AN INVESTIGATION OF THE USE OF BANDWIDTH CRITERIA FOR ROTORCRAFT HANDLING-QUALITIES SPECIFICATIONS

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Abstract

The objective of this study was to investigate bandwidth concepts for deriving rotorcraft handling-qualities criteria from data obtained in two simulator experiments conducted at the Aeromechanics Laboratory. The first experiment was an investigation of the effects of helicopter vertical-thrust-response characteristics on handling qualities; the second experiment investigated the effects of helicopter yaw-control-response characteristics. In both experiments, emphasis was on low-speed nap-of-the-Earth (NOE) tasks. The results from the thrust-response simulation indicate the open-loop vertical velocity to collective $\dot{h}/\delta_c$ bandwidth is greatly influenced by vertical damping. For the task investigated, Level 1 handling qualities may require an open loop bandwidth greater than approximately 0.5 rad/sec for vertical damping of $-0.25\ sec^{-1}$ and approximately 0.75 rad/sec for damping of $-0.65\ sec^{-1}$. These results imply that for the thrust response, criteria based on the open-loop $\dot{h}/\delta_c$ bandwidth are not sufficient to ensure good handling qualities. The results from the yaw-response simulation indicate that an open-loop bandwidth of at least 2.5 rad/sec is required for the deceleration task, that a bandwidth of at least 3 rad/sec is required for the NOE and hover turn tasks, and that a bandwidth of at least between 2.5 and 4 rad/sec is required for the air-to-air target acquisition task. Yaw-response closed-loop bandwidth analysis showed a high correlation with the open-loop analysis and may be useful in predicting the relative merits of a configuration before going to a piloted simulation.

Introduction

There is a major effort under way to revise and update the general specification for handling qualities of military rotorcraft.[1] The current U.S. military rotorcraft-handling-qualities specification, MIL-H-8501A (Ref. 2), is a 1961 revision of a 1952 document. This specification contains many criteria that are inadequate for design guidance or flight testing. New or updated design criteria should be developed and substantiated to provide data for the new specification. These revised criteria must account for the numerous demands on the pilot of an advanced military rotorcraft. These demands will vary, depending on the mission and task and on the environment in which they must be flown. For example, a pilot flying an attack helicopter nap-of-the-Earth (NOE) at night under adverse weather conditions will be subject to different demands, which imply different aircraft design requirements, than a pilot flying a cargo helicopter in clear day conditions. To aid in providing data for mission-oriented handling-qualities criteria, the analysis and correlation associated with a proposed design criteria, called bandwidth, was applied to the results of two helicopter simulations. These piloted simulations, conducted by the U.S. Army Aeromechanics Laboratory at NASA Ames Research Center, investigated the effects of helicopter thrust- and yaw-response characteristics on handling qualities for NOE flight tasks.

The following sections describe the bandwidth concepts as applied in open- and closed-loop analyses; the piloted simulations, including the conduct and variables of the thrust- and yaw-response simulations; the results of applying the bandwidth analysis; and the conclusions and recommendations.

Bandwidth Concepts

Bandwidth is a qualitative measure of the input-to-output response of a dynamic system. Since it is a measure of the system input-to-output response, multi-parameter changes within the system should be captured. This phenomenon makes bandwidth an attractive criterion. Bandwidth analysis is conducted in the frequency domain and results in a fundamental measure of the ability of the system output to follow the system input. A higher system bandwidth reflects a faster and more predictable aircraft response to control inputs. The input and output quantities selected to define the system bandwidth are those

Presented at the International Conference on Rotorcraft Basic Research, American Helicopter Society, Research Triangle Park, North Carolina, Feb. 19-21, 1985.

most appropriate to the task being evaluated; for example, heading regulation involves rudder pedals as the input and yaw angle as the output. The bandwidth hypothesis[3] originated from the idea that the pilot's evaluation of aircraft handling qualities is dominated by the response characteristics of the aircraft when it is operated in a closed-loop tracking task. That is, the pilot's capability to make rapid and precise control inputs to minimize errors and thereby improve closed-loop tracking performance dominates his evaluation.

The classical definition of closed-loop bandwidth[3] is the frequency at which the Bode amplitude is 3 dB less than the steady-state amplitude of the system (see Fig. 1). Note that for a K/s aircraft response characteristic, the bandwidth frequency (ω_{BW}) and the inverse of the system time-constant ($1/T$) are identical.

Open-Loop Bandwidth

Since the open-loop crossover frequency is equal to ([illegible]) for high-order systems approximately equal to the classical closed-loop bandwidth, the definition of bandwidth and crossover frequency are equivalent. That is, the open-loop bandwidth is defined (from Ref. 3) as the crossover frequency for a simple, pure gain pilot with a 45° phase margin or a 6 dB gain margin, whichever frequency is lower. For example, the frequency for neutral stability, ω_{NS}, is observed on the phase curve of a Bode plot. Note that typically the output quantities selected to define the system bandwidth, as related to a vertical-axis and yaw-axis tracking task, are altitude and yaw angle. For convenient application of the closed-loop bandwidth analysis, the open-loop bandwidth criterion is applied to both translational and angular rate control responses. Since these output responses are one integration away from altitude and yaw angle, the margins are measured using 90° of phase angle as a reference (Fig. 2). The frequency for which a 45° phase margin exists is defined as $\omega_{BW_{PHASE}}$. The frequency corresponding to an amplitude ratio that is 6 dB less than the amplitude ratio at neutral stability is denoted as $\omega_{BW_{GAIN}}$. The bandwidth ω_{BW} is the lesser of the two frequencies, $\omega_{BW_{PHASE}}$ and $\omega_{BW_{GAIN}}$.

Closed-Loop Bandwidth

A closed-loop bandwidth analysis using a simplified pilot model was also investigated using the techniques defined in Ref. 4. The intent of this analysis was to take into account the closed-loop nature of the tracking task conducted by a human pilot represented by a gain and an effective time delay. This model represents a "comfortable" pilot who is not providing any lead or lag compensation for deficiencies in the vehicle dynamics. The objective of this analysis is to determine the maximum obtainable bandwidth. The procedure for the pilot-in-the-loop analysis is as follows:

1) After obtaining the characteristic transfer function for the aircraft, for example, $\dot{\psi}/\delta_P$, it is combined with the pilot model (Fig. 3). The assumed form of the pilot's transfer function was $P(s) = K_\psi e^{-\tau s}$, where K_ψ is the pilot gain, τ is the reaction time delay, and s is the Laplace operator. For $e^{-\tau s}$, the Padé approximation was used with the initial value of τ set to 0.3 sec, representative of the human neuromuscular time delay.

2) The pilot gain K_ψ was adjusted to achieve a gain of 0 dB at the specified crossover frequency. For the yaw response, the crossover frequency was 3 rad/sec (Fig. 4). The system was then checked for stability, that is, the phase margin was ±30°, and the gain margin was ±4 dB.

