Flight Evaluation of the New Handling Qualities Criteria Using the BO 105

Carl J. Ockier
Research Scientist
DLR, Institute for Flight Mechanics
Braunschweig, Germany

The Aeronautical Design Standard ADS-33C is a proposed US Army/Navy handling qualities specification for rotorcraft. The DLR at Braunschweig has conducted a partial evaluation of the quantitative forward flight criteria of the ADS-33C by flight testing an unaugmented BO 105 helicopter. This paper describes the flight test and evaluation methods used to obtain the parameters needed for determining handling qualities levels. Applicability and repeatability of the criteria are also discussed. Handling qualities parameters that augment existing handling qualities databases are provided. Finally, some problem areas are identified and improvements are proposed.

Introduction

The need for early consideration of handling qualities in the design process of modern military helicopters led to the publication of an Aeronautical Design Standard (ADS-33C, Ref. 1). Although ADS-33C has already been adopted as a specification for the LH helicopter, studies aimed at elaborating the database are still being conducted by US and international organizations (Refs. 2-10). ADS-33C is essentially a mission-oriented specification, with criteria depending on selected mission task elements, response types, and usable visual cue environments. ADS-33C is applicable to both augmented and unaugmented helicopters. It comprises both quantitative and qualitative criteria. The quantitative requirements are computed directly from the aircraft response to prescribed inputs; the qualitative requirements are determined for specific mission task elements (MTEs) from pilot ratings on the Cooper-Harper scale.

During the summer and fall of 1992, the DLR at Braunschweig conducted a series of flight tests to determine selected handling qualities parameters of the standard BO 105 helicopter in forward flight. The BO 105 is a light, twin-engine, multi-purpose helicopter without any flight control or stabilization systems. The BO 105 and its derivatives (PAH-1 and VBH) are used in both civil (transport, police, ambulance) and military (liaison, scout, anti-tank) applications. Although all mission task elements except air combat would apply to the BO 105, the ADS-33C evaluations were not limited to these mission task elements. The BO 105 is a single rotor helicopter with a hingeless, soft in-plane rotor system with four composite blades, and a very high equivalent hinge offset (of about 14 %). Because of this large hinge offset, the BO 105 has a high control power, an extremely high bandwidth, and is considered one of the most maneuverable helicopters flying today. As such, the BO 105 constitutes an exceptionally interesting testbed for ADS-33C compliance testing.

All flight tests were carried out in calm air at a forward flight speed of 80 kts. By limiting flying time to one hour, aircraft mass was maintained between 2200 and 2050 kg. All maneuvers were started from straight and level trimmed flight, and all inputs were performed manually by the pilot. For some experiments an onboard CRT was used that allowed the pilot to monitor his own control inputs. Because some experiments in ADS-33C take the aircraft to its limits, all tests were approached carefully to ensure that the maneuvers could be carried out safely. Data were sampled at 200 Hz and recorded digitally on a hard disk. Analog filtering was avoided as much as possible to prevent phase shift errors. The sole analog filter was applied to the control input signal and had a cut-off frequency of 80 Hz, which is well beyond the frequency range of interest.

This paper presents the major flight test results. Emphasis is placed on the flight test and evaluation techniques used, as well as on the applicability and repeatability of the ADS-33C criteria. The handling qualities parameters that were obtained in the process should serve to augment and validate existing handling qualities databases.

Bandwidth Criteria

The small amplitude short term criteria in forward flight relate to the aircraft's ability to perform small amplitude tasks such as closed-loop, compensatory tracking (Ref. 11). Requirements for the small amplitude attitude response are formulated in terms of bandwidth and phase delay. Bandwidth, ω_{BW}, and phase delay, τ_p, are determined from a frequency response (Bode) plot of the attitude response to pilot input (Fig. 1). The bandwidth parameter is a measure of the maximum closed-loop frequency a pilot can achieve with pure gain without threatening stability. Phase delay is a measure of how quickly the phase lag increases beyond the neutral stability frequency, ω_{180}. Aircraft with a large phase delay have been shown to be prone to pilot induced oscillations (PIOs).

Frequency responses were obtained from the aircraft response to frequency sweep inputs. Manual frequency sweeps were used as these are somewhat easier to perform and generally yield better results than synthetic sweeps. Special care was taken with all frequency sweeps to

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- *For rate command systems:*
  ω_{BW} is lesser of $\omega_{BW_{gain}}$ and $\omega_{BW_{phase}}$
- *Phase delay:*
  $$\tau_p = \frac{\Delta\Phi_{2\omega_{180}}}{57.3\,(2\omega_{180})}$$

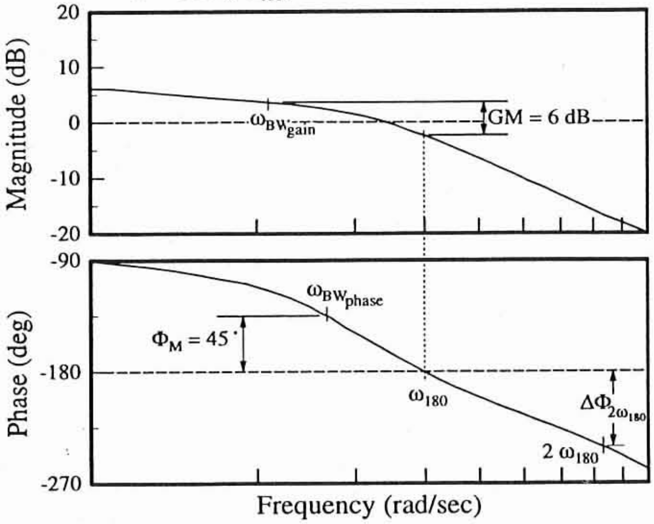

Fig. 1. Definition of bandwidth and phase delay.

avoid excitation of the aircraft resonant modes since that could lead to severe or even catastrophic damage. An improved frequency sweep method was used which consists of three consecutive sweeps without interruption of the data stream. Each individual frequency sweep lasted between 30 and 50 secs, and was preceded and followed by a trim condition. This improved frequency sweep technique allowed for the selection of a larger number of Fourier transform sub-records (windows) without compromising the low-frequency content of the resulting frequency response. Conditioned frequency responses were computed with the DLR program MIMO (Ref. 12). Selected window lengths were about 20-25 secs for pitch and roll attitude responses, and about 15 seconds for yaw responses. By using maximum overlapping of the data windows, this resulted in approximately 10 data windows per test run. To prevent side lobes and leakage, a von Hann weighting and windowing function was selected. No smoothing was applied to the resulting curves.

Frequency responses were taken from the integrated angular rates p, q, and r, rather than from the Euler angles ϕ, θ, and Ψ. This yielded better results at high frequencies (where the integrated rate measurements have a better resolution) and only slightly degraded results at low frequencies. The integration was performed in the frequency domain.

Pitch axis

Fig. 2 shows the bode plot of the pitch response (i.e. integrated pitch rate response) to a longitudinal cyclic input for two different experiments. As can be seen, both curves are smooth, indicating a small random error, and good consistency. Partial coherence is higher than 0.8 between 1 and 23 rad/sec, which covers the frequency range of interest. There is a small drop in coherence at about 16 rad/sec which has been associated with the non-linear coupled rotor-fuselage mode (air resonance mode). From Fig. 2, bandwidth was determined for each experiment separately as 2.5 and 2.8 rad/sec from phase margin criteria. Phase delay in the vicinity of neutral stability was determined at 79 and 75 msecs. The ADS-33C requirements, Fig. 3, clearly indicate Level 1 handling qualities in the pitch axis even for air combat MTEs, which is consistent with pilot evaluations of the standard BO 105 helicopter.

