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An In-flight Investigation into the Relationships Among Control Sensitivity, Control Bandwidth and Disturbance Rejection Bandwidth Using a Variable Stability Helicopter

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Abstract

A series of in-flight evaluations studying the effects of the variation in control bandwidth, control sensitivity and disturbance rejection capability on the handling qualities of rotorcraft was carried out using the NAE Bell 205 Airborne Simulator. The experiment comprised two major phases. In the first of these, the evaluated configurations differed in roll axis characteristics with pitch, yaw and collective axes characteristics kept constant, while in the second phase the pitch axis characteristics were the ones that varied. The results of the evaluations, in terms of subjective handling qualities ratings and pilot comments, validate the currently recognized boundaries on control bandwidth for Level 1 handling qualities (when measured using control position rather than control force) and provide guidance on the desirable level of control sensitivity for highly damped or rate command systems in pitch and roll. The results from the disturbance rejection portion of the program point out that handling qualities for precision tasks are not strongly affected by the level of disturbance present but there is a threshold disturbance level for both pitch and roll axes which, upon exceeding, does degrade handling qualities.

Introduction

Over the past few years, considerable attention has been paid to the definition of the minimum control bandwidth required for satisfactory (Level 1) rotorcraft handling qualities. On a basis of in-flight and ground based simulation programs, the Level 1 control bandwidth limits for rate and attitude response types in pitch and roll have been defined and incorporated into the proposed revision to Mil-H-8501 (Reference 1). These limits have also been adjusted to reflect the requirements imposed by various "mission task elements" and linked with requirements for moderate and large amplitude response characteristics of a rotorcraft.

The research programs upon which the bandwidth requirements are based usually incorporated rotorcraft models in which the control bandwidth was achieved by high gain feedback of aircraft state parameters, consequently, the vehicle capability to reject outside disturbances was intimately related to the control bandwidth. The disturbance rejection characteristics of these vehicles have not, however, been systematically documented, nor has the effect of this quality on handling qualities been adequately investigated. With advanced control system architectures possibly involving both state feedback and control input shaping (feedforward) paths, the disturbance rejection characteristics of the vehicle need no longer be closely related to the control response of the vehicle. In this case, the

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effects of disturbance rejection characteristics on handling qualities may be the factor which limits the extent to which this architecture can be used.

A second important shortcoming with the current bandwidth related handling qualities data base is a lack of guidance on the control sensitivities required to match the requirement in the proposed specification, which states: (the control sensitivity) "...shall be consistent with the aircraft dynamic response...". This 'consistency' implies that the desirable control sensitivity is related to the response characteristics of the vehicle however little data has been produced to describe this relationship. While a significant body of data (References 2,3,4) has been published on control sensitivity for conventional helicopter response types and documented results relating to the standard derivative terms L_p, M_q, L_δ and M_δ are available, this data may not be applicable to advanced command/control systems due to the difficulty in defining certain derivatives (ie. for a "good" rate command system, the effective L_p is usually undefined or swamped by higher order effects). A secondary issue in this area is the use of higher control sensitivities to diminish the effect of reduced control bandwidth. This feature has been demonstrated in limited in-flight trials but has not been adequately documented.

These two areas of interest, namely: the whole issue of defining, measuring and setting handling qualities related limits based on vehicle disturbance rejection characteristics; and the relationship between control bandwidth and control sensitivity for advanced response types, were identified as topics of research for the Flight Research Laboratory (NAE/NRC) program on Advanced Rotorcraft Flying Qualities. Using the NAE Airborne Simulator, a series of in-flight handling qualities evaluations was undertaken to investigate these issues. This paper describes this activity by first discussing the concept of disturbance rejection and related issues, then describing the experiment in more detail and discussing the results of the formal handling qualities evaluations. The paper ends with conclusions drawn from the results and experiences gained through the program.

Control System Considerations

Although it has often been the practice to create, for experimental purposes, high quality rate command, rate command attitude hold or attitude command control systems in pitch and roll using aircraft state feedback techniques, as illustrated in Figure 1, there is no overwhelming reason why this architecture should be chosen over any other. While pure feedback has the advantages of relative simplicity and low sensitivity to errors in the modelling of the unaugmented vehicle characteristics, this architecture also has certain disadvantages, particularly the amplification of sensor noise into actuator inputs or, as a corollary, a distinct susceptibility to extreme system degradation in the event of sensor failure. Referring again to Figure 1, the system response in angular rate (in this example, roll rate, p(s)) is:

$$p(s) = p_c(s)\,\frac{K_pG(s)}{(1+K_pG(s))} - n(s)\,\frac{K_pG(s)}{(1+K_pG(s))} + p_t(s)\,\frac{1}{(1+KpG(s))} \qquad (1)$$