3) The loop was closed around the system in step 2, and the gain $K_\psi/K_{\dot{\psi}}$ and an integrator were combined (Fig. 5). The $K_\psi/K_{\dot{\psi}}$ gain was adjusted to achieve a maximum gain and phase margin of 4 dB and 30°, respectively (Fig. 6).

4) The outer-loop was finally closed around the system in step 3 to obtain the system shown in Fig. 7. A Bode plot was obtained of this closed-loop system, and the bandwidth was determined. For the yaw response experiment, the closed-loop bandwidth was defined as the frequency at which there was either a 3 dB amplitude ratio change or a 90° phase change, whichever was less (Fig. 8).

Piloted Simulation Studies

The bandwidth concepts were applied to two helicopter simulator experiments designed and performed by the U.S. Army Aeromechanics Laboratory at Ames Research Center. These piloted, ground-based simulations were conducted on the Ames Vertical Motion Simulator (VMS) (Fig. 9). The simulator cab was configured to include a typical helicopter instrument panel and controllers. The visual display consisted of a computer-generated image (CGI) scene presented on four windows, furnishing the pilot with a 28° by 120° field of view above the instrument panel; in addition, there was a 29° by 40° right-hand chin-window scene.

Thrust-Response Simulation

The thrust-response simulation studies were performed on the VMS using a ten-degree-of-freedom, nonlinear, full-force mathematical model termed ARMCOP (Ref. 5). Aural cueing of the rotor speed (rpm) fluctuations and blade slap, a visual display of rotor speed, and an overspeed and underspeed warning light were provided to the pilot. The evaluation task (Fig. 10) consisted of two phases: 1) a 40-knot dolphin, or hedge-hopping, phase, and 2) a quick-stop and bob-up/bob-down phase. Three Army and three NASA test pilots served as evaluation pilots. The pilots used the Cooper-Harper Rating Scale[6] to assess the effects of height (or flight path) control and rotor speed control on handling qualities. Each phase of the evaluation task was rated separately.

The Cooper-Harper (C-H) pilot rating scale is structured into three distinct groups or levels. Level 1 corresponds to C-H pilot ratings of 1, 2, and 3; Level 2 corresponds to C-H pilot ratings of 4, 5, and 6; Level 3 to C-H pilot ratings of 7, 8, and 9. Level 1 handling qualities are clearly adequate for the mission task; Level 2 handling qualities are adequate to accomplish the mission task, but some increase in pilot workload or degradation in mission effectiveness exists; and Level 3 handling qualities are such that the aircraft can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate or both.

The primary variables in this study were those which affect the power-system response time. They were the engine-governor response time and the rotor inertia. Other variables were helicopter vertical damping, collective control sensitivity, excess power available, and the requirement that the pilot maintain rotor speed within specified limits. The variations in engine-governor response, rotor inertia, and vertical damping provided the basis for the bandwidth analysis. For the purposes of this paper the engine-governor response characteristics are categorized as slow, intermediate, and fast. Likewise, the values of rotor inertia are categorized as light, medium, and heavy. The two values of vertical damping Z_w were investigated: $-0.25\ sec^{-1}$ and $-0.65\ sec^{-1}$.

Details of these configurations along with C-H pilot rating results and conclusions for all the variables may be found in Ref. 7. The following is a conclusion from Ref. 7:

> Increasing rotor inertia and engine-governor time constant will decrease power-system natural frequency, but for the simulated tasks, will affect handling qualities in different ways: increases in governor time constant can significantly degrade the handling-qualities rating, but increases in rotor inertia have only a minor and desirable effect on handling qualities. These two parameters must, therefore, be treated independently in handling qualities requirements.

It was this conclusion that prompted interest in the bandwidth hypothesis with the hope that these two opposing effects would collapse into one so that a unique parameter (bandwidth) could be used to characterize good handling qualities.

Yaw-Response Simulation

The yaw-control simulation studies were conducted using a small-perturbation helicopter model[8] which has the full nonlinear set of kinematic terms in seven-degree-of-freedom (DOF) equations of motion. (A rotor speed DOF was included.) The evaluation task (Fig. 11) consisted of NOE flight and deceleration, low- and high-maneuvering turns, and an air-to-air target-acquisition and tracking task. Four test pilots served as evaluation pilots. The pilots used the C-H rating scale to assess the effects of directional rate damping N_r, directional control sensitivity N_{δ_p}, and weathercock stability N_v. Each phase of the evaluation task was rated separately. Details of these configurations along with pilot rating results and conclusions are given in Ref. 9. Three points were noted in the evaluations:

1) Higher values of directional gust sensitivity N_v require greater values of yaw damping N_r, to achieve satisfactory handling qualities for NOE flight, deceleration, and hover turns.

2) Performance measures, when used alone, can give misleading information regarding aircraft handling qualities.

3) N_r is not a sufficient parameter for fully defining acceptable handling qualities for the air-to-air target-acquisition task; control-response criteria are also needed, especially for SCAS configurations.

The bandwidth analysis was applied to the various yaw-response configurations to determine if bandwidth would capture these multiparameter effects in a single parameter.

Results of Applying Bandwidth Concepts to Simulation Studies

The results of applying the bandwidth analysis to the thrust-response and a yaw-response simulation results are discussed. The correlation of bandwidth with the pilot ratings is presented together with recommendations for minimum values of system bandwidth to meet handling-qualities requirements for the tasks investigated.

Thrust-Response Simulation

To assist in characterizing the various configurations evaluated by the pilots, frequency-response data were collected. This analysis consisted of 1) applying a single frequency, sinusoidal collective control input, δ_c, to the simulated aircraft; 2) recording this input and selected vehicle output states, such as vertical velocity $\dot{h}$; 3) repeating this procedure with several frequencies, between 0.1 and 10.0 rad/sec; 4) measuring the amplitude ratio and phase-angle shift associated with each frequency; and 5) plotting these data onto a Bode plot. The above procedure was repeated for three different collective input amplitudes, $\|\delta_c\| = \pm 0.2$, ± 0.5, and ± 1.0 in. to account for possible nonlinear effects. Using these frequency-response data obtained from the various thrust-response configurations, an open-loop bandwidth analysis was conducted. The bandwidth analysis is discussed with regard to the effects of 1) the variations in engine-governor response and rotor inertia, 2) the variation in the amplitude of the collective control input, and 3) the variation in vertical damping.

Figure 12 shows a typical Bode plot for a fast- and a slow-responding engine-governor with medium rotor inertia and $\|\delta_c\| = \pm 0.2$. The open-loop bandwidth analysis was applied to these and similar Bode plots for the thrust-response configurations evaluated.

Figure 13 shows the open-loop bandwidth ω_{BW} for the three engine-governor responses and three rotor inertias versus the averaged C-H pilot ratings from the bob-up task. Note that the value of ω_{BW} was derived based on a collective input amplitude of ± 0.2 in. and $Z_w = 0.25\ sec^{-1}$. The data points may be banded to capture the variation of the engine-governor response ranging from fast to slow and the variation of the rotor inertia from light to heavy. The figure indicates that an $\dot{h}/\delta_c$ bandwidth greater than about 0.5 rad/sec is necessary to ensure Level 1 handling qualities.