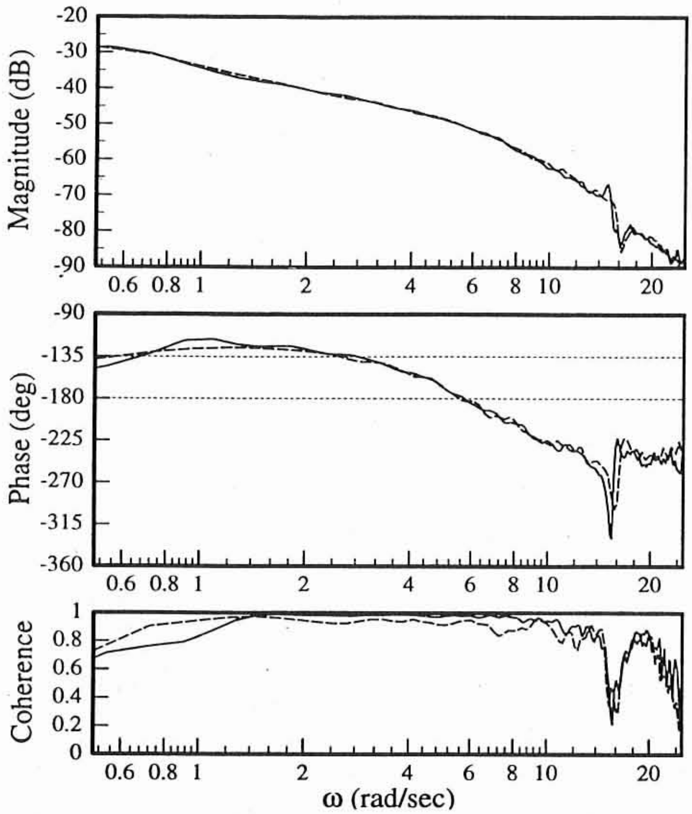

Fig. 2. Pitch attitude frequency response for two experiments.

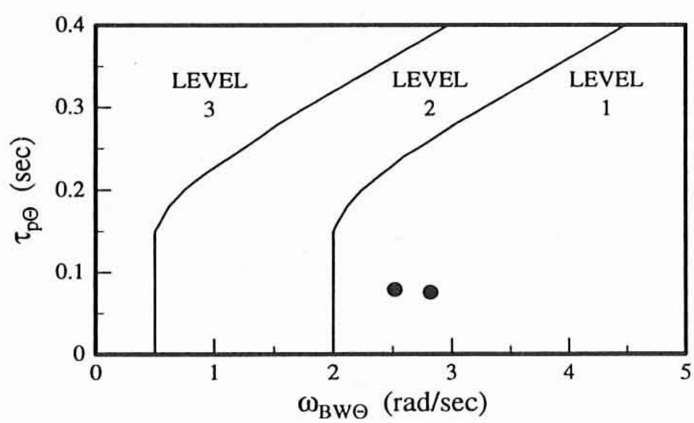

Fig. 3. Small amplitude pitch attitude criterion, forward flight, air combat MTE's.

Roll axis

The Bode plot of the roll response (i.e. integrated roll rate response) to lateral cyclic input is shown in Fig. 4, again for two different data sets. Both frequency response curves are smooth and consistent. Partial coherence is higher than 0.8 between 1 and 25 rad/sec, and is even approaching 1.0 over most of the frequency range of interest. As with the pitch response, there is a small drop of coherence at about 16 rad/sec, the frequency of the coupled rotor-fuselage mode. This is also reflected in the irregularity of the amplitude and phase curves. Bandwidth of the roll responses was determined at 5.5 and 6.1 rad/sec from phase and gain margin criteria, respectively. The relatively large spread in bandwidth is attributed to the flat frequency response curve in the bandwidth range. Time delay was calculated at 49 and 46 msecs. Handling qualities requirements, Fig. 5, show very clearly Level 1 handling qualities even for air combat MTEs. This is also true when the bound-

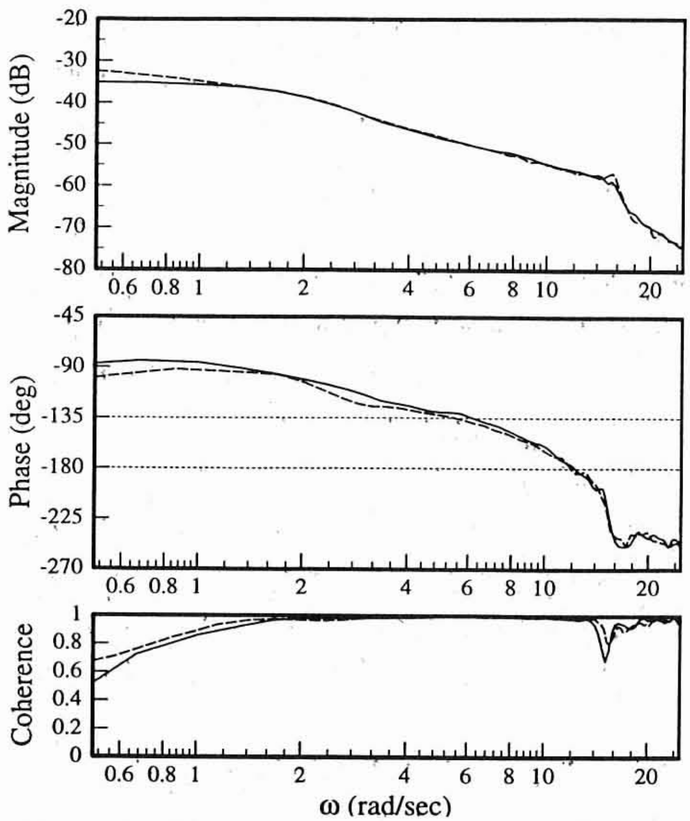

Fig. 4. Roll attitude frequency response for two experiments.

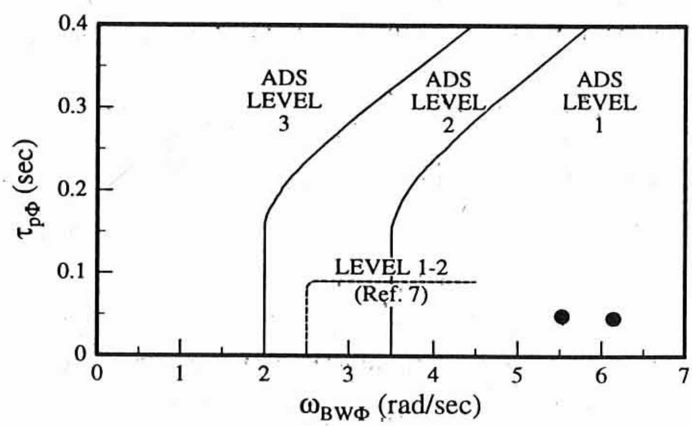

Fig. 5. Small amplitude roll attitude criterion, forward flight, air combat MTE's.

aries from Ref. 7 are used (dashed line).