where $p_c(s)$ is the pilot input or command signal and G(s) is the unaugmented vehicle transfer function of roll rate due to cyclic input. The two other terms in equation (1) deal with $p_t(s)$, which is the unaugmented vehicle roll response to atmospheric turbulence and with n(s) which describes sensor noise. While the feedback of $p_t(s)$ in the system is beneficial, as it generally improves the disturbance rejection characteristics of the vehicle, the same architecture feeds a magnified version of sensor noise (K_p * n(s)) directly to the cyclic actuators. Clearly, the sensitivity of this type of system to sensor malfunction, even to the most benign of all sensor failures, a failure to the current value, is large. In such a simple case, using p_s to represent the failed sensor output, the roll rate from command transfer function becomes a simple open loop system:

$$p(s) \;=\; (\, p_c(s) - p_s \,)\; K_pG(s) \;+\; p_t(s) \tag{2}$$

Since K_p can often be in the order of 15 to 20 inches of cyclic per radian per second of roll rate error, the vehicle described by equation (2) usually possesses handling qualities degraded to well below those of the simple unaugmented aircraft due to excessive control sensitivity. Clearly, any discontinuity in the value of p_s, such as could well occur in the event of a sensor failure to zero or maximum value, would again be amplified by K_p causing large and possibly uncontrollable transients in p.

In cases where the gain on command error, K_p, is driven to extremely high values to achieve good control bandwidth, the pure feedback architecture may also cause significant deficiencies due to its high gain response to disturbances. This high gain response may be excessively abrupt and either impose severe restrictions on the aircraft structural design or consume excessive fatigue life as well as degrading ride quality for the occupants. There are, therefore, numerous reasons for attempting to reduce the value of the in-line gain term, K_p, while maintaining high control bandwidth.

Figure 2 presents an alternative approach to achieving good control bandwidth, while leaving the designer with some freedom to tailor the disturbance and sensor noise responses. In this case the response of the system may be described by:

$$p \;=\; p_c(s)\,\frac{(G(s)/G'(s) + K_pG(s))}{(\,1 + K_p\,G(s)\,)} \;-\; n(s)\,\frac{K_p\,G(s)}{(\,1 + K_p\,G(s)\,)} \;+\; p_t(s)\,\frac{1}{(\,1 + K_p\,G(s)\,)} \tag{3}$$

where G'(s) is a mathematical model of the unaugmented vehicle roll rate response to control input. The first term of equation (3) reduces to the commanded rate, $p_c(s)$, for all gains, K_p, if G(s), the actual vehicle unaugmented transfer function, matches the model, G'(s). This simple reduction yields a perfect rate command system through model feedforward, and permits K_p to be used purely to set the response to disturbances, $p_t(s)$, with the response to sensor noise, n(s), as a design consideration. In practice the first term of equation (3) does not exactly reduce to $p_c(s)$ since: 1) G(s) is generally not known sufficiently well, 2) system non-linearities do not lend themselves to pure transfer function modelling techniques and 3) G'(s) must be modified at high frequency to prevent an unacceptable amplification of high frequency noise resulting from the rapidly increasing gain with frequency implied by $1/G'(s)$. Despite this mismatch, the use of the feedforward term substantially reduces the requirement for large K_p values when trying to achieve high control bandwidth. The consideration of this type of architecture illustrates the need to investigate the handling qualities of vehicles with varying levels of disturbance rejection.

Disturbance Rejection Characteristics

In considering the handling qualities issues related to the disturbance response of a vehicle, it is intuitively clear that the significant factors are the magnitude and frequency content of such responses to turbulence for which the pilot must compensate. As the magnitude of these perturbations becomes larger, the increase in pilot compensation required to achieve the desired performance in a precision task should drive the handling qualities of the vehicle from satisfactory to unsatisfactory, assuming that the vehicle in question has satisfactory handling qualities in a calm environment. Since the issue under consideration is handling qualities alone, the frequency content of perturbations considered can probably be limited to the frequency range of pilot stabilization, approximately 0.5 to 5 rad/sec. Perturbations of higher frequency are more "ride quality" related while those of lower frequency tend to be performance related.

With above discussion in mind, the characterisation of disturbance rejection quality should be made by measurements of the attitude or angular rate perturbations caused by a given turbulence environment. Analytically this can be estimated by combining the gust-to-attitude transfer functions of the vehicle and the power spectral density (PSD) of a representative turbulence model to produce the PSD of attitude perturbations, $\delta\Theta$**. It is expected that this measure, the $\delta\Theta$ (or similar) PSD, will define limits for disturbance rejection quality due to handling qualities considerations just as a similar quantity, the δa_z PSD (where a_z is vertical acceleration), has been used to define ride quality issues for fixed wing aircraft (Reference 6).