Review of the pilot collective control input magnitudes during the initiation of the bob-up maneuver showed ranges from 0.5 to 2 in., depending on the pilot's aggressiveness in performing the maneuver. The open data symbols ($Z_w = -0.25\ sec^{-1}$) in Fig. 14 show the open-loop bandwidth for the three different collective control input magnitudes versus the averaged C-H pilot ratings from the bob-up task where the value of ω_{BW} is based on the medium rotor inertia. The larger collective control inputs ($\|\delta_c\| = \pm 0.5$ and ± 1.0) indicate an $\dot{h}/\delta_c$ bandwidth greater than about 0.4 rad/sec as necessary for Level 1 pilot ratings. It is felt that the larger collective control inputs may be more representative for correlation based on the magnitude of the actual pilots' control inputs required for this task. Note that the open-loop bandwidths for the configurations with $\|\delta_c\| = \pm 1.0$, are very similar, and use of the bandwidth as a discriminator for levels of handling qualities seems marginal. Frequency-response data for collective input amplitudes greater than ± 1.0 in. are necessary before final analysis and recommendations can be made.

Figure 14 also shows the effect of vertical damping Z_w. This figure shows the open-loop bandwidth for two different values of Z_w versus the averaged C-H pilot ratings from the bob-up task. Note that for a medium rotor inertia, the data points may again be banded, but into two distinct groups associated with the two values of vertical damping $Z_w = -0.25\ sec^{-1}$ and $-0.65\ sec^{-1}$. The data points within these bands include the variation in the engine-governor response from fast to slow and variation in the amplitude of the collective control input. Note that the vertical damping appears to have a greater effect on the bandwidth requirement than does the engine-governor response or collective input amplitude. Also note that there are configurations on the Level 2-3 borderline ($Z_w = -0.65\ sec^{-1}$) with a higher bandwidth than some of the Level 1 configurations with $Z_w = -0.25\ sec^{-1}$. These results imply that for the thrust response, criteria based on open-loop $\dot{h}/\delta_c$ bandwidth are not sufficient to ensure good handling qualities. In particular, some requirements based on Z_w and (perhaps) engine-governor characteristics are required.

In summary, the results of the thrust-response simulation indicate that the open-loop bandwidth for Level 1 handling qualities should be greater than about 0.5 rad/sec for $Z_w = -0.25\ sec^{-1}$ and 0.75 rad/sec for $Z_w = -0.65\ sec^{-1}$. The effects of vertical damping on the open-loop bandwidth should be further investigated and analyzed.

The closed-loop analysis for the thrust-response simulation is not discussed in this paper because of the need for additional frequency-response data and analysis in order to interpret further the existing results.

Yaw-Response Simulation

To characterize the configurations evaluated by the pilot in the yaw-response simulation, an idealized heading-rate-to-pedal control-input transfer function $\dot{\psi}/\delta_p$, was assumed. From this transfer function Bode plots were obtained for open-loop and closed-loop analyses, using the matrix of the experimental variables that were evaluated. An idealized form of this transfer function may be assumed with good confidence since the mathematical helicopter model[8] used for these studies was a small-perturbation model utilizing stability derivatives, which are functions of velocity.

The open-loop system block diagram including the assumed form of the $\dot{\psi}/\delta_p$ transfer function where $Y_c = \dot{\psi}/\delta_p$, is shown in Fig. 15. The closed-loop system block diagram is shown in Fig. 7. The experimental matrix showing the primary configurations that were evaluated is shown in Fig. 16. A linear analysis computer program[10] was used to obtain the open-loop Bode plots and to perform the closed-loop analysis and subsequent Bode plots.

Figure 17 shows an example of the open- and closed-loop Bode plot, the corresponding bandwidths, and the averaged C-H pilot ratings for the tasks evaluated. Figure 18 shows the open-loop heading rate bandwidths ω_{BW} for the experimental matrix of variables evaluated versus the averaged C-H pilot ratings for the NOE task, the deceleration task, the low-hover-turn task, and the air-to-air target-acquisition task. The high-hover-turn was omitted here because of the similarity of those data and the low-hover-turn data.

For the NOE task, open-loop bandwidths greater than about 3.0 rad/sec result in considerable improvement in the pilot ratings. Also, for the NOE task there is a relatively high linear correlation between increased open-loop bandwidth and improved C-H pilot ratings. The deceleration and hover turn tasks have some linear correlation, but the overall trend appears nonlinear and task-dependent. The air-to-air task has a nonlinear trend of bandwidth versus C-H pilot ratings. This trend implies that the open-loop bandwidths ω_{BW} corresponding to the best pilot ratings for the task are 2.5 rad/sec $\leq \omega_{BW} \leq$ 4.0 rad/sec. Pilot comments support this trend.

For the configurations with bandwidth greater than 4.0 rad/sec, pilot comments include the following: "the aircraft was slightly sluggish," "the tendency for overshoot," and "yaw aircraft control took moderate pilot compensation." For the configurations with bandwidths less than 2.5 rad/sec, pilots commented about "continuously overshooting and undershooting the target," "unable to hold the pipper steady on target," and "excessive amount of time to decrease the tracking error." The pilot comments for configurations with bandwidths between 2.5 and 4 rad/sec include "easy to generate a rapid yaw rate, acquire, and track target." An exception to this occurs for the configuration with an open-loop bandwidth of 4 rad/sec and an average C-H pilot rating of about 5.5. For this case, even though the bandwidth was between 2.5 and 4 rad/sec, it received a degraded pilot rating because the control-response parameter was set at one-half of the nominal value, that is, it was set at 3.5 $\text{deg.sec}^{-1}\ \text{in.}^{-1}$ of pedal compared with 7.5 $\text{deg.sec}^{-1}\ \text{in.}^{-1}$ of pedal nominally.

In summary, based on the configurations and tasks evaluated in the yaw-response simulation, the open-loop bandwidth for the best C-H pilot ratings show the following:

Task	Open-Loop Bandwidth
NOE	>3 rad/sec
Deceleration	>2.5 rad/sec
Low hover turn	>3.0 rad/sec
Air-to-air target aquisition	2.5 rad/sec $\leq \omega_{BW} \leq$ 4 rad/sec

The closed-loop bandwidth analysis, which was previously described, was applied to the yaw-response configurations and correlated with the C-H pilot ratings. Figure 19 shows the closed-loop bandwidth versus C-H pilot ratings for the NOE task, the deceleration task, the low-hover task, and the air-to-air target-acquisition task. There appears to be a moderate correlation between the C-H pilot ratings and the closed-loop bandwidth. The NOE and deceleration task indicate that closed-loop bandwidths greater than about 3.6 rad/sec are necessary for Level 1 handling qualities. Although Level 1 ratings were not attained for the low-hover-turn and air-to-air target-acquisition tasks, the best ratings for these tasks correspond to closed-loop bandwidths greater than or equal to 3.0 rad/sec.

