DEVEOPMENT OF HANDLING QUALITIES CRITERIA FOR ROTORCRAFT WITH EXTERNALLY SLUNG LOADS

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ABSTRACT

Handling qualities criteria have been developed for cargo helicopters carrying externally slung loads in the degraded visual environment. These consist of quantitative criteria, as well as guidelines for qualitative flight test evaluations. The work was accomplished during several simulation programs conducted on the NASA Ames Vertical Motion Simulator.

INTRODUCTION

The handling qualities criteria described in this paper were derived based on the results of two external load simulations conducted on the NASA Ames Vertical Motion Simulator (VMS); Slung Load 4 and Slung Load 5 (SL4 and SL5). These were the last of a series of five manned simulations intended to explore handling qualities issues for large cargo helicopters, particularly where carriage of slung external loads are involved. The type of aircraft is represented in Figure 1 by the CH-47D with an external load.

The first three VMS experiments served to identify critical flight tasks, define test maneuvers, develop and refine simulator math models, and target the system dynamics that needed special study. These activities culminated in the fourth and fifth simulator experiments, SL4 and SL5, from which the results in this paper have been derived.

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Figure 1 CH-47D with a Single-Point External Load.

The motivation for this work stemmed from a need to include handling qualities criteria for cargo helicopters in an upgrade in the US Army rotorcraft handling qualities specification, ADS-33D (Reference 1) to ADS-33E (Reference 2). Handling qualities with external load were of special interest because there were essentially no existing data upon which to base a criterion at the outset of this program. In addition, it was necessary to develop applicable demonstration flight maneuvers for cargo helicopters with and without external load for the ADS-33E specification.

A detailed reporting of this work that includes pilot comments and ratings, math models, and detailed descriptions of the simulation tasks is contained in Reference 3.

The addition of a heavy external load can result in a substantial degradation in the quality of attitude and translational control. One notable feature is a prominent oscillatory response mode in the frequency range of manual control activity. This oscillatory mode is associated with the pendulum action of the load, and couples with the fundamental response of the basic airframe-Stability-Command-Augmentation-System (SCAS) system. Because of this, a fundamental understanding of the dynamics of external loads as they relate to aircraft handling is essential to development of criterion parameters. Much of the existing literature on external loads was produced during the 1970's, and treats mainly the matter of describing the dynamics. The effect of an externally slung load on handling qualities, particularly in terms of contemporary metrics and standards, has not been studied in detail prior to this effort.

The Attitude Bandwidth Criterion has been found to be an effective means to ensure that the short-term attitude response is sufficiently crisp and predictable to maneuver with adequate aggressiveness and precision, when flying without an external load (see References 2, and 3). The hypothesis of the SL4 and SL5 piloted simulator experiments was to test the applicability of Attitude-Bandwidth type criteria when a heavy external load is attached. Analyses of the simulation data and pilot commentary revealed that the bandwidth of the translational rate response is a better handling qualities metric than attitude bandwidth for helicopters with external loads.

OVERVIEW OF SIMULATION

All simulations to support this program were conducted on the NASA Ames Vertical Motion Simulator (VMS) facility at Moffett Field, CA. This facility provides large-amplitude motion, a four-window ESIG-2000 visual system, and a generic cockpit with controls and instruments representative of a large cargo helicopter.

The aircraft math model was based on the CH-47D Chinook airframe and propulsion system. The flight control system was modified to reflect a generic attitude-command/attitude-hold (ACAH) Response-Type in pitch and roll. An Altitude-Hold system (HH) was also implemented and used for all data runs. The use of ACAH + HH is consistent with the requirement for Response-Type in ADS-33D/E for flight in a degraded visual environment (DVE). Specifically, when the useable cue environment (UCE) is greater than 1, ADS 33D/E requires an ACAH+HH Response-Type for Level 1 handling qualities. The simulation visual scene was measured using the techniques in ADS-33D/E, resulting in UCE = 2 (albeit very close to UCE=1), which is judged to be due to a lack of sufficient fine grained texture (see Reference 5).

The UCE=2 rating implies that a Rate Response-Type, that is normally rated as Level 1, would receive handling qualities ratings (HQRs) consistent with Level 2 due to a lack of adequate visual cueing.

The NASA Ames Vertical Motion Simulator is capable of a reasonably valid representation of external load operations by virtue of its large amplitude motion system. However, even with the large field-of-view visual, and large amplitude lateral and vertical motion, the cueing was somewhat compromised compared to the real world. Motion cues have a significant impact on the pilot's impressions of the swinging load, and even with the maximum possible motion gains, the actual accelerations at the cockpit were approximately 1/10 of those experienced in the real world. Nonetheless, the pilots commented that the motions were representative of their experience in carrying external loads, and that the motion was beneficial in the conduct of their evaluations.

The pilots were not able to see the load, and therefore had to deduce what the load was doing from motion and visual cues. The hover altitude was fixed at 50 ft so that the visual cues were constant for all runs. This artifact resulted in the longer slings being partially under ground. The pilots were not able to observe this artifact.

The motion gains in simulation SL5 were appreciably higher than in simulation SL4. This resulted from a motion gain optimization process that concentrated on the Precision Hover maneuver in SL5. SL4 tasks included Precision Hover, Normal Departure Abort, and Lateral Reposition (See Reference 3). The VMS cab was oriented to maximize longitudinal motion for the Normal Departure Abort, and was re-oriented 90 degrees to maximize lateral motion for the Precision Hover and Lateral Reposition. Only the Precision Hover Maneuver was accomplished in SL5, because the results of SL4 indicated that this was the most critical maneuver. The reason for this is that the effect of the swinging load is most noticeable when attempting to accomplish very precise position control. All of the data correlations in this paper are based on the Precision Hover task. The pilot ratings for the precision hover, and for other maneuvers are given in Reference 3.

All of the results discussed herein are based on a high density load suspended from a single point at or directly below the helicopter center-of-gravity (c.g.). Load aerodynamics were not simulated.

QUANTITATIVE CRITERIA

The quantitative handling-qualities criteria for rotorcraft with external loads, that resulted from this study, are presented in this section. Further work should be accomplished to verify these criteria in a flight test environment. Such testing should also examine the ability to reliably measure the criterion parameters. This work should be accomplished before the quantitative criteria are included as an update to ADS-33E (Reference 2). Once included in ADS 33, it is expected that the quantitative criteria would be used in lieu of the Attitude Bandwidth criteria for configurations with an external load.

In addition to the quantitative criteria, flight test maneuvers and performance criteria were developed for cargo helicopters with external load. These maneuvers and performance criteria are given in Reference 3 and have been included in ADS-33E.

The quantitative criteria apply to low speed and hover operations in the DVE with UCE = 2. If the operational missions do not require carrying an external load in the DVE, it is not necessary to meet the quantitative criteria for external loads.

The external-load bandwidth criteria provide guidance as to what is required to obtain Level 1 pilot ratings with load-on in the DVE, in addition to meeting the load-off handling qualities criteria in ADS-33. These external-load criteria are based on the assumption that the basic rotorcraft without an external load is Level 1. It is cautioned that the combination of not meeting the external-load criteria, and a rotorcraft that is Level 2, load-off, will probably result in Level 3 handling qualities in the DVE.

The effect of the external load on handling qualities was found to be a strong function of the Load Mass Ratio - the ratio of the mass of the load to the mass of the helicopter plus load (m_L / m_{Total}). The effect of an external load on helicopter handling qualities was found to be significant when the Load-Mass-Ratio is equal to or greater than 0.33 of the total mass, i.e., $m_L / m_{Total} \geq 0.33$.