Ideally, since the analytical prediction of helicopter dynamics can be suspect at many flight conditions, especially in the low speed and hover regimes, a direct measurement of disturbance rejection capability is desired. Unfortunately the $\delta\Theta$ PSD cannot be measured directly since one has no direct measure of the turbulence input. A technique which may describe the significant features of disturbance rejection for low speed flight conditions and which is relatively simple to use is measurement of the actuator-to-attitude transfer function. This technique, its implications and limitations will be discussed below.

Actuator Sweeps as a Method of Determining the Disturbance Rejection Characteristics

In the low speed and hover flight regimes, the flight dynamics of most rotorcraft are dominated by the aerodynamics of the rotor system. This is particularly true in the pitch, roll and heave axes. For these regimes and axes, a turbulent gust creates a localized perturbation primarily in angle of attack over the rotor system. For gust wavelengths comparable to the diameter of the rotor or larger, a rotor lift distribution similar to that

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** This calculation is actually $G(s)*[H(s)]^2$ where $G(s)$ is the turbulence power spectral density and $H(s)$ is the gust-to-attitude transfer function of the vehicle (Reference 5).

induced by the gust can be achieved by a perturbation in cyclic or collective setting. It can therefore be expected that the gust transfer functions for a conventional rotorcraft in hover and low speed flight should be approximately the same as the control transfer functions. Analytical calculations of these two transfer functions for pitch and roll axes of a Bell 205 (without stabilizer bar, Reference 7), which are included as Figures 3 and 4, substantiate this reasoning since the shapes of the two functions are similar over the frequency range which has already been identified as important for handling qualities issues. With this in mind, the method of injecting inputs at the actuators of a rotorcraft and measuring the actuator input to state response transfer function clearly provides information relevant to the vehicle disturbance rejection ability.

While the phase information of most transfer functions is generally relied upon for specifications (ie. bandwidth specifications) it is the amplitude distribution over frequency for the actuator response transfer function which could be expected to be significant for disturbance rejection purposes, since this distribution includes a description of the size of disturbances for which the pilot must compensate. In the limited experience of tailoring variations in disturbance rejection characteristics on the NAE Airborne Simulator however, the actuator to attitude transfer functions have behaved like simple fixed gain filters ($k/(s+\alpha)^n$). With this behaviour, α varies in proportion to disturbance rejection ability and so the amplitude distribution and phase defined bandwidth have a one to one correlation (As α decreases, signifying a reduction in disturbance rejection capability, the gain of the gust response transfer function at any frequency w increases like $1/(w+\alpha)$). For the purposes of this research program both the actuator response bandwidth and the entire amplitude distribution were documented.

Experimental Description

The primary goal of this program was to investigate the handling qualities degradation caused by a reduction in the disturbance rejection characteristics of rotorcraft that possess rate-type response to control inputs in pitch and roll axes. Additional goals included further verification of the handling qualities control bandwidth criterion and accurate documentation of the effect of control sensitivity variation on handling qualities. The program had two distinct phases, in the first phase the configurations differed in roll axis characteristics with pitch, yaw and collective axes characteristics kept constant, and in the second phase the pitch axis characteristics were the ones that varied.

<u>The NAE Airborne Simulator</u> - The primary research tool used in this experiment was the NAE Airborne Simulator, a highly modified, fly-by-wire, Bell 205 A1 helicopter (Figure 5). In converting this vehicle to operate in a fly-by-wire mode, the most significant modifications were 1) the standard control actuators were replaced with full authority dual mode units, capable of accepting either electrical or mechanical signals, 2) the Bell stabiliser bar was removed to quicken the rotor dynamic response and 3) the horizontal stabiliser, normally linked to the swash-plate mechanically, was provided with its own actuator for independent control. All pilot commands from the evaluation station are electrically sensed and read into a high speed digital computing system which in turn drives the aircraft actuators. A full set of state sensors is provided for loop closure and state recovery purposes. Sixty four parameters are recorded on a magnetic tape cartridge at 64 Hz for post flight analysis. Safety of flight issues are addressed by the use of system health monitoring modules (both hardware and software) and a safety pilot. The aircraft is flown routinely through its full flight envelope in the fly-by-wire/simulator

mode. A full description of the NAE Airborne Simulator can be found in Reference 8.