Yaw axis

The Bode plot of the yaw response (i.e. integrated yaw rate response) to pedal inputs is given for two data sets in Fig. 6. Although the curves are still consistent, their appearance is not as smooth as in the previous examples. Also the partial coherence is significantly lower. This is attributed to the strong non-linearity of the yaw response and perturbations from the main rotor downwash. Similar results were obtained by Ham (Ref. 5) in his study of the OH-58D helicopter. Despite their poor coherence, the frequency responses were still considered usable for the determination of the ADS-33C criteria. Bandwidth was determined at 3.3 and 3.6 rad/sec from phase margin criteria. Phase delay was determined at 28 and 5 msecs. The large difference in phase delays is evidently due to the randomness in the frequency response in the range where

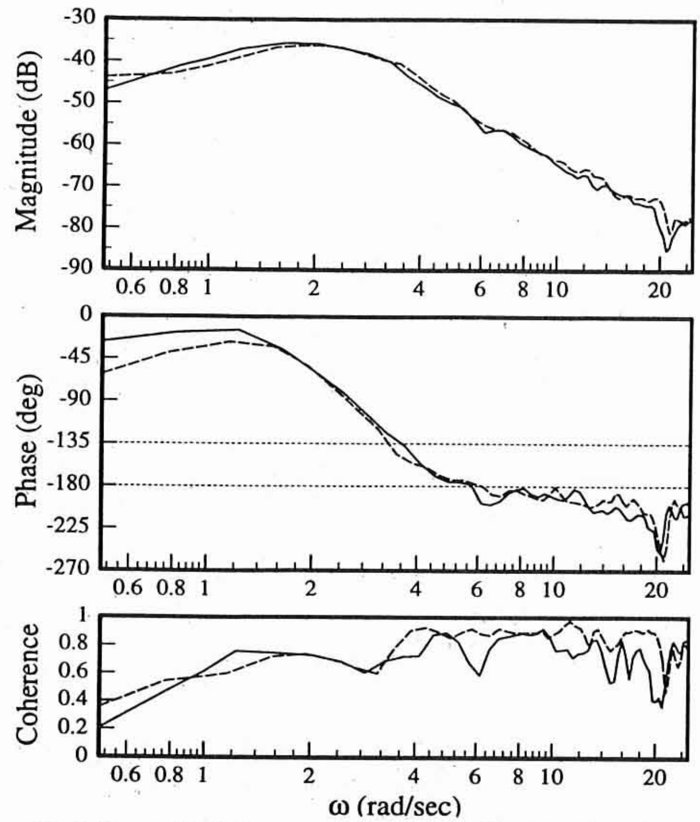

Fig. 6. Yaw attitude frequency response for two experiments.

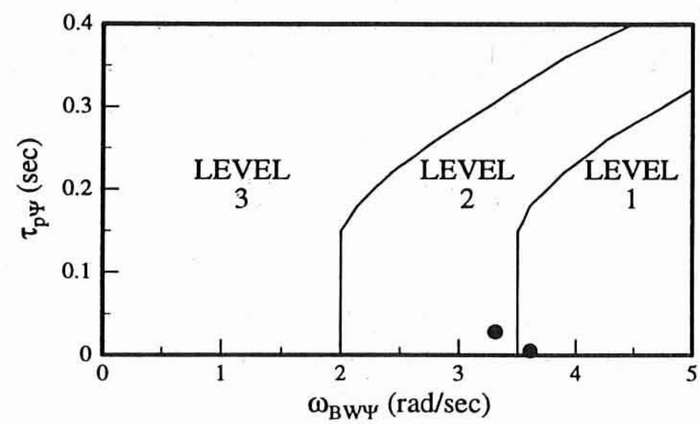

Fig. 7. Small amplitude roll criterion, forward flight, air combat MTE's.

phase delay is determined. ADS-33C criteria, Fig. 7, show the yaw response to be borderline Level 1 - Level 2 for air combat requirements.

From these results, it follows that when proper flight test and analysis techniques are used, consistent estimates of bandwidth and phase delay are possible, even with high bandwidth helicopters like the BO 105.

Longitudinal Criteria

Mid-term pitch oscillations

The mid-term pitch attitude response criterion places requirements on the damping of the oscillatory mode following a longitudinal pulse input. For fully attended operations with rate response type controllers, minimum damping must be as specified in Fig. 8.

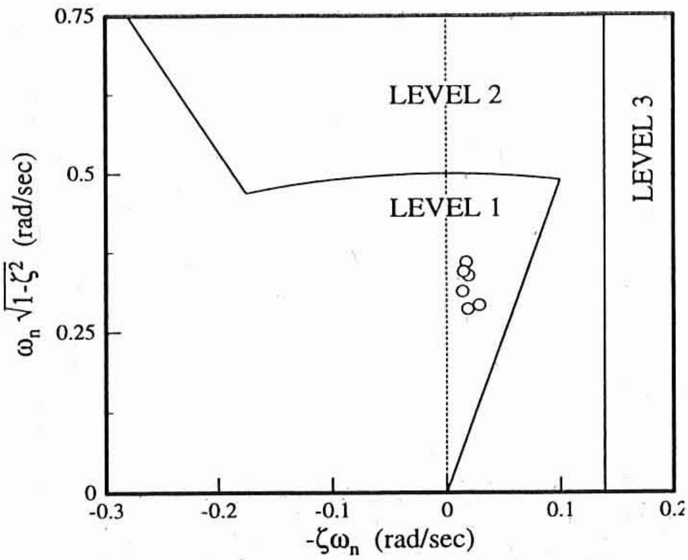

Fig. 8. Limits on mid-term pitch oscillations, fully attended operations, forward flight.

From straight and level trimmed flight, the phugoid mode was excited with a small longitudinal pulse input, after which the controls were returned to trim. The resulting free oscillation was recorded until recovery of the aircraft became necessary. From the time responses of the aircraft, the natural frequency, ω_n, and damping ratio, ζ, of the phugoid oscillation were obtained using a matching technique based on maximum likelihood parameter identification.

Average natural frequency and damping ratio were determined at 0.32 rad/sec and -0.06, respectively. This means the phugoid motion of the BO 105 is slightly unstable with a period of about 19.5 seconds and a time to double amplitude of about 37 secs. From Fig. 8 it follows that the BO 105 has Level 1 handling qualities for attended operations.

The mid-term pitch response criterion is a classical criterion in that it uses frequency and damping to determine handling qualities ratings. Determination of the parameters is straightforward and seems to provide consistent results.

Flight path control

The flight path control criterion measures the vertical rate response to a collective step input. It is a measure of how well the flight path can be controlled in maneuvers like landing approaches or contour flying. The criterion requires the vertical rate response to have a "qualitative first order appearance for at least 5 seconds following a step collective input". Compliance is tested through parameters estimated from an equivalent first order system with transfer function:

$$\frac{\dot{h}}{\delta_c} = \frac{K e^{-\tau_{\dot{h}} s}}{T_{\dot{h}} s + 1}$$

Where the gain K, the time delay $\tau_{\dot{h}}$, and the time constant $T_{\dot{h}}$ are to be estimated using a non-linear least squares time domain fitting method. For Level 1 handling qualities, the time delay must be less than 200 msecs and the time constant must be less than 5 seconds. For Level 2 handling qualities it is only required that the time delay be between 200 and 300 msecs. Further criteria are specified for the 'goodness of fit' of the estimation.

Direct measurement of the vertical rate with barometric instruments generally does not have the required resolution and/or introduces too much unknown dynamics to be usable for parameter identification. Therefore, the vertical rate had to be computed in two steps from acceleration and angular data. First, the aircraft velocity components, u, v, and w, were calculated using a flight path reconstruction technique (Ref. 13). This was necessary to overcome the inaccuracy and dynamics of the installed air data system. In a second step, the vertical velocity was calculated from the velocities and Euler angles using:

$$\dot{h} = u \sin\theta - v \sin\phi \cos\theta - w \cos\phi \cos\theta$$

Where $\dot{h}$ is positive during climb. For the estimation of time delays and constants the maximum likelihood software available at the DLR was used, rather than the methods proposed in the ADS-33C. It was hoped that this would avoid some of the pitfalls outlined by Howitt (Ref. 14).

Although ADS-33C specifies a collective step input for compliance testing, it is not indicated whether this input should be made with the other controls fixed, or if it should be tried to maintain the pitch angle, θ, constant. Therefore, both approaches were tested.