The handling qualities criteria specific to rotorcraft with external load are defined in terms of two parameters - Translational Rate Bandwidth and Load-Coupling.

The horizontal translation Bandwidths shall be as follows for Level 1.

$$Longitudinal \quad \omega_{BW_{\dot{X}}} \geq 0.44\, rad/\sec$$
$$Lateral \quad \omega_{BW_{\dot{Y}}} \geq 0.59\, rad/\sec$$

The frequency range of favorable load-coupling shall be as follows for Level 1.

$$Longitudinal \quad \Delta\omega_{L_X} \geq 0.39\, rad/\sec$$
$$Lateral \quad \Delta\omega_{L_Y} \geq 0.73\, rad/\sec$$

Not meeting these criteria will result in handling qualities that are no worse than Level 2 with an externally slung load in the DVE, as long as the load-off handling qualities are Level 1. There is no Level 2-3 limit that is specifically due to external load.

The translational rate Bandwidth and Load-Coupling parameters are presented in detail in subsequent sections of this paper.

It is recognized that it may be difficult to obtain Bode plots of translational rate-to-cyclic response with sufficient accuracy and resolution to accurately measure these parameters. Therefore, it is acceptable to use an analytically derived Bode plot if the math model used to generate the Bode plot has been shown to correlate with flight data for input-output responses other than the translational rate to cyclic. For example, if the analytically derived Bode plots for pitch and roll attitude to cyclic inputs (with external load) is well correlated with flight test data, the math model may be assumed to be acceptable to calculate the translational-rate criterion parameters.

QUALITATIVE TESTING WITH EXTERNAL LOAD

Testing with external loads should be accomplished with $m_L / m_{Total} = 0.33$ or the maximum load that will be used for operational missions, whichever is less. In addition, external load testing should be accomplished in the DVE, unless this is not part of the required operational missions. The recommended maneuvers are given in Reference 3

The existence of an external load will degrade handling qualities, and it was not found to be practical to require Level 1 as defined by averaged

HQRs less than 3.5 ($\overline{HQR} \le 3.5$) for heavy loads. The simulations conducted in this program indicated that no combination of SCAS and sling geometry resulted in average ratings of better than 4 for $m_L / m_{Total} = 0.33$. On that basis, the requirement for Level 1 during tests with external loads in the DVE, with $m_L / m_{Total} = 0.33$, is relaxed so that the average HQR ($\overline{HQR}$) must be no greater than 4 (compared to 3.5 load-off). The rationale for this is that an HQR of 4 requires desired performance and some increased workload is unavoidable with a heavy external load in the DVE.

If $m_L / m_{Total} > 0.33$, the simulation studies showed that the ratings degrade linearly with increasing Load Mass Ratio (shown later in Figure 11). The caveat being that the averaged ratings did not exceed 6.5 for any of the tested cases. That is, the effect of a heavy swinging load never caused problems severe enough to be classified as Level 3 (as long as the load-off handling qualities were rated as Level 1).

Conversely it was shown that for load mass ratios less than 0.25, the effect of the load was reduced to the point where averaged HQRs of 3.5 or better were achievable. On the basis of those results, the maximum allowable averaged HQR as a function of load mass ratio is as follows:

$$For \quad m_L / m_{Total} > 0.33$$

$$\overline{HQR} \le \left[4.0 + 5.2\left(\frac{m_L}{m_{Total}} - 0.33\right) \right]$$

$$For \quad 0.25 \le m_L / m_{Total} \le 0.33 \text{ - } \overline{HQR} \le 4.0$$

$$For \quad m_L / m_{Total} \le 0.25 \text{ - } \overline{HQR} \le 3.5$$

In addition to testing for acceptable handling qualities, it should be determined that any load oscillations that occur during deceleration to hover are damped quickly enough so that they do not interfere with the ability of the ground crew to safely detach the load without damaging it, in a reasonable period of time.

DEVELOPMENT OF QUANTITATIVE CRITERIA

The quantitative criteria developed in this study apply to low speed and hover tasks, i.e., tasks where the groundspeed is, for the most part, under 45 kts. The criteria are based on the Precision Hover task as accomplished in two simulations (SL4 and SL5). Other more aggressive tasks were accomplished in SL4 (Lateral Reposition, and Normal Depart/Abort) as described in Reference 3). The pilot rating data and commentary from SL4 indicated that the Precision Hover task was the most critical task in terms of handling qualities. That was because the perturbations that resulted from the swinging load were much more noticeable and intrusive when trying to accomplish a precision station-keeping task. The SL5 simulation focused entirely on the Precision Hover task.

The Precision Hover task included a moderately aggressive deceleration from a 6 to 10 kt. translation. This tended to excite the load, and the pilot was allowed 13 seconds to stabilize the helicopter plus load oscillation for desired performance, and 18 seconds for adequate performance. Desired performance required that the pilot maintain longitudinal and lateral position, with within a 3 ft hover box and altitude within 4 ft. for 30 seconds. Adequate performance relaxed the hover position to a 6 ft box, and altitude to within 6 ft. for 30 seconds.

Analysis of simulation data (SL4 and SL5) for variations in external load and flight control system characteristics has shown that pilot opinion was strongly impacted by changes in the characteristics of the longitudinal and lateral <u>translational velocity</u> response. This is in contrast to the load-off case where pilot opinion is best correlated with <u>attitude</u> response characteristics. Without an external load, the attitude and translational rate responses are highly correlated. This is not the case with an external load, where the phasing between the translational rate and attitude responses is highly dependent on the sling geometry, load-mass, and flight control system.

Recall that the basic hypothesis that was used to guide the development of test configurations for this experiment was that the Attitude Bandwidth criteria for load-off could be extended to load-on. Considerable analysis was accomplished in an attempt to correlate the pilot rating data with various definitions of Attitude Bandwidth (see Reference 3, Appendix E). This was ultimately not successful, which led to correlation efforts using the characteristics of the surge and sway (translational velocity $\dot{x}$ *and* $\dot{y}$) responses.[1]

Good position control is dependent the ability of the pilot to precisely control speed. It follows that the criteria development effort can be focused on an analysis of the $\dot{x}\, to\, \dot{x}_c$ loop closure. That is, the shape of the frequency response of $\dot{x}/\delta$ *and* $\dot{y}/\delta$ can be quantified, and correlated with pilot opinion and ratings from the SL4 and SL5 simulation experiments. These dynamics can be related to physical characteristics such as sling geometry (e.g., hook-to-c.g. distance and sling length) and flight control system characteristics.

A quantitative criterion could not be derived for Rate Response-Types with an external load, so it is necessary to check the handling qualities using specified flight test maneuvers as provided in References 2 or 3, and the pilot rating guidelines noted above in the section on Qualitative Testing With External Load.

The development of quantitative criteria for external loads with Rate Response-Types was not possible because the simulation visual environment was measured to be UCE = 2 (using the techniques in ADS-33D/E). Piloted evaluations of a Level 1 Rate System with the nominal load, resulted in HQRs of 7 – 8. This verified that the simulation environment was UCE=2, because it is well known that Level 1 handling qualities are possible with Rate Response Types in UCE=1. The remainder of this development pertains to an ACAH Response-Type.

A typical frequency response and root locus plot that describes the longitudinal velocity response to longitudinal cyclic input is shown in Figure 2 for a helicopter without a load. The effect of adding an external load that is suspended from a single point is shown in Figure 3. Comparison of the dynamics in Figures 2 and 3 reveal that the short-period mode (ω_{sp}) is only slightly affected, and that the primary effect of the load on the surge response is described by the addition of a lightly damped pole-zero complex pair[2].