A linear correlation analysis was performed on the open- versus closed-loop bandwidth data for each configuration. Figure 20 shows that the correlation was extremely high, thus indicating that either analysis may be used with a linearized simulation model.

Finally, an investigation was made into the use of a simple pilot model as a predictive tool for yaw-control handling-qualities research. The pilot gain resulting from the closed-loop bandwidth analysis was correlated with the C-H pilot ratings for the NOE task (see Fig. 21). The correlation indicates that if an aircraft system and pilot model produce a pilot gain greater than 20 in. rad^{-1} then the handling qualities will be relatively good for that task. To confirm the validity of this approach, a configuration not evaluated during the simulation but known to be a bad configuration from the initial simulation checkout phase was analyzed. Closed-loop bandwidth analysis of this configuration produced a pilot gain of 13.86 in. rad^{-1}. Comparing this pilot gain with the results presented in Fig. 21 shows this configuration to yield predicted handling qualities in the Level 2 region (C-H pilot rating of 6). This analysis provides a preliminary confirmation of the predictive capability of the closed-loop bandwidth analysis.

Conclusions and Recommendations

The concepts of bandwidth, open- and closed-loop, were evaluated for deriving handling-qualities criteria from data obtained during two helicopter simulator experiments. The first experiment, a thrust-response simulation, was an investigation of handling-qualities effects of engine-governor response time, rotor inertia, vertical damping, collective control sensitivity, excess power, and rotor speed control. Application of a bandwidth analysis to these simulation data indicates the following.

1) The variations in engine-governor response times and rotor inertia and their effects on handling qualities can be captured by an open-loop bandwidth criterion. But the bandwidth criterion must be accompanied by requirements for the aircraft vertical damping. For a bob-up task, with vertical damping of -0.25 sec^{-1}, the open-loop ($\dot{h}/\delta_c$) bandwidth to ensure Level 1 handling qualities must be greater than approximately 0.5 rad/sec. With a vertical damping of -0.65 sec^{-1}, the open-loop bandwidth to ensure Level 1 handling qualities must be greater than approximately 0.75 rad/sec. The effects of vertical damping on the open-loop $\dot{h}/\delta_c$ bandwidth needs further investigation and analysis.

2) Since the frequency-response data ($\dot{h}/\delta_c$) were gathered for collective control inputs equal to or less than ±1.0 in., additional frequency-response data with larger collective control inputs will also have to be investigated before a final bandwidth criterion recommendation can be made.

The second experiment, a yaw-response simulation, was an investigation of the handling-qualities effects of directional rate damping, directional control sensitivity, and weathercock stability. Application of a bandwidth analysis to these simulator data indicates the following.

1) The trends of the effects of variations in directional rate damping and weathercock stability on handling qualities can be predicted by an open-loop ($\dot{\psi}/\delta_p$) bandwidth analysis.

2) For the configurations evaluated the following open-loop bandwidths provide the best handling qualities: greater than 2.5 rad/sec for the deceleration task, greater than 3 rad/sec for the NOE and hover tasks, and between 2.5 and 4 rad/sec for the air-to-air target-acquisition task.

3) Yaw-response closed-loop bandwidth analysis results showed a high correlation with those of the open-loop analysis and may be useful in predicting the handling qualities of a particular configuration for a specific flight task.

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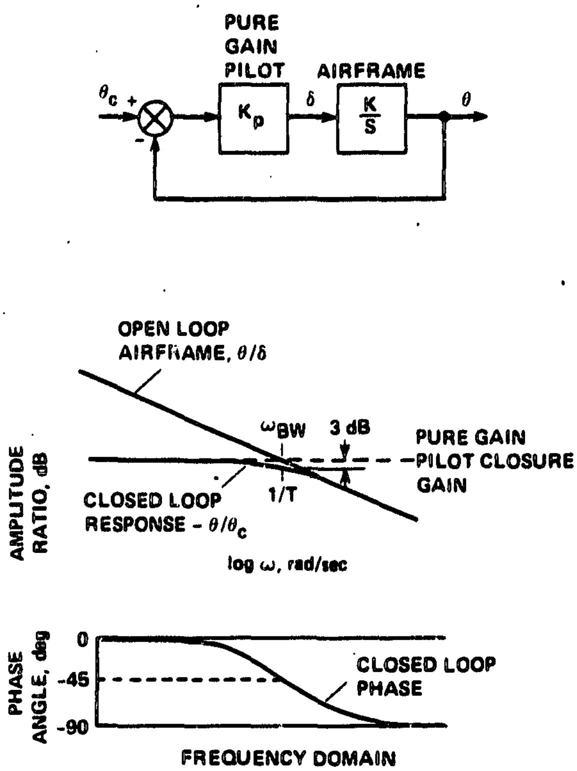


Fig. 1 Classical definition of bandwidth from (from Ref. 3).

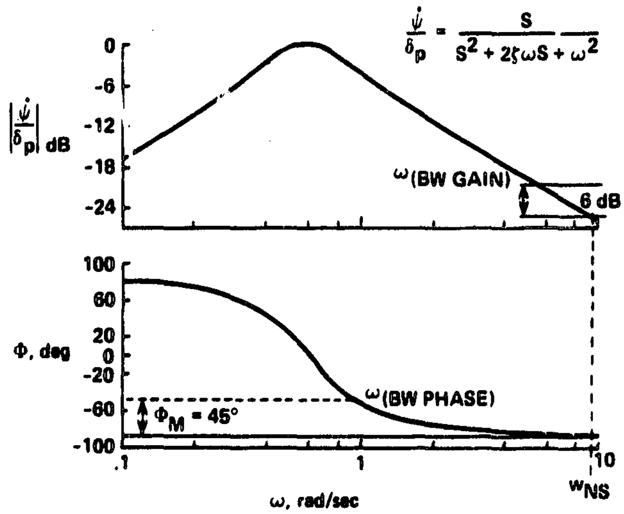
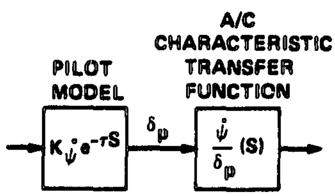


Fig. 2 Definition of closed-loop bandwidth, ω_{BW} (ω_{BW} = lesser of $\omega_{BW_{PHASE}}$ or $\omega_{BW_{GAIN}}$).



$$\text{WHERE } e^{-\tau S} = \frac{1 + (\frac{-\tau}{2}S) + \frac{1}{2}(\frac{-\tau S}{2})^2 + \frac{1}{6}(\frac{-\tau S}{2})^3 + \ldots}{1 + (\frac{\tau S}{2}) + \frac{1}{2}(\frac{\tau S}{2})^2 + \frac{1}{6}(\frac{\tau S}{2})^3 + \ldots} \quad \text{(PADÉ APPROXIMATION)}$$

Fig. 3 Pilot model and aircraft transfer function.