Fig. 9 shows a typical vertical rate response of the BO 105 to a collective step up with the other controls fixed. As can be seen, the response does not have a "qualitative first order appearance", as required for compliance testing. Instead, the BO 105 responds with a phugoid-type motion, with the largest contributions to the vertical rate coming from the forward velocity/pitch angle component, $u \sin\theta$, rather than from the vertical velocity component, $w \cos\phi \cos\theta$. This did not seem to be the intent of ADS-33C.

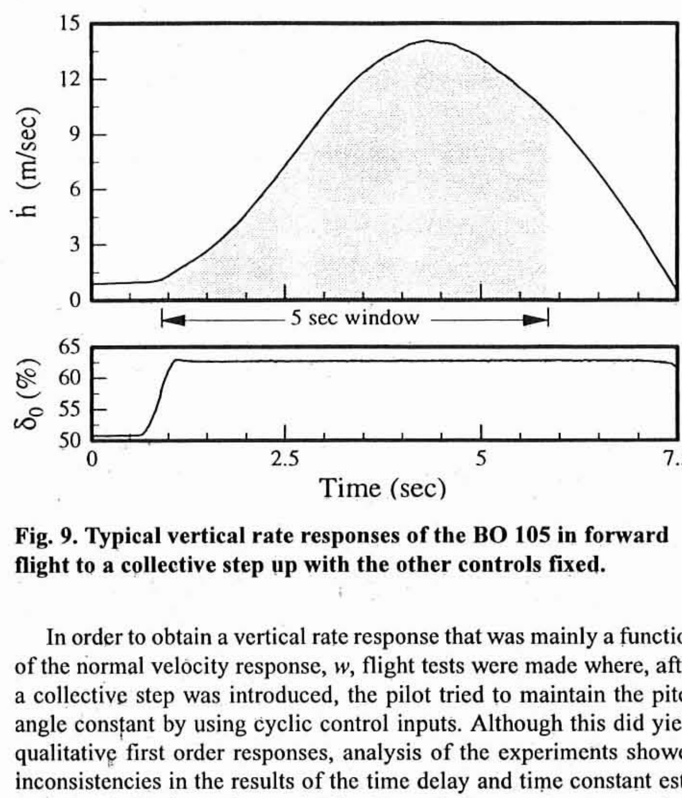

Fig. 9. Typical vertical rate responses of the BO 105 in forward flight to a collective step up with the other controls fixed.

In order to obtain a vertical rate response that was mainly a function of the normal velocity response, w, flight tests were made where, after a collective step was introduced, the pilot tried to maintain the pitch angle constant by using cyclic control inputs. Although this did yield qualitative first order responses, analysis of the experiments showed inconsistencies in the results of the time delay and time constant estimates. Fig. 10 shows the results for 15 vertical rate responses, each of which met the ADS-33C 'goodness of fit' criterion. For these responses, time delays ranged from -50 to 370 msecs, while the time constant was estimated between 0.6 and 2.3 secs.

Additional analysis of the vertical rate requirement showed that for systems with a time constant close to or larger than the 5 second limit, estimation of the time constant is very difficult. For such systems, the vertical rate does not reach a steady state within the observation window, and the gain, K, cannot be accurately estimated. Without a valid K, estimations of the time constant, $T_{\dot{h}}$, are arbitrary.

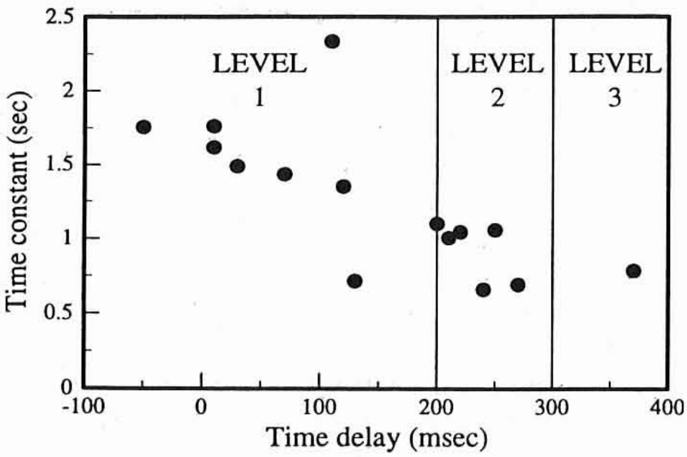

Fig. 10. Time delays and time constants as determined from 15 vertical rate responses, each of which met the ADS-33C 'goodness of fit' criterion.

ADS-33C does not specify the precise flight test procedure for the vertical rate response criterion. For unaugmented helicopters, using a collective step input with the other controls fixed will not produce a first order response, while trying to keep pitch angle constant seems to yield somewhat erratic results. It is therefore suggested that refinements to the flight path criterion be made with additional consideration given to methods for obtaining the criterion parameters.

Lateral-Directional Criteria

Moderate amplitude roll criteria

The moderate amplitude roll criterion pertains to the aircraft's agility or attitude quickness. It measures the ability to achieve rapid, moderately precise attitude changes as required in pursuit tracking. The criterion is based on two parameters which are defined in Fig. 11. These parameters are the ratio of the maximum roll rate to the peak bank angle change, $p_{pk}/\Delta\phi_{pk}$, and the minimum attitude change during transition from one bank angle to another, $\Delta\phi_{min}$. It is required that the given attitude changes be made "as rapidly as possible, without significant reversals in the sign of the cockpit control input relative to the trim position." Requirements for the moderate amplitude roll response criterion are shown in Fig. 12.

For the determination of the moderate amplitude criterion short duration pulse inputs were used. All inputs were made at maximum amplitude, as this produced the highest handling qualities levels. During the tests, no specific attitude was targeted, rather duration of the pulses

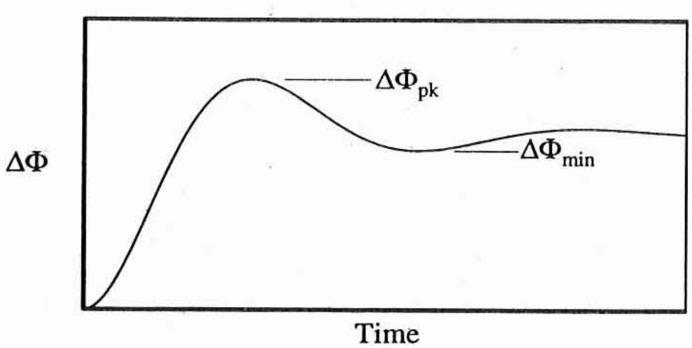

Fig. 11. Definition of the moderate amplitude criterion parameters.

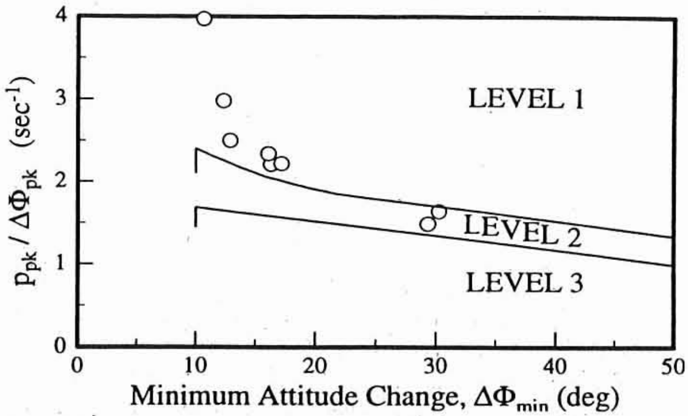

Fig. 12. Moderate amplitude roll attitude criterion, forward flight, air combat MTE's.

was varied to obtain different minimum bank angles. During early tests, it often proved difficult to obtain a value for $\Delta\phi_{min}$, as the bank angle response tended to drift back to zero. Experience taught, however, that careful trimming of the helicopter before the input, and releasing the stick after the input could eliminate this problem and produce usable responses.