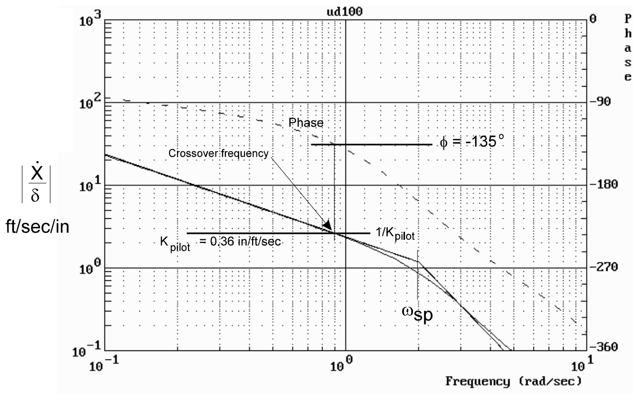
The effect of increasing the pilot gain, K_{pilot}, is indicated by the root locus plots in Figures 2b and 3b. These plots indicate the following results.

- An increase in $1/T_{\dot{x}}$ which defines the fundamental speed and path response (Load on and off). Higher values of $1/T_{\dot{x}}$ allow for a more predictable velocity response and hence a more stable position loop closure.
- Decrease in damping of the short period mode (load on and off).
- The load-mode pole (ω_{L_p}) is driven towards decreased damping and eventually unstable (load-on only).

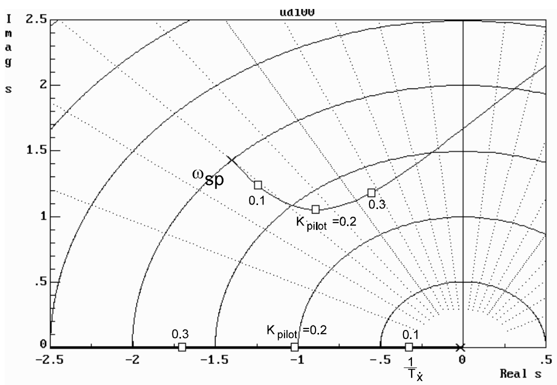
Good handling qualities would be expected to exist when the pilot is able to augment the basic path mode, $1/T_{\dot{x}}$, without driving the short period mode (ω_{sp}) and/or load-mode (ω_{L_p}) poles to unacceptably low damping or unstable.

[1] The correlation of pilot rating data with surge and sway characteristics was also suggested by pilot commentary that indicated significant concern with those degrees of freedom (see Reference 3).

[2] The generic effect of external load on the lateral axis is very similar to the longitudinal axis and is therefore not discussed separately.

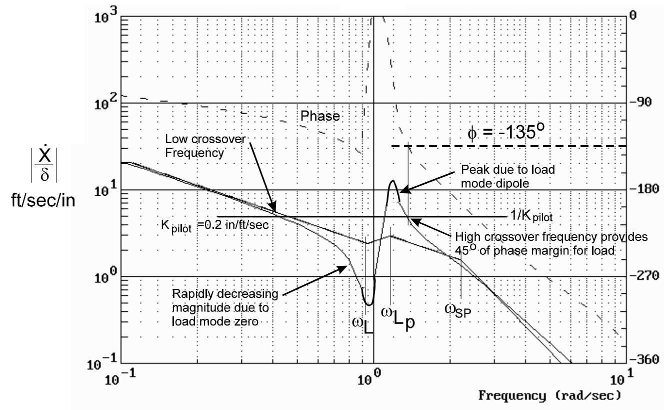


a) Frequency Response of Surge to Longitudinal Cyclic

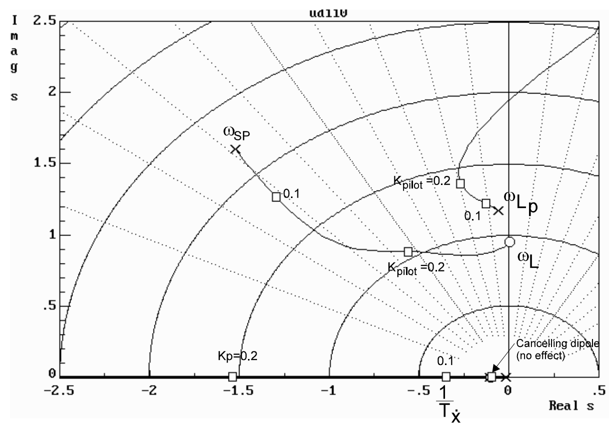


b) Root Locus of Pure Gain Pilot Loop Closure of Speed Loop

Figure 2 Bode and Root Locus for Load-Off



a) Frequency Response of Surge to Longitudinal Cyclic



b) Root Locus of Pure Gain Pilot Loop Closure of Speed Loop

Figure 3 Bode and Root Locus With Load On

It will be shown that the ability to augment $1/T_{\dot{x}}$ to the level needed to accomplish the task is defined by the Translational Rate Bandwidth parameters, $\omega_{BW_{\dot{X}}}$ *and* $\omega_{BW_{\dot{Y}}}$ [1]. That is, low Bandwidth is an indicator that the pilot loop closure will result in low $1/T_{\dot{x}}$ (and hence poor control of speed and position). Bandwidth is either limited by stability considerations, or by the load mode zero. The natural frequency of the load mode zero ω_L is approximated by,

[1] Bandwidth as used in this Report refers to the Translational Rate Bandwidth unless otherwise noted. As with the attitude Bandwidth, it is defined as the frequency for 45 degrees of phase margin and 6 dB of gain margin.

$\omega_L \cong \sqrt{\dfrac{g}{l_{sling} * m_{helo} / m_{total}}}$ where l_{sling} is the length of the sling (hook to c.g. of load).

Note that when the load mass is much less than the total mass ($m_{helo} / m_{total} \approx 1$), the load-mode zero has the frequency of a classic pendulum, $\omega = \sqrt{g / l}$.

The load-mode pole always occurs in the vicinity of the load mode zero.

Without an external load, Bandwidth is defined in ADS-33D/E as the frequency where the phase margin is equal to 45 degrees, or the gain margin is equal to 2 (6 dB) in the attitude response. As an example, the piloted crossover in Figure 2 is shown to occur at the bandwidth frequency (phase margin is 45 degrees).

The effect of pilot gain on the crossover frequency can be determined by noting that the crossover frequency occurs when $1 + K_{pilot} G = 0$ or $G = -1 / K_{pilot}$ (where G is $\dot{x} / \delta$)[1]. We can graphically determine the crossover frequency by plotting $1 / K_{pilot}$ and $\dot{x} / \delta$ on the same grid and noting where they intersect. Normally there is one intersection, and that is defined as the crossover frequency. The conventional definition of Bandwidth is when this crossover frequency occurs at –135 deg of phase or 45 deg of phase margin (e.g., Figure 2).

For the external load case, the translational-rate response is used, and the additional mode induced by the load results in several piloted crossover frequencies as shown in Figure 3. The "low crossover frequency" is akin to the classical piloted crossover illustrated in Figure 2. The "high crossover frequency" occurs due to the load mode. The fact that the pilot gain-line ($1/K_{pilot}$) intersects the load mode peak, indicates that these dynamics are being excited. The phase margin for this high crossover determines the load stability.

The concept of the "high crossover" allows the inclusion of load stability as a factor in the handling qualities criteria. Without an external load, Bandwidth is defined by two parameters, gain and phase margin of the basic augmented aircraft. Adding the effect of an external load requires the addition of two additional parameters. These are the gain and phase margin associated with the load stability (high crossover). The four criterion parameters are defined as follows.