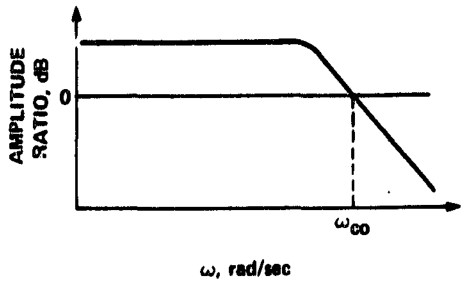


Fig. 4 Crossover frequency.

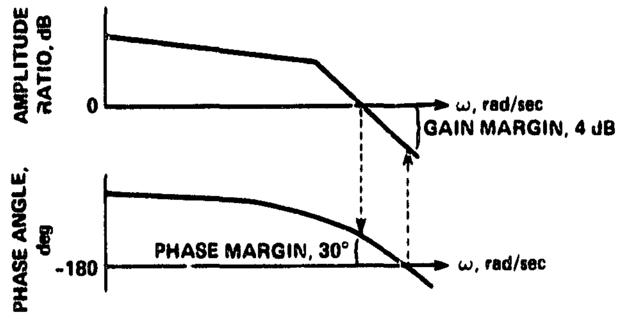


Fig. 5 Intermediate step in closed-loop analysis combines $K_\psi/K_{\dot\psi}$ gain and integrator.

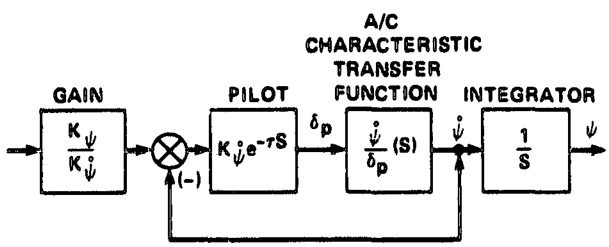


Fig. 6 Margins for $K_\psi/K_{\dot\psi}$ gain adjustment.

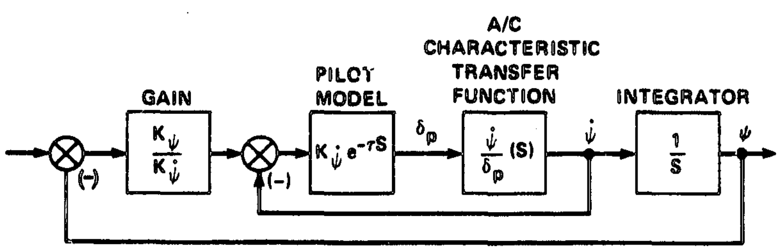


Fig. 7 Complete closed-loop model.

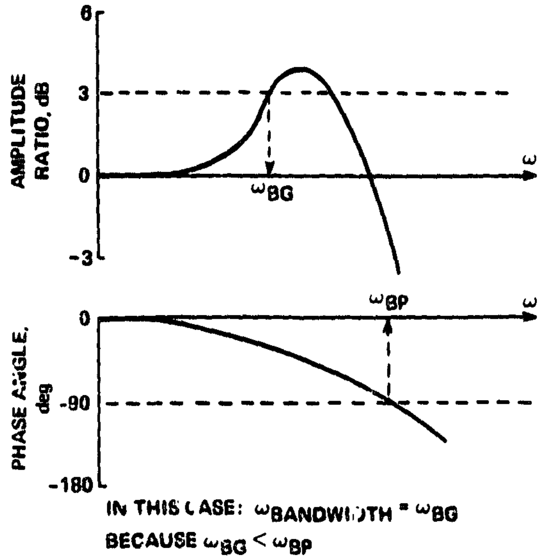
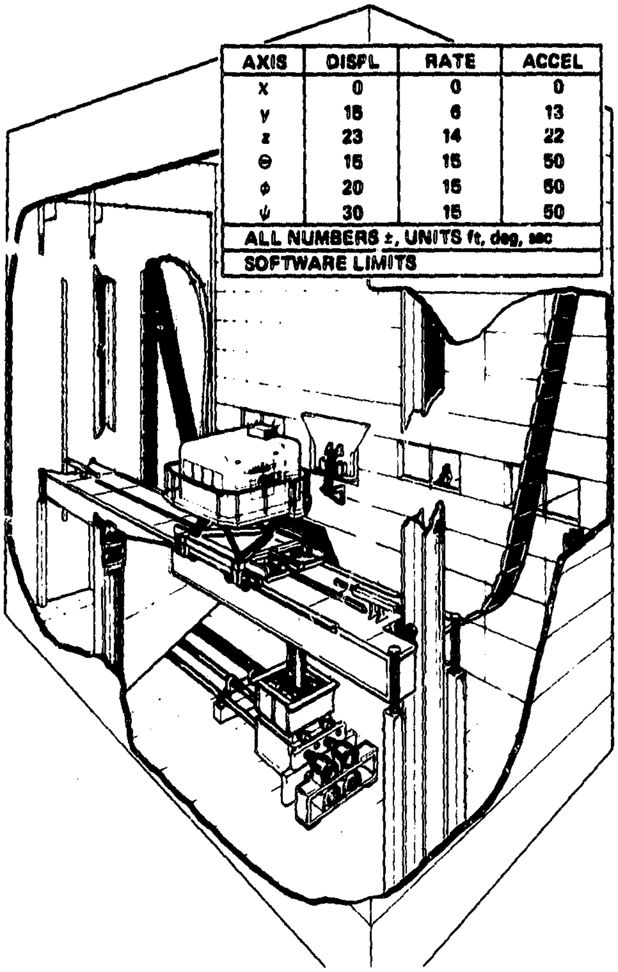


Fig. 8 Definition of closed-loop bandwidth (Ref. 4).



AXIS	DISPL	RATE	ACCEL
x	0	0	0
y	15	6	13
z	23	14	22
Θ	15	15	50
φ	20	15	50
ψ	30	15	50

ALL NUMBERS ±, UNITS ft, deg, sec

SOFTWARE LIMITS

Fig. 9 Vertical Motion Simulator (VMS).

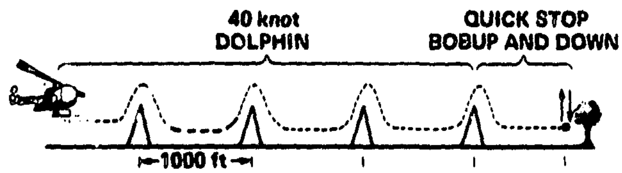


Fig. 10 Thrust-response simulation task.

