is to stay out of the loop with the load dynamics — similar to crossover frequency regression referenced in [9].

Figure 14 shows the corresponding bandwidth phase delay plots for the roll axes, which also shows very little change in phase delay due to the external load. The 5100 lb load with 78 ft sling case does not have a –135 degree crossing due to the load, however this aircraft is rate command and the effect of the external load mode is captured by the gain bandwidth. The plots show that the phase delay and bandwidth for the 5100 lb and 7150 lb cases are very similar for corresponding sling length except the 78 ft case. With this sling length and a 5100 lb load, the pilots rated the lateral reposition an average HQR 4.8 ($\omega_{BW\phi}$ = 0.7 rad/sec from gain bandwidth), while with a 7150 lb load an average HQR 7.0 ($\omega_{BW\phi}$ = 0.5 rad/sec from phase bandwidth).

Figures 15 and 16 show the lateral attitude frequency responses obtained by integrating the rate responses for the 5100 lb and 7150 lb cases respectively. These responses also have the cutoff frequencies from the same pilot noted on the plots as circles. For the unloaded aircraft, the pilot's cutoff frequency is about 1.1 rad/sec. With the addition of the 5100 lb external load and a 13 ft sling, the pilot's cutoff frequency decreases slightly and the average handling quality rating remains about the same. Note that as the length of the sling increases, the frequency of the load mode decreases, forcing a corresponding regression in the pilot's operating frequency.

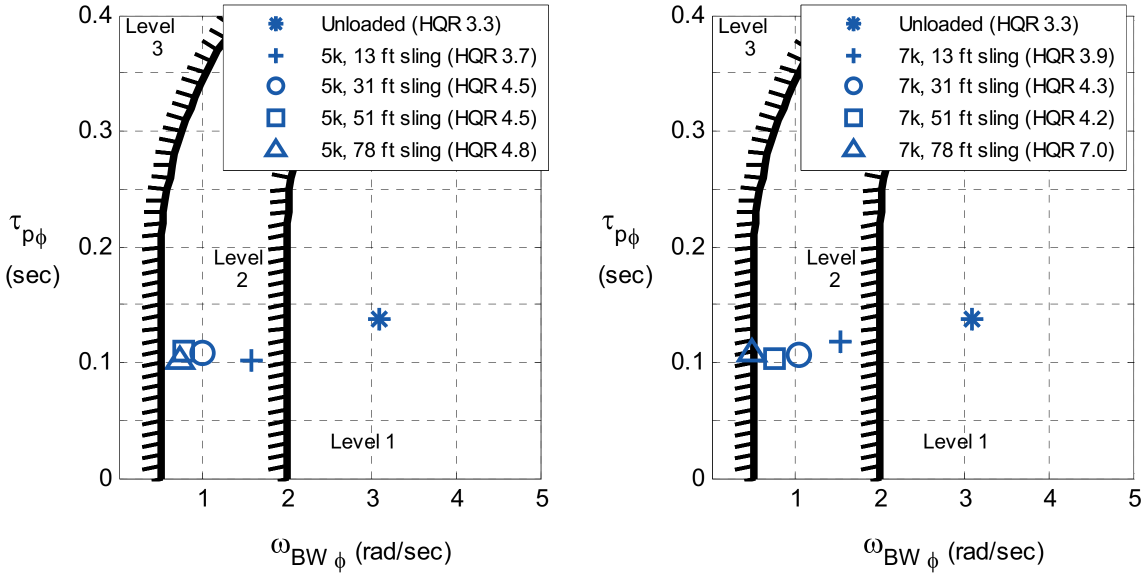


Figure 14. Hover low-speed small amplitude roll attitude change requirement, 5100 lb and 7150 lb external loads, average HQRs for the Lateral Reposition maneuver.