1. $\omega_{BW_{\phi 1}}$ - Phase margin Bandwidth of basic aircraft – (Figure 4)

$\omega_{BW_{\phi 1}}$ is the phase margin bandwidth that is defined as the lowest frequency where the phase passes through –135 degrees, as shown in Figure 4. This is akin to the load-off case (e.g., Figure 2), and represents the basic path/speed-mode response limit. The first-order pole that defines the fundamental speed and path response ($1/T_{\dot{x}}$) is directly proportional to $\omega_{BW_{\phi 1}}$. If the phase margin does not decrease below 45 degrees at frequencies below ω_L , set $\omega_{BW_{\phi 1}} = \omega_L$. This recognizes that the load mode zero represents an upper limit on piloted crossover frequency. This limit occurs because the Bode magnitude decreases rapidly as the crossover frequency approaches the zero at ω_L , and it would require an unreasonably high pilot gain to crossover at frequencies near ω_L (see note at bottom-left in Figure 3a).

2. $\omega_{BW_{\phi 2}}$ - Phase margin Bandwidth due to load - Figure 5

$\omega_{BW_{\phi 2}}$ is defined as the low crossover frequency that results when the pilot gain provides 45 degrees of phase margin ($\phi = -135^o$) for the load mode. The procedure for determination of that pilot gain, and the resulting $\omega_{BW_{\phi 2}}$ is as follows:

- Determine the highest frequency where the phase margin is 45 degrees (defined as the "high" crossover frequency in Figure 3a).
- Draw a vertical line at that frequency and note where it crosses the magnitude curve. Draw a horizontal line at that magnitude. This represents the pilot gain (its magnitude is $1/K_{pilot}$) required to maintain 45 degrees of phase margin for the load mode.
- Note lowest frequency where the horizontal line ($1/K_{pilot}$) intersects the magnitude curve

[1] See Reference 6 for a more complete description of pilot-vehicle analysis procedures.

("low" crossover frequency). That value is $\omega_{BW_{\phi 2}}$.

The load mode dipole results in a peak in the Bode magnitude plot at frequencies above the load mode zero. This peak represents the surge response of the rotorcraft due the swinging load. This may be thought of as the first harmonic of the overall response, that is superimposed on the first-order path/speed response that is characterized by $1/T_{\dot{x}}$. An increase in the magnitude of the peak of the load response indicates more response in $\dot{x}$ due to the swinging load.

The additional mode introduced by the swinging load can result in multiple crossover frequencies (e.g., Figure 3a. 4, and 5). The phase at the "high" crossover frequency is an indicator of the stability of the load at a given value of pilot gain. If this high crossover results in low or negative phase margin, the pilot is forced to reduce or "back-off" on his gain to avoid unacceptable oscillations in surge due to the swinging load. There were numerous pilot comments during the SL4 and SL5 simulations regarding the need to back-off on control aggressiveness avoid exciting the load. When the pilot lowers his gain to stabilize the load, the "low crossover frequency" must necessarily decrease, (because the line defined by $1/K_{pilot}$ moves upwards) resulting in less precise control over $\dot{x}$, and hence position.

The above discussion reveals that $\omega_{BW_{\phi 2}}$ defines the bandwidth limit that occurs as a result of a need to stabilize the load. If $\omega_{BW_{\phi 2}} < \omega_{BW_{\phi 1}}$, speed and position control is limited by load stability (e.g. as in Figure 5).

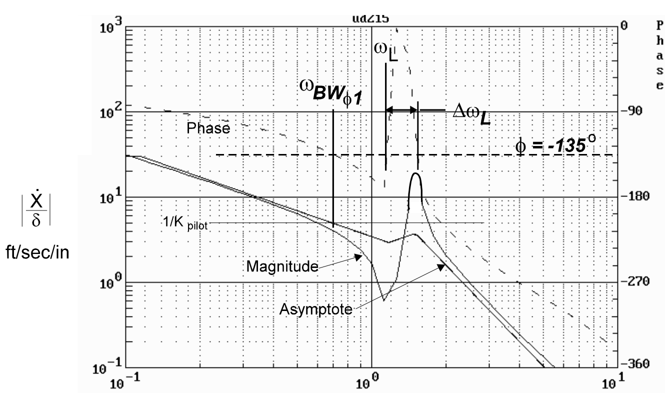


Figure 4 Definition of $\omega_{BW_{\phi 1}}$ and $\Delta\omega_L$

This was more common in the pitch axis, because the high moment of inertia in that axis tended to suppress favorable coupling between the load and pitch attitude (see subsequent discussion on $\Delta\omega_L$).

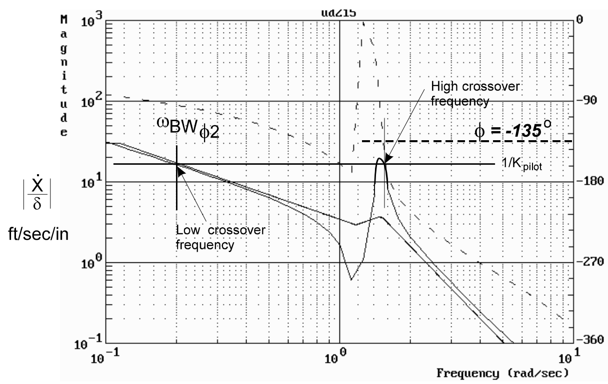


Figure 5 Definition of $\omega_{BW_{\phi 2}}$

3. $\omega_{BW_{G1}}$ - Gain margin Bandwidth of basic aircraft - Figure 6

This parameter is equivalent to the gain-margin bandwidth used for load-off handling qualities. The definition of $\omega_{BW_{G1}}$ is illustrated in Figure 6 and is calculated as follows.

1) Find the Bode magnitude that occurs at the lowest frequency where the phase equals minus180 deg (this is defined as the pilot crossover for neutral stability; $1/K_{pilot}$ = G at the frequency where $\phi = -180^o$)

2) Find the lowest crossover that occurs if the pilot reduces the gain calculated in step 1 by 1/2 or $2/K_{pilot}$. This is $\omega_{BW_{G1}}$.

As an aside, note that this illustration uses the lateral response as an example. A longitudinal example could just as easily have been used, as the dynamics are the same.

4. $\omega_{BW_{G2}}$ - Gain margin Bandwidth due to load – (Figure 7)

This parameter defines the gain margin limit associated with stabilization of the load mode. It is the gain margin limit that goes along with the

$\omega_{BW_{\phi 2}}$ phase margin limit. The definition of $\omega_{BW_{G2}}$ is illustrated in Figure 7 and is calculated as follows

1) Find the magnitude that occurs at the highest frequency where the phase equals –180 deg. This is the pilot gain ($1/K_{pilot}$) for neutral load stability

2) Find the lowest crossover that occurs if the pilot reduces the gain calculated in step 1 by 1/2 or $2/K_{pilot}$. This is $\omega_{BW_{G2}}$.

5. $\Delta\omega_L$ - Load Coupling Parameter – (Figure 4)

The load coupling parameter, $\Delta\omega_L$, defines the range of frequencies where the phase of the swinging load results in damping of speed and path excursions. The mechanism is as follows. If the load swings forward, the momentum of the load will tend to increase the forward velocity. However, if the forward load swing causes the helicopter to pitch up, the horizontal component of the lift vector will oppose the increase in speed. If the net effect is to damp the overall motion, the load coupling is said to be favorable. Such favorable load coupling manifests as positive phase margin in the vicinity of the load-mode dipole.

$\Delta\omega_L$ is defined as the range of frequencies where the phase margin is equal to or greater than 45 degrees, as shown in Figure 4.