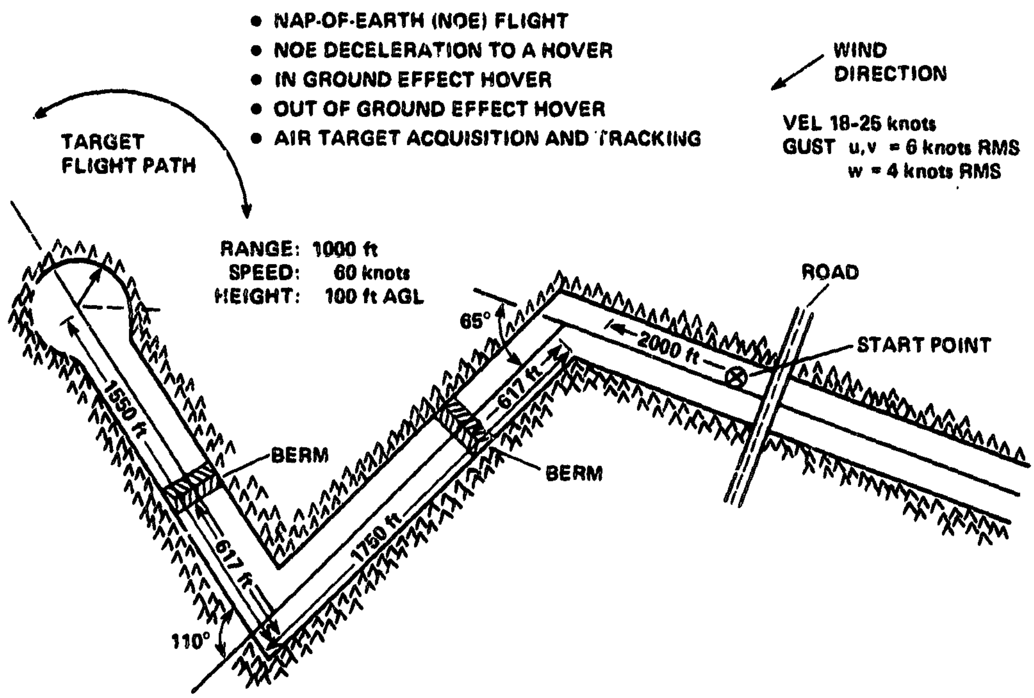


Fig. 11 Yaw-response simulation task.

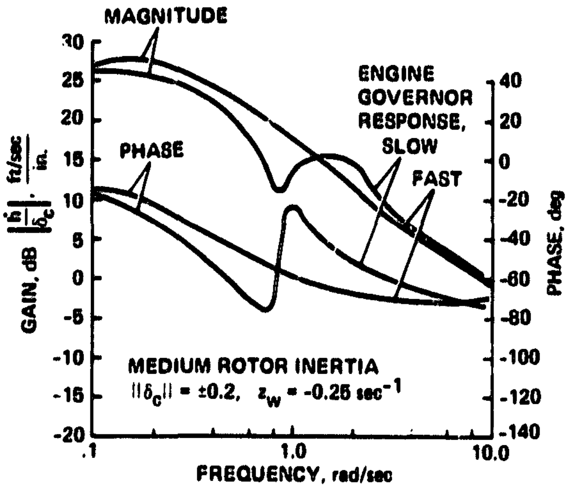


Fig. 12 Typical thrust response, $\dot{h}/\delta_c$ Bode plot.

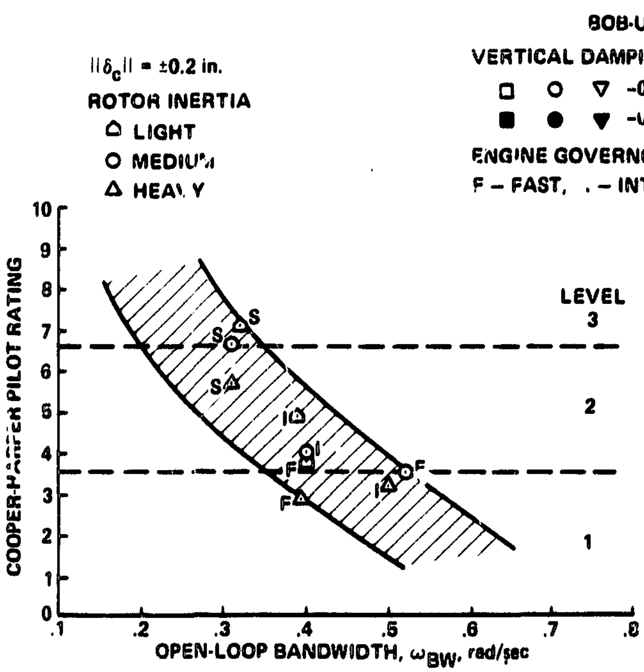


Fig. 13 Correlation of pilot rating with thrust-response open-loop bandwidth; effects of rotor inertia and engine-governor response.

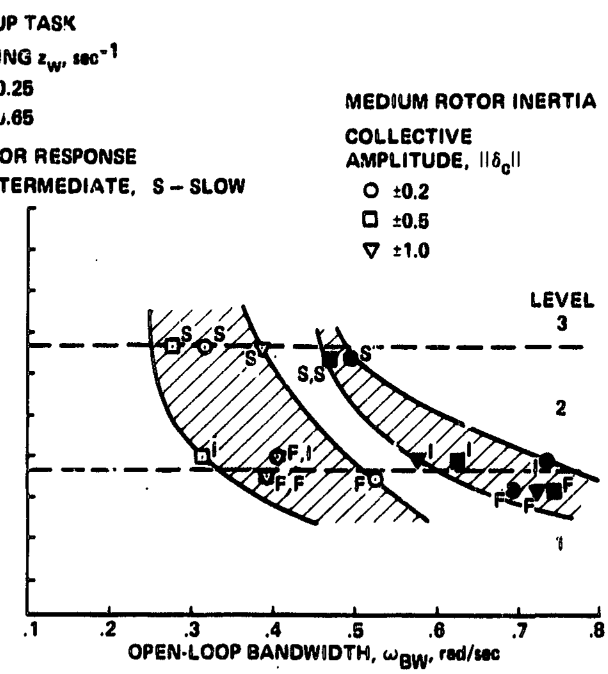


Fig. 14 Correlation of pilot rating with thrust-response open-loop bandwidth; effects of input amplitude, vertical damping and engine-governor response.

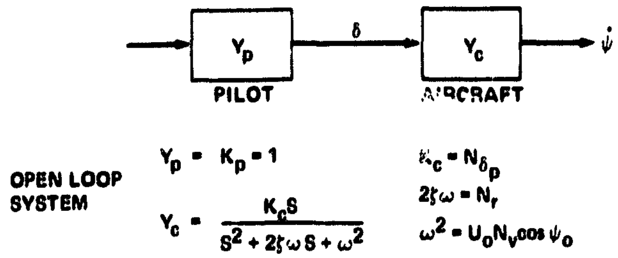


Fig. 15 Yaw-response block diagram for open-loop analysis.