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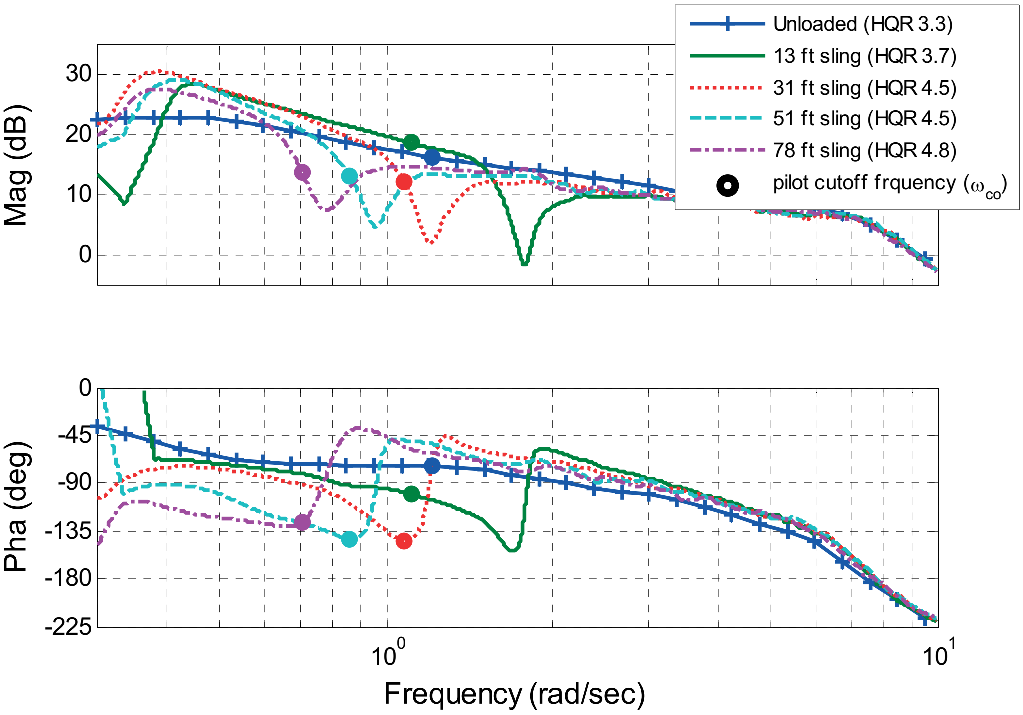

Figure 15. Roll attitude frequency responses for increasing sling length, 5100 lb external load, average HQRs from the Lateral Reposition maneuver.

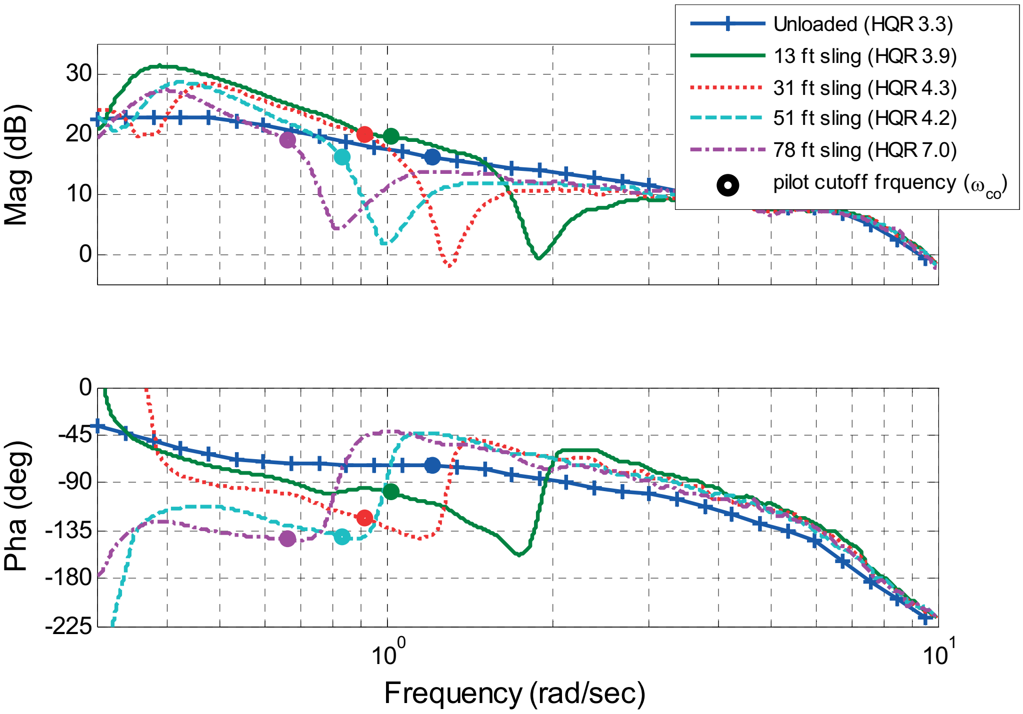

Figure 16. Roll attitude frequency responses for increasing sling length, 7150 lb external load, average HQRs from the Lateral Reposition maneuver.