Increasing the hook-to-c.g. distance below the vertical c.g. of the helicopter tends to improve favorable load-mode coupling (larger $\Delta\omega_L$), because the effect of the swinging load on pitching moment is increased. Conversely increasing the pitch moment of inertia tends to reduce $\Delta\omega_L$ since the aircraft does not pitch as much due to the applied moment of the swinging load.

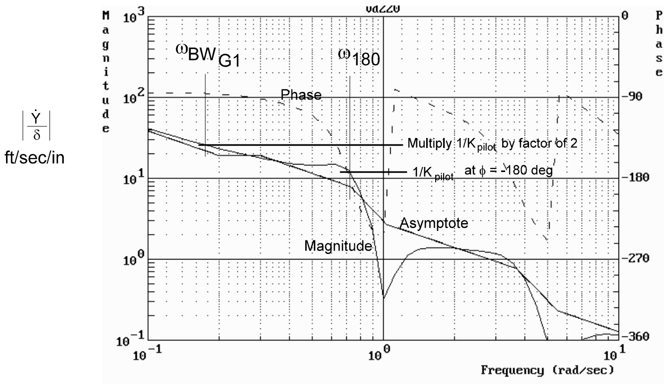


Figure 6 Definition of $\omega_{BW_{G1}}$

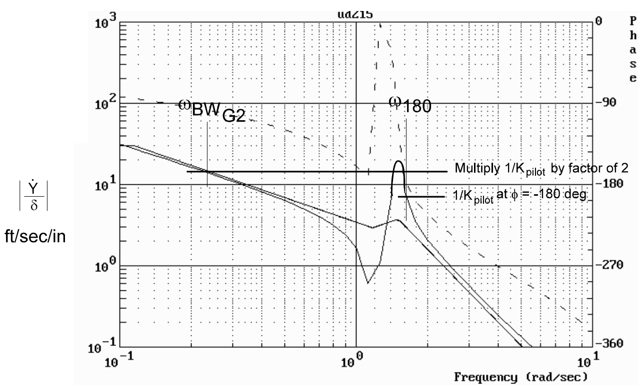


Figure 7 Definition of $\omega_{BW_{G2}}$

TESTED CONFIGURATIONS

The SL4 and SL5 VMS simulations were accomplished to verify, or if necessary, modify the hypothesis that the handling qualities of helicopters with external load can be specified using an extension of the basic Attitude Bandwidth Criteria in ADS-33D. The required perturbations in Attitude Bandwidth were achieved through systematic variations in external load parameters as well as a variable lag-lead filter in the flight control system. These parametric variations are summarized as follows.

- Sling length from 20 to 150 ft
- Hook-to-c.g. distance from 0 to 21 ft (below the c.g.)
- Attitude-Command-Attitude-Hold (ACAH) flight control systems with load off Bandwidths of 2.6 rad/sec (ACAH1) 2.0 rad/sec (ACAH2), and 1.17 rad/sec (ACAH3) and 0.7 rad/sec (ACAH4). The gains were adjusted so that the pitch and roll bandwidths were identical in hover.
- Effect of lag-lead equalization on ACAH1 and ACAH2
- Effect of ratio of load weight to helicopter weight. (load + helicopter weight was held constant at 46000 lbs). This included some cases with no load, which served as a baseline, and provided data for internally loaded cargo helicopters (see Reference 3).
- Effect of variation in roll moment of inertia. Results of this are given in Reference 3.

A complete description of the configurations is given in Reference 3.

CORRELATION WITH BANDWIDTH AND LOAD COUPLING PARAMETERS

The pilot rating data from SL4 and SL5 for the Precision Hover Task are plotted on a grid of Bandwidth vs. the Load Coupling Parameter, $\Delta\omega_L$ in Figures 8 and 9 for the nominal 16,000 lb load.

The pilot rating data indicates that with a load mass ratio of 0.33 or greater (16000 lb or greater load) it was not possible to achieve the commonly accepted definition of Level 1 ($\overline{HQR} \leq 3.5$) with any of the configurations. A review of the pilot commentary reveals that this was due to the uncommanded motions of the rotorcraft resulting from the swinging load. With lighter loads these motions were less objectionable, and average HQRs of 3.5 or better were common. The effect of load mass is further discussed in a subsequent section.

As discussed earlier, the Level 1-2 boundaries shown in Figures 8 and 9 were based on HQR=4.

With only one exception, the pilot ratings never were worse than 6.5. Therefore, a Level 2-3 boundary could not be derived. Decreasing Bandwidth resulted in a gradual degradation in HQR, whereas unfavorable load coupling was found to be more objectionable.

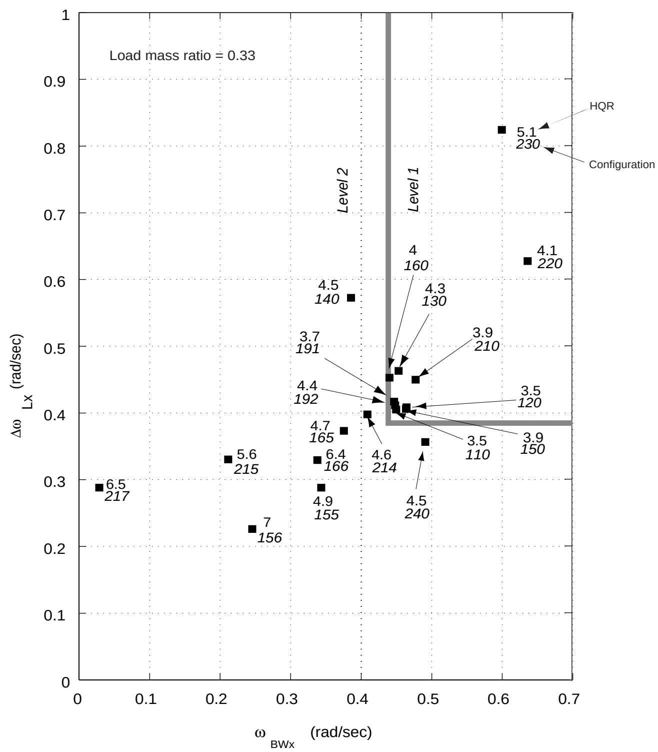


Figure 8 Correlation of Cooper-Harper Pilot Rating Data for Longitudinal Axis

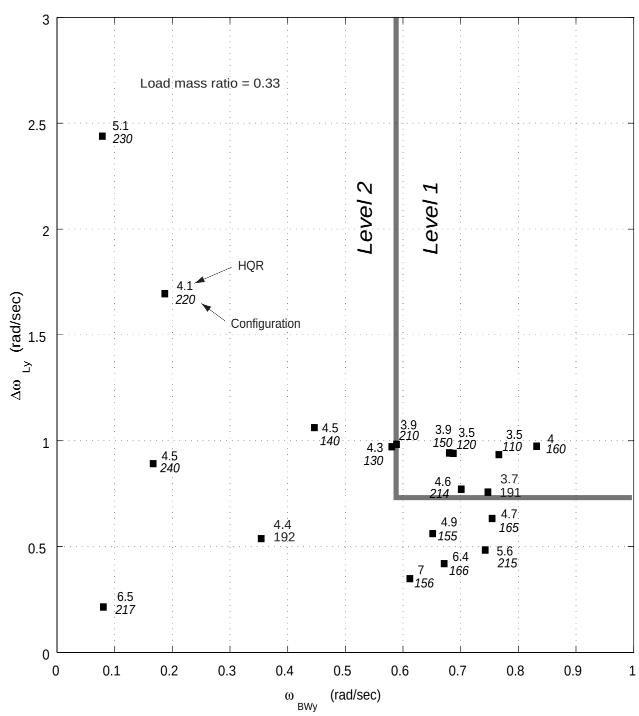


Figure 9 Correlation of Cooper-Harper Pilot Rating Data for Lateral Axis

The Level 1-2 boundaries shown in Figures 8 and 9 provide a reasonably good separation for cases rated worse than HQR = 4 and those that were rated better. Cases that are rated Level 2 and fall in the Level 1 region in one axis, tend to fall in the Level 2 region in the other axis. For example Case 230 falls in the Level 1 region for the longitudinal axis and the Level 2 region for the lateral axis. It is rated Level 2 ($\overline{HQR} = 5.1$).