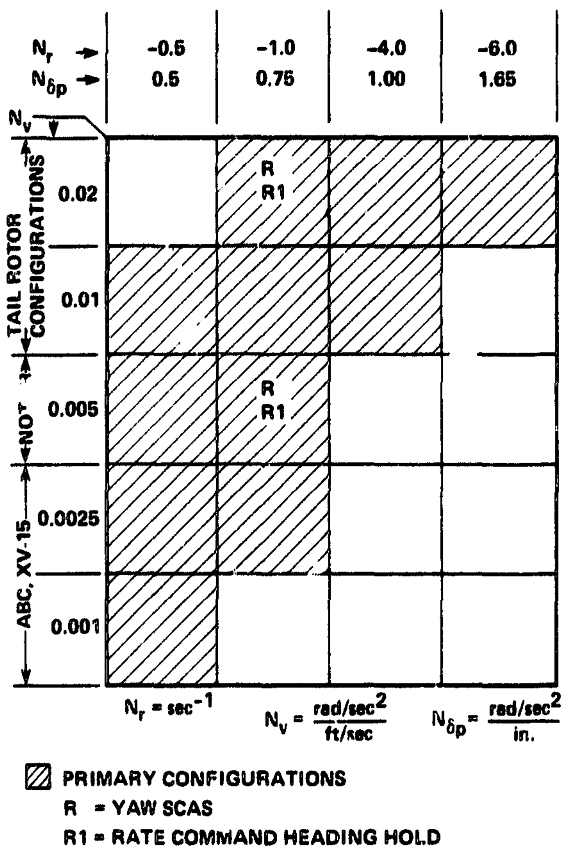


Fig. 16 Yaw-response variables matrix.

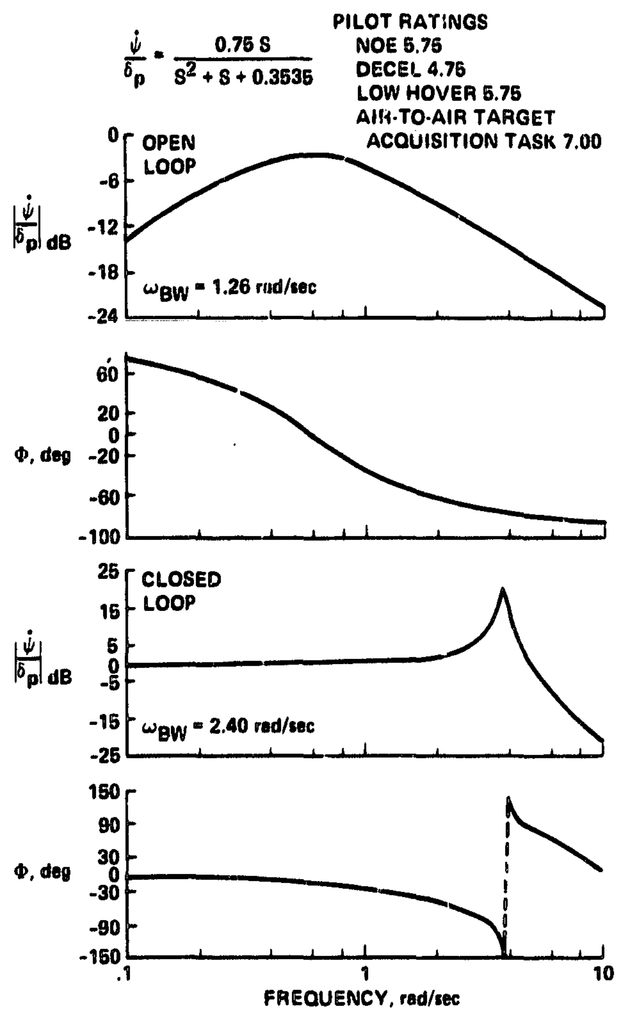


Fig. 17 Typical yaw-response open- and closed-loop Bode plot.

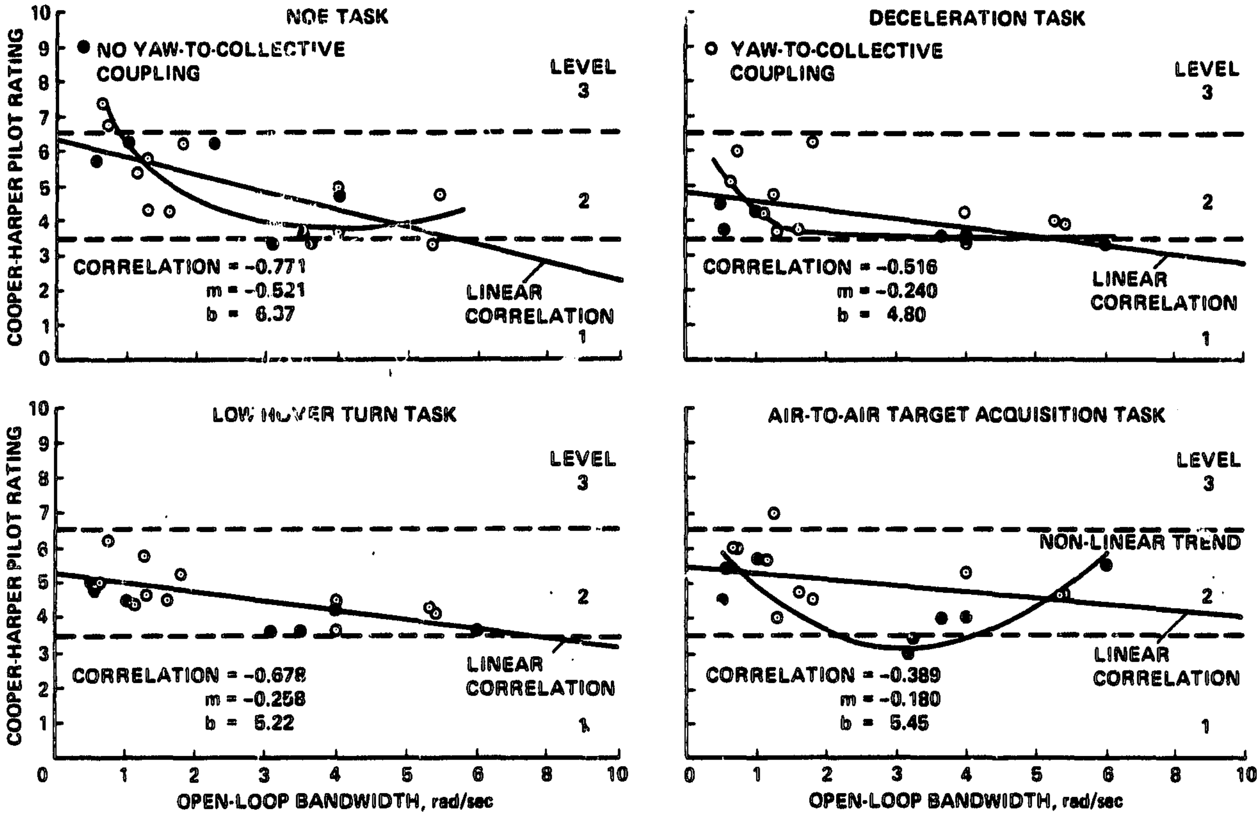


Fig. 18 Correlation of pilot rating with yaw-response open-loop bandwidth.