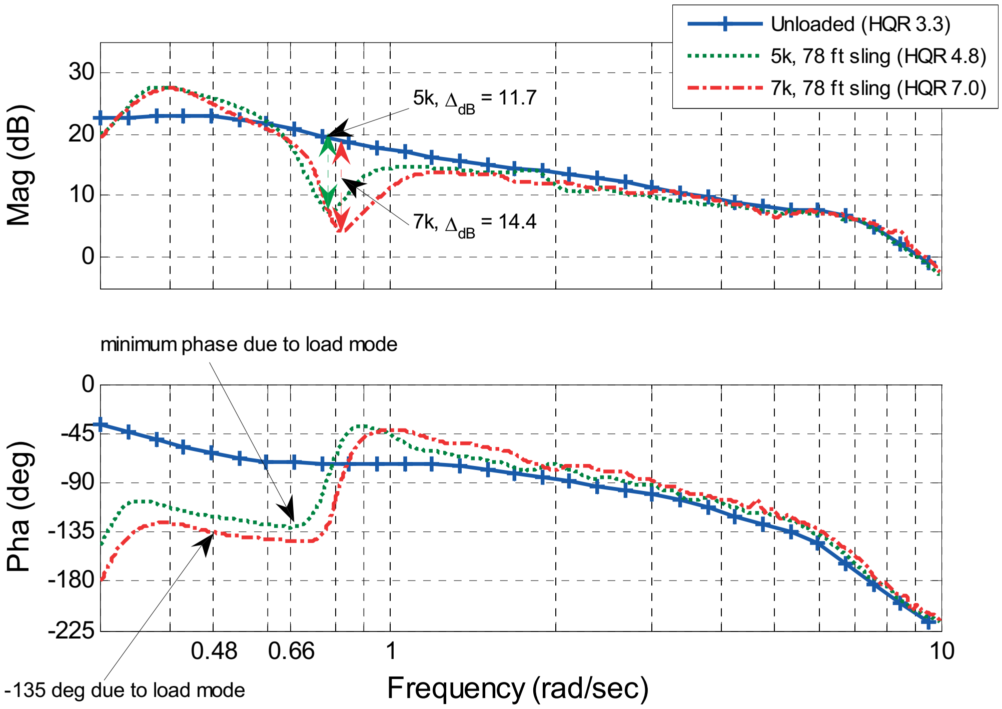

Figure 17. Comparison of roll attitude frequency responses for 5100 lb and 7150 lb external load, 78 ft sling.

A similar correlation between the external load mode frequency and the pilot's cutoff frequency is evident in the responses for the 7150 lb cases shown in Fig. 16. For the cases with sling lengths up to 51 ft, the average handling qualities ratings are very similar for corresponding sling lengths for both external load weights. For the 78 ft sling length however, the average handling qualities rating for the 5100 lb load is 4.8, while for the 7150 lb load is 7.0.

Figure 17 shows the two main distinguishing features between the two 78 ft sling length cases; 1) the depth of the notch in the magnitude curve due to the load with respect to the unloaded case, Δ_{dB} = 11.7 for 5100 lb case, and Δ_{dB} = 14.4 for the 7150 lb case, and 2) the reduction in phase due to the load mode. For the 7150 lb case, the phase curve crosses –135 deg due to the load mode at 0.48 rad/sec. The phase curve from the 5100 lb case does not cross –135 deg due to the load, however it is clear that the pilot is sensitive to the load mode as the pilot's cutoff frequency (ω_{co} = 0.70 rad/sec) is just above the minimum phase due to the load mode (0.66 rad/sec).

8. CRITERIA TO PREDICT HANDLING QUALITIES WITH EXTERNAL LOADS

The two parameters, ΔdB the deformation of the magnitude curve due to the load, and the bandwidth defined as the lesser of the –135 degree decreasing phase crossing or the minimum phase due to the load mode as shown in Fig. 17 provide parameters that can be used to characterize the effect of the external load on the attitude response of the aircraft/external load system. A plot of these parameters obtained from the longitudinal frequency sweeps of each configuration is shown in Fig. 18. The average handling qualities ratings from the Depart/Abort (DA) MTE are also shown on the plot.[2]