The effects of sling geometry, load mass, and lag-lead compensation in the flight control system are isolated and discussed in the following paragraphs

EFFECT OF LOAD MASS RATIO

As would be expected, the load mass ratio (mass of load divided by total mass) had a strong effect on handling qualities. When excited, the swinging load resulted in un-commanded translational motions, which were directly proportional to the Load Mass Ratio. A typical pilot comment for the precision hover task follows:

"When I would bring it to a stop, and try to back out of the loop during a hover, the oscillations of the airframe would cause the aircraft to translate fore or aft or left or right, depending on which way the load was going, which would take the aircraft out of the desired box."

The load also disturbed the pitch and roll attitude as evidenced by the following pilot commentary.

"I put an input in and then the load would respond and I could feel a lateral acceleration, like I was being pulled sideways. And then some time after that, it seemed like I would get a roll in the opposite direction, kind of a stabilizing effect."

These effects scale directly with the Load Mass Ratio since a heavier load contributes more momentum to the system. As noted by the above comment, the effect of the load on the aircraft response can be favorable. This effect is captured by the Load Coupling Parameter, $\Delta\omega_L$.

Decreasing the weight of the load results in a decrease in the load coupling parameter in the longitudinal and lateral axes. That is because a lighter swinging load does not impose a sufficiently large moment on the rotorcraft to provide the stabilization noted above. This results in small values of $\Delta\omega_L$ that are in the Level 2 region. However, the light load also does not disturb the helicopter sufficiently for the pilot to be concerned so that the HQRs are Level 1. Because of this, the

Level 1-2 boundaries derived in Figures 8 and 9 only apply when the load mass ratio is sufficiently large ($m_L / m_{Total} = 0.33$).

It is not possible to determine the effect of increasing m_L / m_{Total} beyond 0.33 with confidence from the available data. Only two configurations with load weight greater than 16000 lbs were investigated (Configurations 189 and 290), and these were both rated as Level 2.

The configurations where load weight was independently varied (sling length and hook-to-c.g., held constant at nominal values) indicate an essentially linear trend in pilot rating vs. load mass ratio as shown in Figure 11. The effect of increased attitude bandwidth (ACAH1 vs. ACAH2) appears to be unimportant for load mass ratios greater than 0.18 for these "nominal" cases (i.e, 20 ft sling and 7 ft hook-to-c.g. distance).

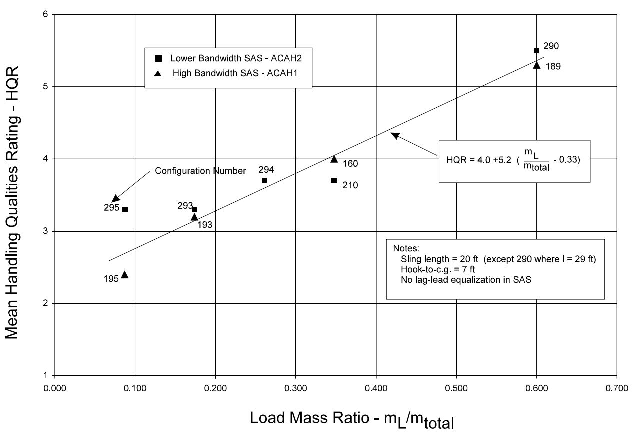


Figure 11 Effect of Load Mass Ratio on Handling Qualities Ratings

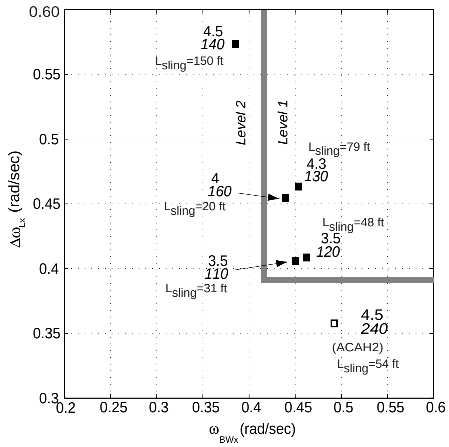
These data indicate that pilot ratings degrade as an essentially linear function of increasing load weight. It follows that the proposed quantitative criteria apply only for the tested load weight, $m_L / m_{Total} = 0.33$. The criteria are too stringent for lighter loads and too lenient for heavier loads. Until more comprehensive criteria are developed, it will be necessary to determine the handling qualities for lighter and heavier loads using the maneuvers in Reference 3. The HQRs obtained from such evaluations are allowed to degrade according to the formula in Figure 11 when $m_L / m_{Total} \geq 0.33$.

The qualitative flight test criteria given above allows the average HQR to degrade with increasing load mass ratio per the formula in Figure 11 when $m_L / m_{Total} > 0.33$. Conversely, when $m_L / m_{Total} \leq 0.25$, the data in Figure 11 indicate that the HQRs should be no worse than 3.5.

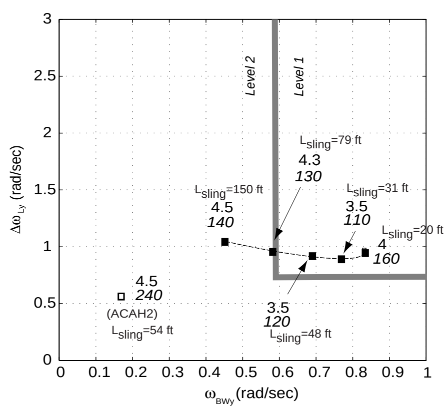
From a design standpoint, meeting the quantitative criteria developed herein for $m_L / m_{Total} = 0.33$, provides reasonable assurance that the best possible handling qualities are achieved for all load weights. The caveat being that for much heavier loads, the best possible handling qualities may not be very good. For such cases, the pilots are required to "fly the load". Pilots who fly very heavy loads refer to moving the helicopter over the load to damp the motion. It is normally not possible to do this in the DVE, since the pilot cannot see the load (especially with night vision goggles). In that case, there seems no choice but to live with the increased workload and degraded performance. Meeting the Bandwidth and Load Coupling criteria presented above ensures that the workload is as low as possible.

EFFECT OF SLING LENGTH

The result obtained for variations in sling length are shown in Figure 12. These data indicate that the pilot commentary and ratings were not highly sensitive to sling length.



a) Effect of Sling Length - Longitudinal Axis, ACAH1 Unless Otherwise Noted



b) Effect of Sling Length - Lateral Axis, ACAH1 Unless Otherwise Noted

Figure 12 Effect of Sling Length

Longitudinal Axis – Increasing the sling length from 20 ft to 79 ft caused only small variations in $\Delta\omega_{LX}$ and Bandwidth (see Figure 12a). A substantial increase in $\Delta\omega_{LX}$ occurred when the sling length was increased to 150 ft (Configuration 140). The averaged pilot ratings did not vary significantly with sling length ($\overline{HQR} = 3.5$ for 20 foot sling length and $\overline{HQR} = 4.5$ for 150 ft sling length). A detailed examination of the data indicates a small but steady degradation in pilot rating with increasing sling length. Case 160 (20 ft sling) received a number of ratings of 3 and one 2.5. Case 140 (150 ft sling) was frequently rated 4.5 to 5, and never better than 3.5. The subtle nature of the degradation with a long sling (due to decreased lateral bandwidth) required a large number of runs to identify.