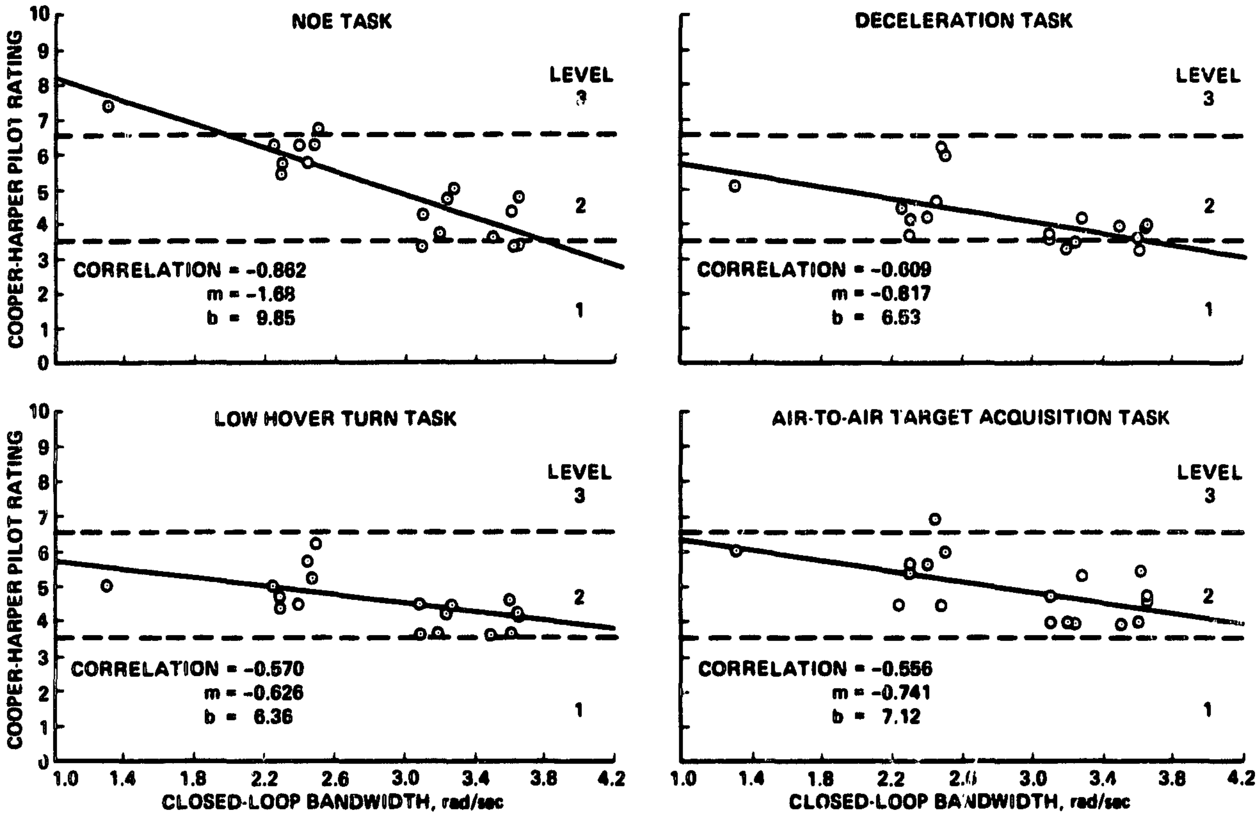


Fig. 19 Correlation of pilot rating with yaw-response closed-loop bandwidth.

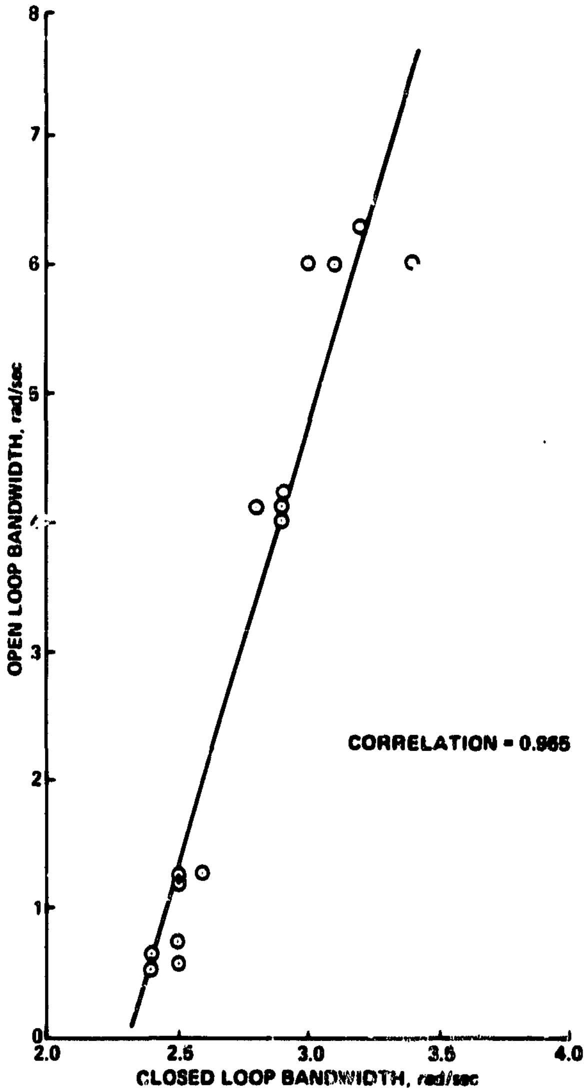


Fig. 20 Correlation of yaw-response open- and closed-loop bandwidth.

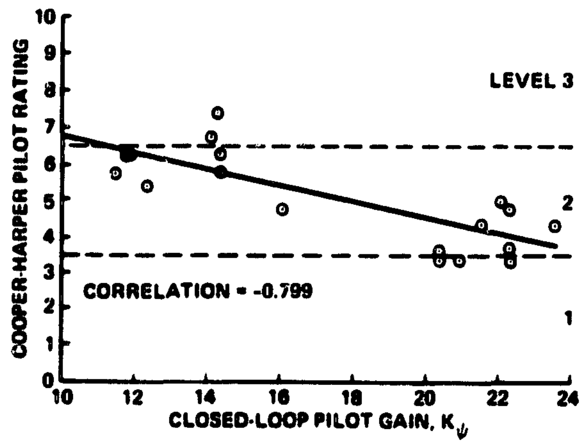


Fig. 21 Correlation of pilot rating with yaw-response closed-loop pilot gain.