This data shows that as the length of the sling increases, the bandwidth decreases, and that in general for a given sling length, as the LMR increases, the ΔdB parameter increases. As can be seen from the handling qualities ratings, the lower right region of the plot contains the best ratings (short sling length and small LMRs) and when moving toward the upper left region the ratings degrade (long sling lengths and larger LMRs). From these data, the Level 1-2 boundary based on a HQR of 4.0 can be defined and is shown in Fig. 19 for the longitudinal axis. Although no data were collected with LMRs greater than 0.33, the boundary for ΔdB values above 12dB is set to 1 rad/sec recognizing that for large LMRs, the bandwidth requirements to perform the MTE to external load standards would never exceed the bandwidth requirements for an unloaded aircraft as specified in ADS-33. Conversely for ΔdB values less than 6 dB or the region where the LMR is small enough that the external load does not impact the pilot's ability to perform the task, the boundary is set to 0.5 rad/sec which is slightly above the lowest observed pilot crossover frequency that still received a HQR of 4.0. This decrease from 1 rad/sec to 0.5 rad/sec for very light external loads reflects the relaxed performance standards for the MTE when performed with external load. The points between 0.5 rad/sec and 6 dB, and 1.0 rad/sec and 12 dB are connected with a line that passes through the case that received a HQR of 4.0.

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[2] The data point for the 6000 lb external load and 16 ft sling are from external Load Handling Qualities testing that was performed in 1999 with a UH-60A at Moffett Field [4].

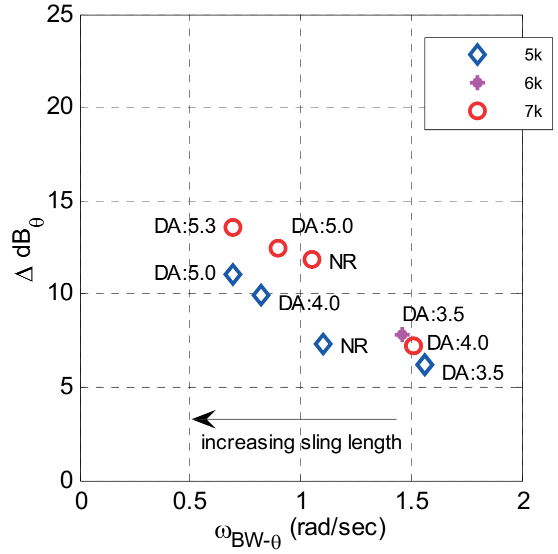

Figure 18. Depart/Abort (DA) HQRs for longitudinal ΔdB and bandwidth parameters.

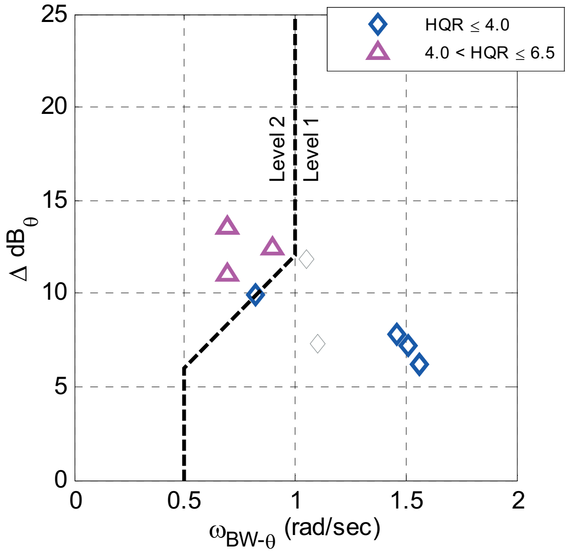

Figure 19. Longitudinal criteria with external loads.

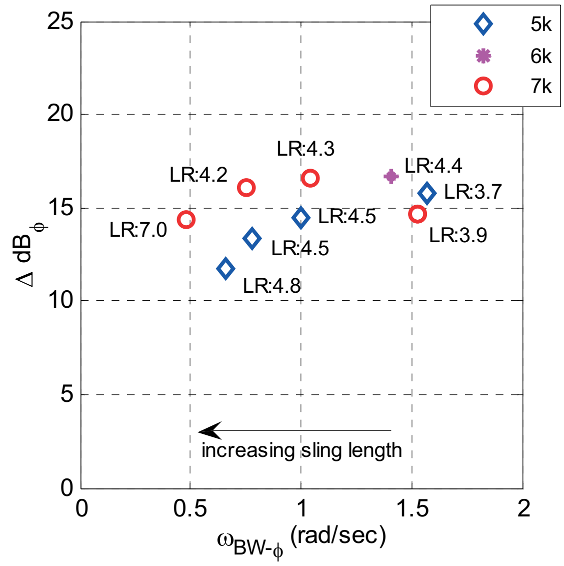

Figure 20. Lateral Reposition (LR) HQRs for lateral ΔdB and bandwidth parameters.