From Fig. 12, comparison of the BO 105 characteristics with the ADS-33C requirement for air combat MTEs shows that the BO 105 has borderline Level 1 moderate amplitude roll characteristics. It can also be seen that all flight test data lie within a relatively narrow band, which indicates good repeatability.

Small amplitude roll oscillations

ADS-33C requires that any oscillations following a pulse controller input have a natural frequency, ω_n, and damping ratio, ζ, that meet the requirements of Fig. 13. Although not stated specifically, this requirement was assumed to apply to the Dutch roll response of the BO 105 and not to higher frequency oscillations such as those caused by rotor-fuselage modes.

Spike shaped lateral pulse inputs of various amplitude were used to excite the Dutch roll oscillation in the roll axis. Fig. 13 shows the re-

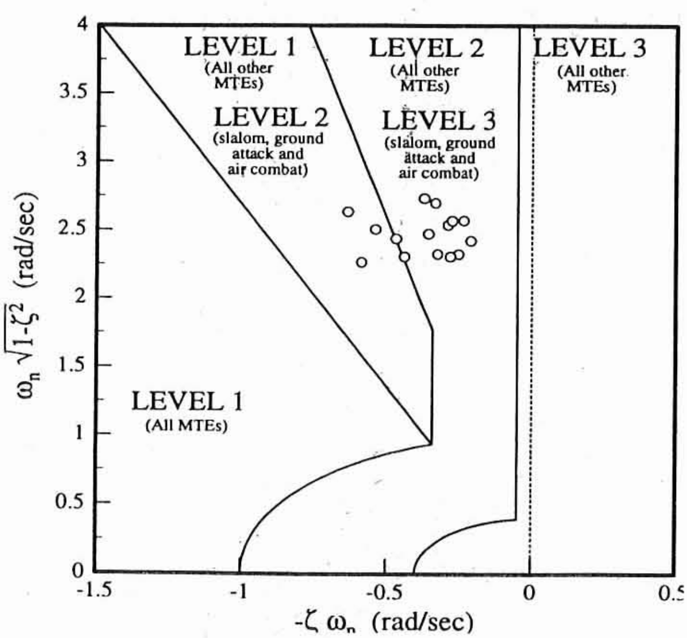

Fig. 13. Limits on roll oscillations in forward flight.

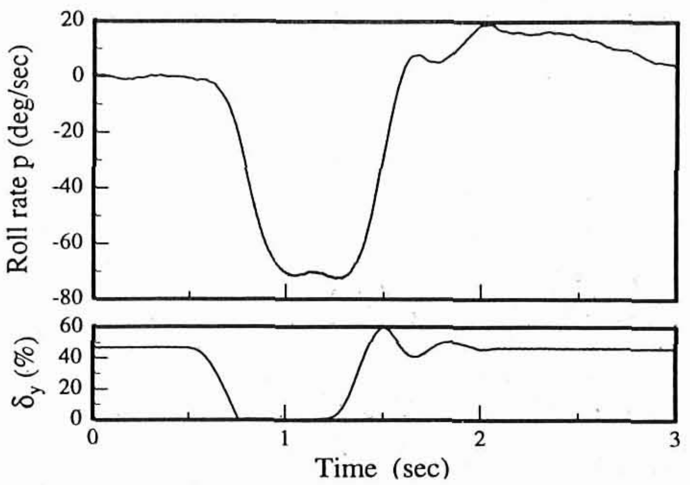

Fig. 14. Roll rate response to a maximum amplitude lateral pulse input.

sults for the BO 105. Average natural frequency and damping ratio of the Dutch roll mode were determined to be 2.44 rad/sec and 0.155, respectively.

Although determination of the small amplitude roll oscillation criterion is rather straightforward, it might be worth considering if different input types (e.g. a doublet input) cannot improve the rather poor excitation of the Dutch roll mode.

Large amplitude roll attitude changes

The large amplitude roll response criterion is essentially a measure of the available control power that would be required in emergency situations. It is defined in terms of maximum achievable roll rate in the case of rate response vehicles and in terms of maximum achievable bank angle when attitude response is used. For rate response systems, Level 1 handling qualities require a minimum roll rate of 50 deg/sec for all aggressive maneuvering tasks and 90 deg/sec for air combat MTEs.

Maximum lateral cyclic input was applied to achieve the maximum roll rate. Because of the dangerous attitudes that developed, such inputs could not be sustained. Fig. 14 shows the roll rate response to a full deflection stick input to the left. A short duration steady roll rate can be seen. From this, the maximum roll rate to the left for the BO 105 was determined to be about 72 deg/sec. Maximum roll rate to the right was found to be about 85 deg/sec.

The large amplitude roll criterion is determined easily from maximum amplitude lateral inputs. Starting the roll maneuver from a nonzero bank angle can give the roll rate some time to build up to its maximum, but that did not seem to be a necessity.

Lateral-directional oscillations

The criterion regarding lateral-directional oscillations requires the frequency, ω_n, and damping ratio, ζ, of the oscillatory (Dutch roll) motion following a pedal doublet to meet the specified minima.

Fig. 15 shows the results of the lateral-directional oscillations criterion as they were determined from yaw rate response. As can be seen, the BO 105 is considered Level 2 for all MTEs except slalom, ground attack and air combat. Average natural frequency, ω_n, is 2.44 rad/sec and damping ratio, ζ, is 0.162. This is almost identical to the natural frequency and damping ratio of the Dutch roll mode as calculated from the roll response to lateral pulse inputs.

The lateral-directional oscillation criterion provides results very similar to the results obtained from the small amplitude roll oscillation criterion. However, the pedal inputs seem to excite Dutch roll better than the roll pulses, so results from this criterion show less scatter than the

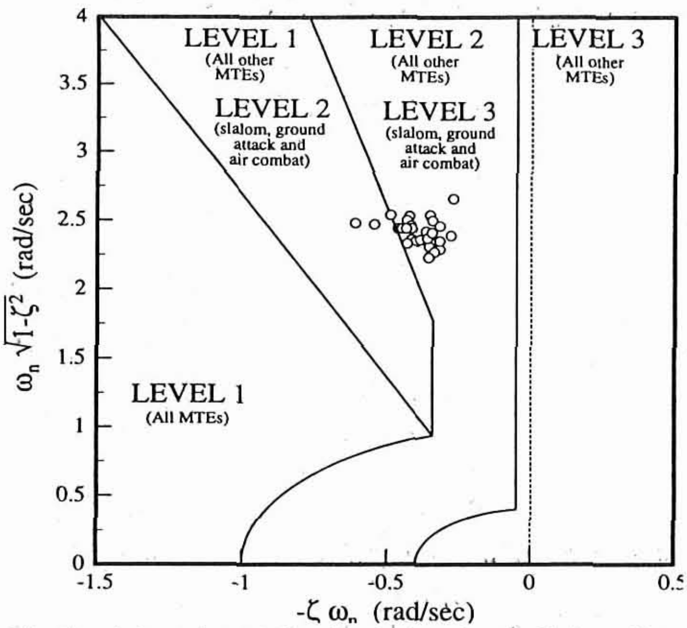

Fig. 15. Limits on lateral-directional oscillations in forward flight.