There does not appear to be a handling-qualities cliff associated with sling-length. There were numerous pilot comments that the system is well behaved if the pilot backs out of the loop (all sling lengths), which was due to the favorable load coupling ($\Delta\omega_L$) that existed for all of the cases where sling length was varied.

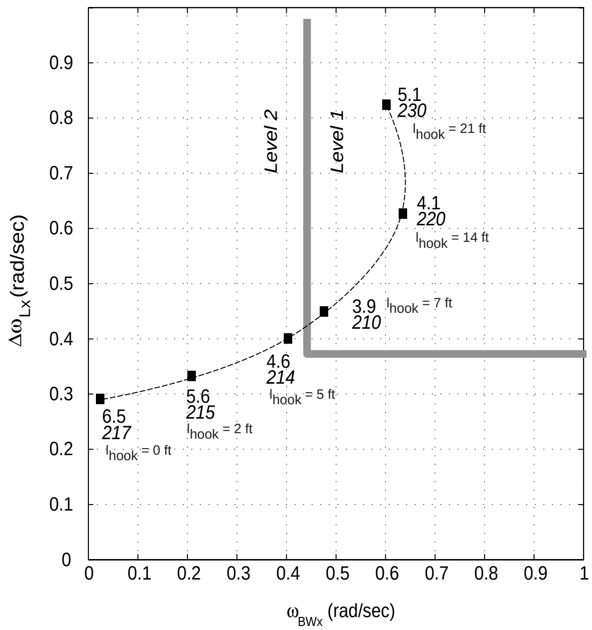
All but one of the sling-length variation cases were run with the higher attitude Bandwidth (ACAH1). Case (240) was run with a 54 ft sling and ACAH2 ($\overline{HQR} = 4.5$). Comparison with Configuration 120 (48 ft sling and ACAH1, with $\overline{HQR} = 3.5$) indicates that the effect of the attitude SAS is significant for longer slings. This is discussed further under Effect of Higher Order Flight Control System and Attitude Bandwidth.

Lateral Axis – Increasing the sling length resulted in a monotonic decrease in bandwidth at approximately constant $\Delta\omega_{LY}$ (Figure 12b). The primary pilot complaint for Configuration 140 (150 ft sling) was lack of predictability, which is consistent with the decreased lateral Bandwidth.

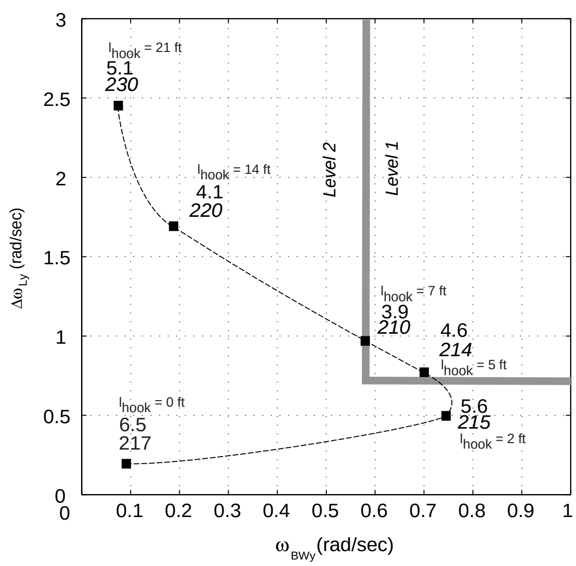
EFFECT OF HOOK-TO-C.G. DISTANCE, l_{hook}

The nominal value of l_{hook} was 7 ft, which is the geometry that is commonly used by the U.S. Army when carrying external loads on the CH-47. A range of hook-to-c.g. distances between 0 ft and 21 ft was tested. All of the hook-to-c.g. variations were run with the lower attitude bandwidth system (ACAH2).

Increasing l_{hook} from 0 to 21 ft resulted in a corresponding increase in the Load Coupling Parameter, $\Delta\omega_L$, from very low to very high values as shown in Figures 13a and 13b. This is a direct result of the increase in moment transmitted to the rotorcraft from the swinging load as l_{hook} is increased. In the longitudinal axis, the translational



a) Effect of Hook-to-c.g Distance on Longitudinal Axis, ACAH2



b) Effect of Hook-to-c.g Distance on Lateral Axis, ACAH2

Figure 13 Effect of Hook-to-C.G. Distance

rate bandwidth increases steadily with l_{hook} (Figure13a), which would be expected to result in improved handling qualities in that axis. In the lateral axis, $\omega_{BW_{\dot{Y}}}$ increases up to $l_{hook} \approx 3\ ft$, and abruptly decreases for greater values (Figure 13b). The decrease in bandwidth for $l_{hook} > 7\ ft$ would be expected to result in degraded pilot ratings (moves into Level 2 region in Figure 13b). The actual degradations in the average HQR were somewhat less than might be expected, based on the significant decrease in lateral Bandwidth (ω_{BWy}) shown in Figure 13b. This is discussed below.

The decrease in Bandwidth in the lateral axis for $l_{hook} > 3\ ft$ (Figure 13b) is due to gain margin limiting. Configuration 220 is severely gain margin limited, but surprisingly the averaged pilot ratings ($\overline{HQR} = 4.1$) do not indicate a significant degradation in handling qualities[1]. The ratings from SL4 were 5/2/3/4/4/5/5. For SL5 one rating of 4 was obtained from the same pilot (W) who gave it a 2 on SL4. A review of the pilot commentary provides some insight. Pilots G and W gave the following ratings and commentary for Configuration 220 in SL4.

Pilot G HQR=5

"I'll just call it not predictable because of the effect of the load, and it varies depending on how much you disturb it. I find that I'm trying very hard to enter any maneuver in a way so as to not start the load swinging. On a couple of my runs, one of them when I rolled out over the hover point, I did it just right so as I rolled out somehow I just damped the load right out and I couldn't believe how good I did that. And the next one was terrible, so it's hard to be consistent".

Pilot W HQR = 2

"It was one steady smooth transition into the final hover target with very little influence from the load on the aircraft, very, very small perturbations. Felt more than seen. And it didn't require the pilot to get into the loop, require myself to get into the loop to chase them around a little bit, they were stable, you know, they weren't divergent, I just pretty much stayed out of the loop and let the aircraft bounce around a little bit. Some undesirable oscillations in roll".

These comments suggest that the handling problems depend on how tightly the pilot is in the loop, which is classic for gain-margin limited systems. This can vary from run-to-run as noted by Pilot G, who down-rated the configuration based on lack of consistency. Pilot W had an entire series where he did not get into the loop tight enough to expose the gain-margin limit problem. He did see a

[1] The gain margin limiting was such that $\omega_{BW_{G1}}$ was the limiting parameter (e.g., see Figure 6).

hint of the roll problem, but not enough to downrate the configuration.

The Level 1 load coupling characteristics (high $\Delta\omega_L$) cause Configuration 220 to be very well behaved if the pilot backs out of the loop (load swing inherently stabilizes the motions). However, the Level 2 Bandwidth, due to gain-margin limiting in the lateral axis, makes the configuration susceptible to divergent oscillations if the pilot tries to aggressively control position or speed. The large spread in ratings (2 to 5) is indicative of a handling qualities problem that is highly dependent on pilot technique, which can vary from run-to-run.

These results expose the subtle nature of gain-margin limited systems. The lesson to be learned is that configurations that exhibit low bandwidth due to gain-margin, but are rated favorably by evaluation pilots, could indeed have major deficiencies. In such cases, the favorable ratings would be because the pilots were not sufficiently aggressive during the evaluations to expose the problem.