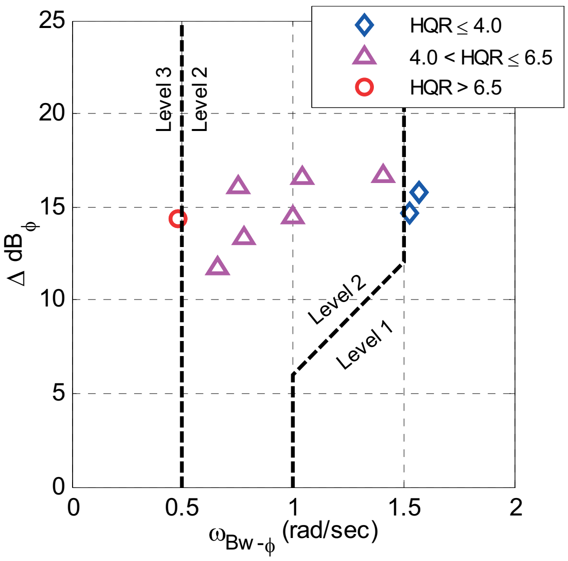

Figure 21. Lateral criteria with external loads.

A plot of the ΔdB and bandwidth parameters obtained from the lateral attitude frequency responses is shown in Fig. 20. This plot contains the average handling qualities ratings for each point from the Lateral Reposition (LR) MTE. The same trends that were observed in the longitudinal axis with regards to sling length and load weight are also observed in the lateral axis. Boundaries for the lateral axes based on the ΔdB and bandwidth parameter are defined in Fig. 21. The Level 2-3 boundary is set at 0.5 rad/sec based on the ratings assigned for the Lateral Reposition task. This boundary is consistent with the current Level 2-3 boundary in the ADS-33E requirements for small-amplitude roll attitude changes and applies for both large and small LMRs. The Level 1-2 boundary for ΔdB > 12 dB is set to 1.5 rad/sec based on the observed ratings from flight. For ΔdB < 6 dB the bandwidth is reduced to 1 rad/sec based on the observed reduction in pilot cutoff frequency when performing the task to external load standards without an external load.

The criteria boundaries presented are based on the available flight test data. To ensure that this attitude bandwidth/delta dB criteria is robust, it would be desirable to collect additional flight data points around the Level 1-2 boundaries for ΔdB < 12 dB for both the lateral and longitudinal axes with both rate command and attitude command control law architectures.

9. SUMMARY AND CONCLUSIONS

A series of flight test experiments have been conducted at the U.S. Army Aeroflightdynamics Directorate to generate a database of quantitative and qualitative data for the assessment and development of criteria to predict the effects of external loads on handling qualities. From the data that has been collected, the following conclusions can be drawn:

1) The effects of external loads on handling qualities are the most pronounced for high load weight (high LMRs) coupled with long sling lengths. This results in lower load pendulum frequencies causing the frequency of the load mode to encroach on the pilot's operating frequency and negatively impacting the pilot's ability to perform a given task.

2) An earlier proposed external load handling qualities criterion based on bandwidth parameters and a load-coupling parameter obtained from translational rate responses did not completely correlate with flight test data. However, bandwidth parameters obtained from the translational rate responses did correlate with trends in handling qualities ratings obtained from flight testing.

3) Pilot comments from flight testing indicate that load-mass ratios of 0.25 coupled with long sling lengths can have a significant impact on piloted handling qualities.

4) Analysis of pilot in the loop data with external loads shows a regression of piloted crossover frequency to frequencies below the load mode for the load-mass ratios tested. This is consistent with the relaxation of the performance standards for mission task elements with external loads.

5) An external load handling qualities criteria has been developed herein based on a bandwidth and a magnitude deformation parameter obtained from easily generated attitude responses. These correlate well with handling qualities ratings obtained from flight tests.

10. ACKNOWLEDGEMENTS

The authors would like to thank all the individuals that contributed to this research effort. First the experimental test pilots (XPs) in addition to MAJ Braddom who participated in this project, LTC Dwight Robinson the former head of the Flight Projects Office at AFDD who conducted the frequency sweeps of each configuration and the two XPs from the Aviation Technical Test Center, MAJ Carl Ott and MAJ Adam Mouser who performed evaluations. Thanks also to the engineering personnel at AFDD, Gary Leong, Eugene Kasper, Joe Leung, and the L3 Vertex ground and air crews who support flight testing at AFDD.

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