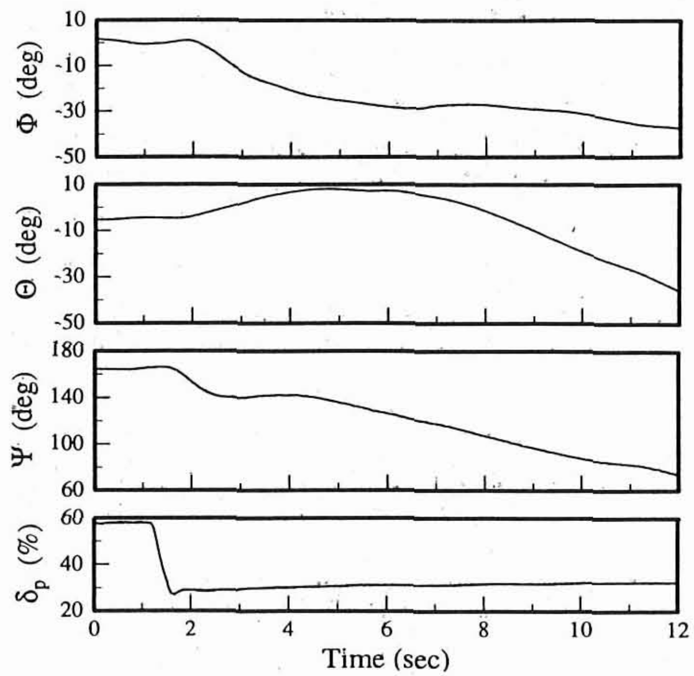

Fig. 16. Response of the BO 105 to an abrupt pedal input with all other controls fixed.

earlier results.

Large amplitude heading changes

The large amplitude yaw axis criterion in forward flight requires the minimum heading that can be obtained from a yaw control input, to be larger than 16 deg (or β_L, where β_L is the sideslip limit) for Level 1 handling qualities, 8 deg (or $1/2\,\beta_L$) for Level 2 handling qualities, and 4 deg (or $1/4\,\beta_L$) for Level 3 handling qualities. It is specified that this heading change be obtained from an abrupt pedal step input with all other cockpit controls fixed.

Fig. 16 shows the response of the BO 105 to an abrupt pedal input with all other controls fixed. Because of significant pitching and rolling, heading changes obtained with cyclic and collective controls fixed are less meaningful for unaugmented helicopters like the BO 105. For compliance testing, heading changes were obtained by applying maximum pedal inputs while keeping bank angle and pitch angle constant. In order to avoid errors resulting from incorrect bank angle corrections, sideslip angle was taken as a measure of heading change. The maximum sideslip angles that were obtained were about 33 deg to the left and 30 deg to the right.

Since unaugmented helicopters generally will not obtain a steady heading after a pedal input with the other controls fixed, it is suggested that helicopter pitch and roll attitude is maintained during the pedal step. It is also suggested that maximum sideslip angle change is used instead of heading change.

Roll-sideslip coupling

The roll-sideslip coupling criterion places requirements on the amount of coupling that can exist between roll and sideslip for moderate bank angle change maneuvers such as turn entry. Excessive roll-sideslip coupling makes precise flight path control difficult, increases pilot workload by placing additional demands on control coordination, and can in extreme cases lead to PIOs. The roll-sideslip criteria for rotorcraft are identical to the requirements for V/STOL aircraft (Ref. 15).

The way in which roll-sideslip coupling manifests itself is mainly a function of two parameters, the ratio of the amplitudes of the bank angle and sideslip angle envelopes of the Dutch roll mode, $|\phi/\beta|_d$, and the phase angle of the Dutch roll oscillation in sideslip following a lateral cyclic input, Ψ_β. For relatively low values of $|\phi/\beta|_d$, the Dutch roll motion appears mainly as a sideslip oscillation. When excitation of this sideslip by roll rate or lateral cyclic is excessive, handling qualities can be seriously degraded by such motions as an oscillation of the nose on the horizon during a turn, by a lag or initial reversal in yaw during a turn entry, or by difficulty in quickly and precisely acquiring a desired heading. For moderate values of $|\phi/\beta|_d$, the coupling of sideslip with ö causes relatively large oscillations, which can lead to difficulty in control. For extremely large values of $|\phi/\beta|_d$, the sensitivity of roll response to sideslip disturbances (from pedal inputs or atmospheric turbulence) may be so high that the helicopter flying qualities are seriously degraded.

The parameter, Ψ_β, is a measure of how well unwanted motions can be prevented through coordination of pedal inputs. If an aircraft is easy to coordinate during turn entry, the pilot may tolerate more roll-sideslip coupling.

The roll-sideslip criterion consists of two requirements: (1) a limit on bank angle oscillations, and (2) a limit on sideslip excursions during turn coordination. The bank angle oscillation criterion is directed at determining the ease of bank angle control for rotorcraft with moderate to high $|\phi/\beta|_d$ response ratios and low ζ_d. Experiments with fixed wing aircraft (Ref. 15) have shown that the degradation of handling qualities due to the excitation of the Dutch roll mode in roll is roughly proportional to the ratio of the amount of Dutch roll oscillation vs the mean bank angle, ϕ_{OSC}/ϕ_{AV}. Where ϕ_{OSC}/ϕ_{AV} is determined as follows:

$$\frac{\phi_{OSC}}{\phi_{AV}} = \frac{\phi_1 + \phi_3 - 2\phi_2}{\phi_1 + \phi_3 + 2\phi_2} \qquad (\zeta_d \leq 0.2)$$

$$\frac{\phi_{OSC}}{\phi_{AV}} = \frac{\phi_1 - \phi_2}{\phi_1 + \phi_2} \qquad (\zeta_d > 0.2)$$

with ϕ_1, ϕ_2 and ϕ_3 the bank angles at the first, second and third peaks following an impulse lateral cyclic input, and with ζ_d the damping ratio of the Dutch roll oscillation (as determined from the lateral-directional oscillation criterion). This leads to the handling qualities requirement shown in Fig. 17, where it should be noted that only the Ψ_β scale for positive dihedral (p leads β by 45 to 225 deg) is shown, as this is common in helicopters (Ref. 16).

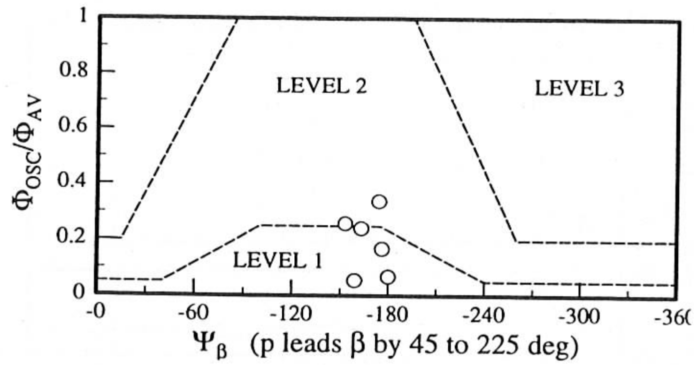

Fig. 17. Bank angle oscillation limitations.

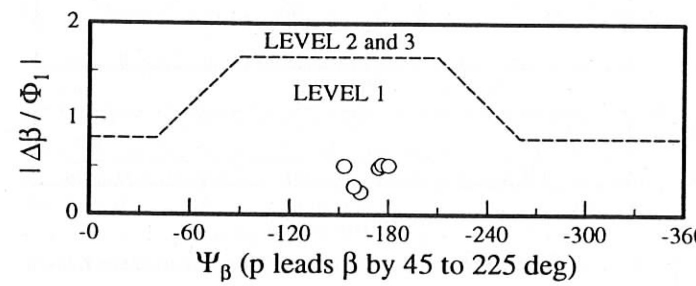

Fig. 18. Sideslip excursion limitations (boundary for $|\Delta\beta/\phi_1|$).

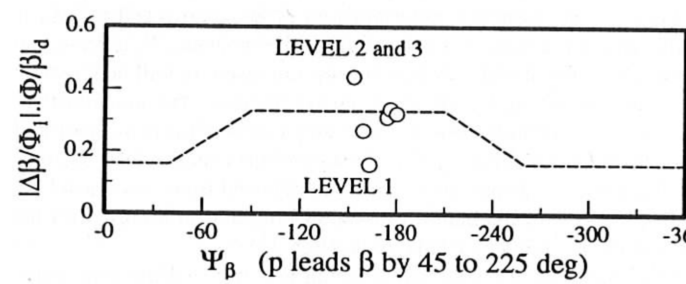

Fig. 19. Sideslip excursion limitations (boundary for $|\Delta\beta/\phi_1| \cdot |\phi/\beta|_d$).