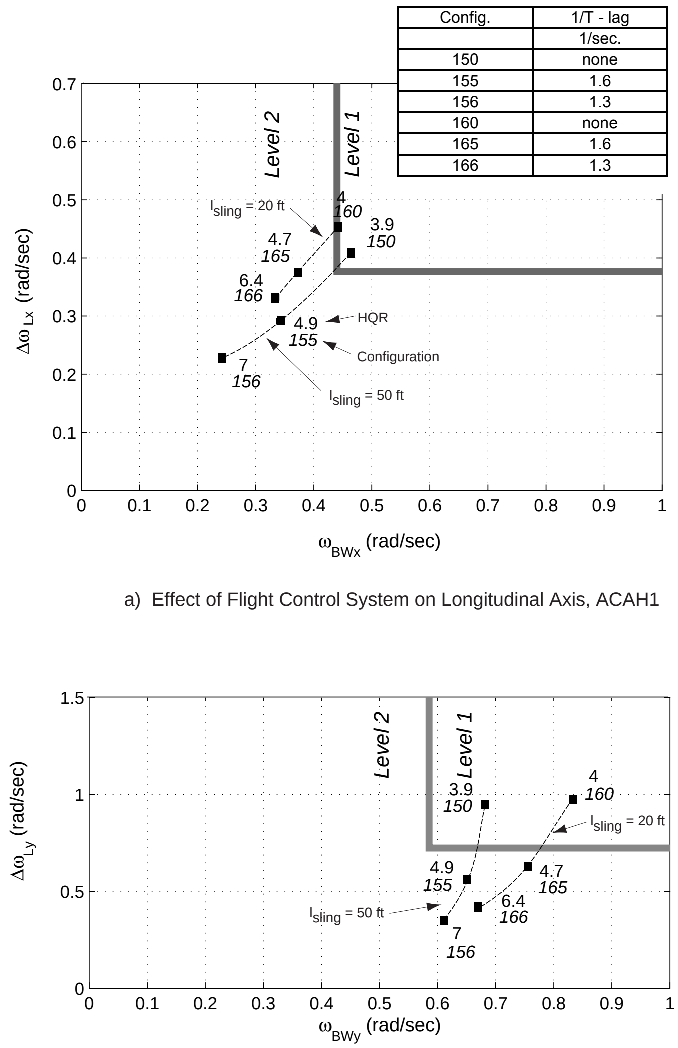
EFFECTS OF HIGHER ORDER FLIGHT CONTROL SYSTEM AND ATTITUDE BANDWIDTH

These cases were achieved by adding lag/lead compensation in front of the ACAH1 SAS of Case 160 (nominal 20 ft sling) and Case 150 (50 ft sling). The effect of additional lag compensation is seen to cause a decrease in the translational rate Bandwidth ($\omega_{BW_{\dot{X}}}$) and load coupling ($\Delta\omega_L$) in both the lateral and longitudinal axes in Figure 14.

In all the lag-lead cases the lead inverse time constant was $1/T_{LEAD} = 2.0\,\sec$.

The expected degradation in pilot ratings is seen to occur as the configurations move away from the Level 1/2 boundaries, deeper into the region of predicted Level 2 handling qualities.

These results illustrate that lags in the flight control system can have a significant effect on handling qualities with an external load. It was surprising to find this result because <u>the lag-lead compensation did not adversely affect the attitude Bandwidth frequency</u>. In fact, the original intent of configurations 165 and 166 was to achieve a similar attitude Bandwidth to the Level 1 baseline configuration (210) by adding a lag/lead to the high bandwidth configuration (160).



a) Effect of Flight Control System on Longitudinal Axis, ACAH1

b) Effect of Flight Control System on Lateral Axis

Figure 14 Effect of Lag-Lead in Flight Control System, ACAH1

Table 1 compares the load-on attitude bandwidth of 210 with the lag/lead configurations 165 and 166. It was surprising to find that even though the pitch and roll attitude bandwidths of 165 and 166 are equal to or greater than 210, the pilot ratings are noticeably degraded. This was one of the scenarios that led to an understanding that the Bandwidth of the attitude response is not a consistently valid handling qualities parameter for external load configurations.

Table 1 Effect of Control System Lag-Lead on Attitude Bandwidth and HQR (l_{sling} = 20 ft.)

Config	$\dfrac{(\frac{1}{T_{Lead}})}{(\frac{1}{T_{Lag}})}$	Pitch Attitude Bandwidth ω_{BW_θ} rad/sec	Roll Attitude Bandwidth ω_{BW_ϕ} rad/sec	Avg. HQR
210	No filter	1.35	1.09	4.0
165	(2)/(1.6)	1.44	1.25	4.7
166	(2)/(1.3)	1.36	1.17	6.4

The effect of sling length was studied for the lag-lead configurations. The data plotted in Figure 14 indicate that increasing the sling from 20 ft to 50 ft resulted in a small decrease in the translational rate bandwidth for most cases. The effect of sling length is compared to the effect of adding a lag-lead filter to the flight control system in Table 2.

Table 2 Comparison of Effects of Control System Lag and Sling Length

Config.	$\dfrac{(\frac{1}{T_{Lead}})}{(\frac{1}{T_{Lag}})}$	Sling length ft.	Avg. HQR
150	No filter	50	3.9
160	No filter	20	4.0
155	(2)/(1.6)	50	4.9
165	(2)/(1.6)	20	4.7
156	(2)/(1.3)	50	7.0
166	(2)/(1.3)	20	6.4

Here it is seen that the effect of increasing the sling length from 20 ft to 50 ft is negligible when compared to the effect of adding a lag/lead filter to the flight control system. This, even though the lag-lead does not have a significant impact on the attitude bandwidth (Table 1).

COMPARISON OF LATERAL AND LONGITUDINAL CRITERION BOUNDARIES

The reason that the roll axis boundaries are more stringent than the pitch axis is not completely understood. It is possible that the lateral task was more stringent than the longitudinal task for the precision hover. That is because the hover cues for the test course (see Reference 2 or 3) are somewhat more sensitive to lateral deviations than longitudinal deviations. Another possibility is that it is normal for helicopters to have significantly higher pitch inertia than roll inertia so that the pilots expect a more sluggish response in pitch.

SUMMARY AND CONCLUSIONS

Handling qualities criteria have been developed for cargo helicopters carrying externally slung loads in the degraded visual environment. If satisfied, these criteria provide assurance that the HQR will be 4 or better for operations in the DVE, and with a Load Mass Ratio of 0.33 or less. For lighter loads, flying qualities were found to be less dependent on the load geometry and therefore the significance of the criteria is less. For heavier loads, meeting the criteria ensures the best possible handling qualities, albeit Level 2 for Load Mass Ratios greater than 0.33.

Because the task of carrying a heavy load in the DVE with precision is inherently high workload, the Level 1-2 boundary has been relaxed from a Cooper Harper Handling Qualities Rating of 3.5 to 4.0.

Level 1 handling qualities in the DVE require a stability augmentation system (SAS) that provides an attitude-command-attitude-hold + altitude hold (ACAH+HH) Response-Type with no external load (see ADS-33D/E). These tests verified that this result applies to an even greater extent when carrying an external load. Therefore, the criteria developed herein only ensure Level 1 handling in the DVE if an ACAH+HH SAS is used.

The quantitative criteria developed in this report are based solely on piloted simulation. Some flight test verification is felt to be necessary before these criteria can be deemed sufficiently mature for inclusion into ADS-33. Until such verification can be accomplished, it is suggested that the quantitative criteria be used for design guidance.

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