The criterion on sideslip excursions during turn coordination is aimed at eliminating large sideslip angles as a result of lateral control inputs. The parameter $|\Delta\beta/\phi_1| \cdot |\phi/\beta|_d$ was used to correlate pilot rating with sideslip excursions. However, since this parameter becomes meaningless as $|\phi/\beta|_d$ approaches zero, a second parameter, $|\Delta\beta/\phi_1|$, was introduced as a measure of the amount of sideslip that occurs as a result of a given amount of bank angle change. $\Delta\beta$ is defined as the maximum change in sideslip within time $t_{\Delta\beta}$ from a lateral spike input, where $t_{\Delta\beta}$ is the lesser of 6 seconds and half the Dutch roll period. Figs. 18 and 19 show the sideslip excursion requirements which are again given as a function of Ψ_β. For rate command systems, both criteria must be determined from the response to a lateral pulse input.

Spiked lateral control inputs were used to measure roll-sideslip coupling. Measurement of the sideslip angle, as obtained from the air data system, was found to be too noisy to be used for analysis. Therefore, flight path reconstruction techniques (Ref. 13) were used to obtain an

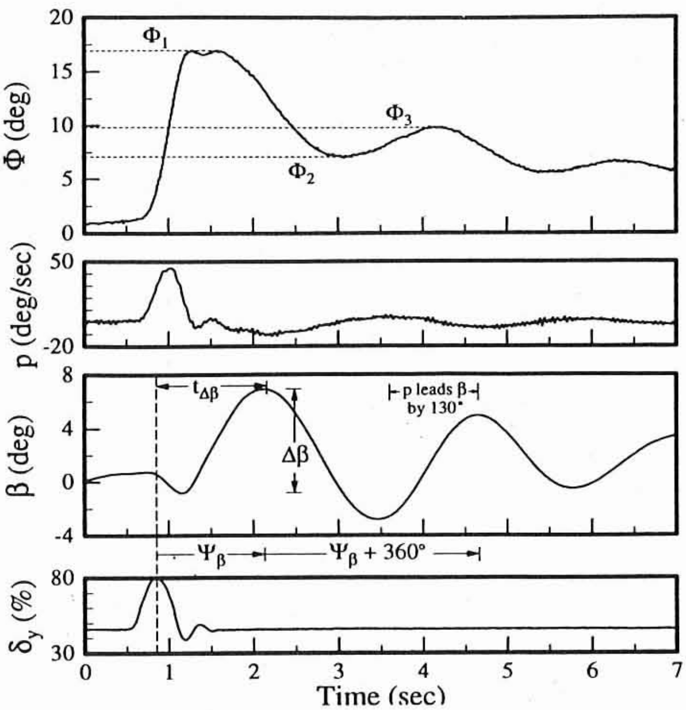

Fig. 20. Definition of the roll-sideslip coupling parameters from a measured lateral pulse response.

estimate of the sideslip angle.

Fig. 20 shows a time response of the BO 105 to a lateral step input. From this time response, determination of $|\phi_{OSC}/\phi_{AV}|$ and $|\Delta\beta/\phi_1|$ is rather straightforward. The calculation of the parameter Ψ_β leaves some ambiguity since it assumes that the sideslip response will be a perfect periodic oscillation, which is not always the case. The most difficult parameter to obtain is the ratio of the amplitudes of the bank angle and sideslip angle envelopes, $|\phi/\beta|_d$. Because of the exponentially decreasing bank angle, this parameter had to be obtained from curve matching with a maximum likelihood estimation program, in accord with the procedure described by Chalk, *et al*, (Ref. 17).

The bank angle oscillation criterion assumes that the bank angle response to a lateral pulse input consists of a zero order roll response and a Dutch roll oscillation. As can be seen from Fig. 20, the BO 105 response is much more complex, containing a second order roll/flap mode, a spiral mode, and interaxis coupling effects. Furthermore, this motion is very sensitive to atmospheric disturbances. Therefore, the roll angle response contains a number of uncertainties that lead to the large scatter in the data of $|\phi_{OSC}/\phi_{AV}|$ (Fig. 17). As could be expected from the low Dutch roll damping ratio, the roll oscillation requirement is borderline Level 1.

The parameter $|\Delta\beta/\phi_1|$ also shows some degree of uncertainty (Fig. 18) which is attributed to the non-linearity of the response and to the sensitivity of sideslip to small perturbations. The parameter $|\phi/\beta|_d$, although very difficult to determine, showed slightly less scatter in its results. However, the product of the two parameters $|\Delta\beta/\phi_1|\,|\phi/\beta|_d$, again shows scatter which extends beyond the level boundaries (Fig. 19).

The roll-sideslip criteria used by ADS-33C are slightly modified fixed wing requirements (Ref. 17). For helicopters, they seem difficult to measure and interpret. It is suggested that the roll-sideslip criteria are subjected to a critical review. This review may start with, but should not be limited to, reviewing the recent modifications to the fixed wing requirements (Ref. 18). In these requirements, the criterion for $|\Delta\beta/\phi_1|\bullet|\phi/\beta|_d$ was eliminated, and the roll oscillation requirement was replaced by the Dutch roll requirement.

Interaxis coupling criteria

Collective to pitch attitude coupling

The criterion for collective to attitude coupling is separated in two parts: (1) small collective inputs of less than 20 % of full control, and (2) large collective inputs of more than 20 % of full control. The parameter which determines the criterion is the absolute value of the ratio of the peak change in pitch attitude to the peak change in normal acceleration, $|\theta_{pk}/n_{z,pk}|$, that occurs "within the first 3 seconds following an abrupt change in collective." For small collective steps, $|\theta_{pk}/n_{z,pk}|$ must be less than 3.0 deg sec^2/m for Level 1 handling qualities. For large collective steps, $|\theta_{pk}/n_{z,pk}|$ must be less than 1.5 deg sec^2/m in the up direction and less than 0.76 deg sec^2/m in the down direction for Level 1 handling qualities.

Collective steps with the other controls fixed were performed to measure collective to attitude coupling. Only small collective steps (< 20 %) could be sustained for 3 seconds. Performing collective steps of more than 20 % of full authority was not possible because of rotor speed requirements and because of the attitudes that developed.

Fig. 21 shows the results of the collective to attitude coupling criterion for small collective inputs. As can be seen, the BO 105 has Level 2 collective to attitude coupling handling qualities. There are no notable differences from the direction of the collective step, nor does there seem to be a strong effect of step amplitude.

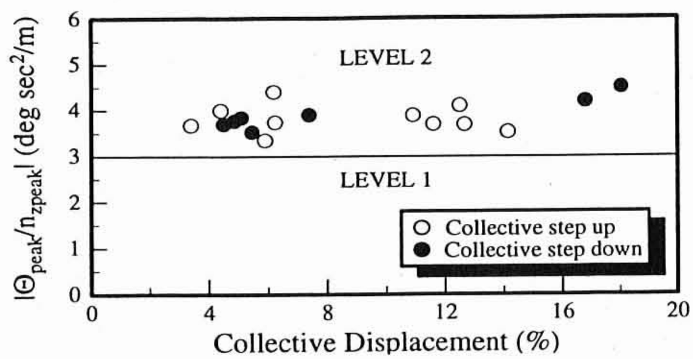

Fig. 21. Collective to attitude coupling criterion for forward flight.

Roll-to-pitch and pitch-to-roll coupling

The cross coupling criterion provides a measure of the degree of cross coupling between the longitudinal and lateral directional responses. The criterion is defined in terms of the ratio of the peak off-axis response to the peak on-axis response, i.e. θ_{pk}/ϕ for roll to pitch and θ_{pk}/ϕ for pitch to roll. From consultation with the authors of ADS-33C it was learned that the peak off-axis response should be measured within 4 seconds following an abrupt longitudinal or lateral cyclic step input, and that the peak on-axis response must be measured after 4 seconds. For determination of the handling qualities, roll to pitch and pitch to roll coupling have the same requirements. Coupling must be less than ±25 % for Level 1 handling qualities, and less than ±60 % for Level 2 handling qualities. This equality between roll to pitch and pitch to roll, although valid for hover, does not reflect reality in forward flight, where, for unaugmented helicopters, pitch to roll is generally a lot stronger than roll to pitch.

Longitudinal and lateral cyclic steps with other controls fixed were performed. Although it is specified that the criterion be evaluated for input magnitudes up to those required for aggressive maneuvers such as slalom, pull-up/push-over, and air combat, only relatively small steps

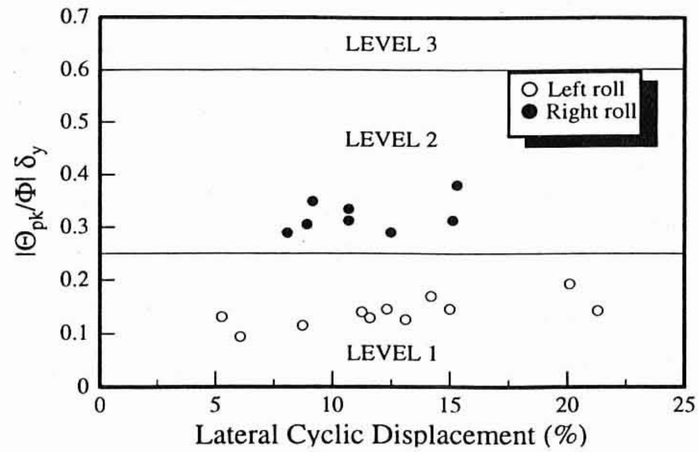

Fig. 22. Roll to pitch coupling direction.

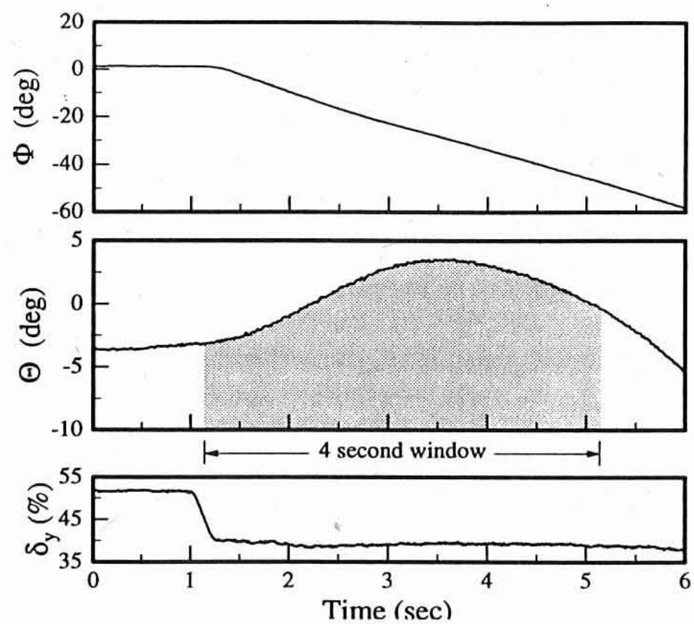

Fig. 23. Typical BO 105 coupling response to a lateral step input to the left.

could be maintained safely for 4 secs.

Fig. 22 shows the measured roll to pitch coupling. There is a noticeable difference between coupling during left and right rolls. Fig. 23 shows the time history of a roll input to the left. As can be seen, the helicopter initially pitches nose up and then drops its nose, causing the pitch attitude to peak well before reaching four seconds. This results in significantly lower coupling rates for rolls to the left than for rolls to the right, where the initial pitch rate is not reversed. However, BO 105 pilots claim they notice no significant differences in coupling between rolling to the left and to the right. Further study indicated this difference was mainly a result of the large resulting bank angles and turn coordination effects. Using a shorter window, could bring the coupling parameters back in line with the pilot observations. Average coupling rate of the BO 105, calculated from right rolls only, is about 30 %.

Fig. 24 shows the measured pitch to roll coupling. Pitch to roll coupling was determined at about 125 % (i.e. a pitch input causes more roll than pitch).

When handling qualities levels are considered, roll to pitch coupling has Level 2 handling qualities, whereas pitch to roll has very severe Level 3 handling qualities. This follows from the equality of the roll to pitch and pitch to roll criteria in forward flight. The severe Level 3

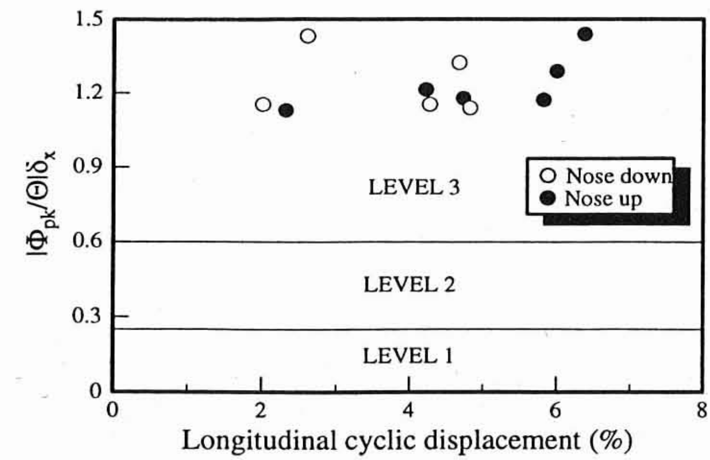

Fig. 24. Pitch to roll coupling criterion.

pitch to roll handling qualities could not, however, be substantiated by the pilots.

The cross coupling criteria, as they were defined by the authors of ADS-33C, do not seem to produce the desired results. The use of a 4 second step input made it impossible to evaluate the required large amplitude inputs due to extreme attitudes. This led to an inequality between left and right roll response that was not corroborated by the pilots. Also the equality of the criteria in forward flight should be studied further.

Conclusions and Recommendations

Aeronautical Design Standard ADS-33C shows a significant improvement over the original military specification for rotorcraft handling qualities, MIL-H-8501A. Its qualitative requirements should provide an excellent tool for the prediction and evaluation of handling qualities, especially during design and early flight testing phases. This paper has presented the results of an evaluation of the handling qualities of the BO 105 in forward flight. Flight test techniques and evaluation methods used for the determination of the qualitative handling qualities parameters were presented. For several ADS-33C requirements, robustness of the criterion was demonstrated by showing good repeatability of the experiment. There remain, however, a few recommendations to be made:

1) The flight path control criterion in forward flight should be refined with consideration given to repeatability of the experiment and unambiguous determination of the parameters.

2) Using cockpit controls to keep bank and pitch angle constant should be allowed for the determination of large amplitude heading changes.

3) It should be investigated if the mid-term roll oscillation criterion, the roll-sideslip criterion, and the lateral-directional oscillations criterion, all of which are concerned with the effects of the Dutch roll motion, cannot be combined to form fewer criteria that are easier to determine.

4) The equality of the requirements for roll-to-pitch and pitch-to-roll coupling should be re-evaluated, as should the use of a 4 second step input.

5) Although most of the experiments are very repeatable, it is recommended that all criteria be evaluated from average values determined from a number of consistent experiments. This would avoid inaccurate interpretations of flight test data influenced by small perturbations.

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