Experimental Configurations - The airborne simulator was configured with a control system architecture similar to that shown in Figure 2 to possess a wide variety of control bandwidths, actuator response bandwidths (or disturbance rejection abilities) and control sensitivity levels in both pitch and roll axes. Conventional flight controls were used during the experiment with pitch and roll cyclic force gradients of 2.5 and 1.75 lb/inch respectively. The yaw axis was implemented as a rate command with a pseudo heading hold while the vertical axis was the unaugmented Bell 205.

Turbulence Model - To evaluate the disturbance rejection effects on handling qualities, it is obvious that a known level of disturbance must be present and consistent throughout all evaluations. The disturbance environment for this experiment was simulated for all evaluations using data derived from a record of aircraft motion measured during the flight of a Bell 205 in heavy turbulence (hovering in the lee of a large building in strong winds). The remnant angular rates and vertical accelerations of this time history were fed into a simple, first order inverse model of a Bell 205 to create data traces which, when fed directly to the actuators of a Bell 205, would cause similar angular and vertical motion of the vehicle. These time histories were empirically scaled and filtered until the point where pilots flying the same Bell 205 with these inputs being fed to the actuators agreed that the aircraft felt subjectively as though it was flying in moderate turbulence. By taking the power spectral density of these actuator inputs and combining them with the measured actuator-to-attitude transfer functions of each configuration, the $\delta\theta$ and $\delta\phi$ PSDs were defined for each configuration of the experiment. These disturbance perturbation PSDs are presented as Figures 6 and 7.

One experimental difficulty arising during this experiment was that the response of the aircraft to the artificial turbulence model was superimposed on the disturbances caused by any natural turbulence or wind present at the time of evaluation. To ensure that all evaluations were comparable, the safety pilot continuously evaluated his perceptions of the ambient turbulence level when he was in control of the unaugmented vehicle. When the safety pilot ratings exceeded a "nil to light turbulence" description, the ratings and other data from that particular flight were set aside from the main body of results.

Evaluation Tasks - Evaluation tasks for the experiment centred on those requiring significant closed loop control and stabilization by the evaluation pilot. Precision hover and landing tasks to position accuracies of $\pm$ 3 and $\pm$ 1.5 feet, respectively, provided the highest stabilization demands on the pilot. The additional tasks of sidestep (lateral unmask/remask) and quickstop (rapid accel/decel), were tasks in which a single axis (pitch or roll) required significant large amplitude commands while all other axes required significant stabilisation at the completion of the manoeuvre. The final task was a pirouette (a laterally translating pedal turn) which is a good indicator of the ability to stabilise and control all axes simultaneously. Cooper Harper Handling Qualities Ratings (Reference 9), pilot comments and measures of task performance were compiled throughout the evaluation period.

Experimental Results

Over the four month period of December 1988 to March 1989, over 200 evaluations of various configurations were accomplished using just over 90 hours of training and evaluation flight time. These evaluations were split roughly equally between roll and pitch axis varied configurations. In total, seven qualified experimental test pilots performed the evaluations. These pilots included personnel from the Canadian Forces, NASA/Ames and the Royal Aerospace Establishment (UK) as well as members of the flight operations staff at NAE/NRC. The detailed results of the experiment, including all pilot comments, ratings and extensive documentation of all evaluated configurations will be published in an NRC publication later this year. The following section will discuss the major trends and results which have become clear.

Control Bandwidth - Ratings gathered for configurations with variations in control bandwidth and with the optimum control sensitivity values demonstrate the trends predicted by previous research. As shown in Figures 8 to 13 the averaged handling qualities ratings for the task groups of hover and landing, sidestep and pirouette, and quickstop tasks conform well with the currently accepted bandwidth, τ_p boundaries suggested for Level 1 and 2 handling qualities. Considerations of the data representing only those configurations with the best level of disturbance rejection capability on these figures clearly validate the boundaries and suggest that the Level 2 boundary for the roll axis may be slightly conservative. These results, unlike previous research results, are derived from vehicles flying in a moderately turbulent environment and thus lend further credence to the boundary placement.

The figures show only one exception to the Level 1 boundaries and that is the configuration at (2.6,.26,good) on the pitch bandwidth, τ_p diagram. The average rating of 4 for hover and landing tasks for this configuration is based only on two evaluations and may be related to a non-optimum sensitivity selection or gain margin limit issues rather than bandwidth, τ_p considerations. At this point in time these ratings are still in question.

While the figures mentioned above show an overall agreement between the suggested handling qualities boundaries and evaluations carried out during this experiment, it must be pointed out that the placement of configurations on the bandwidth/τ_p diagram was made using control position as the input for the measurement of control bandwidth. Figures 14 and 15 show the movement of the configurations if control force, rather than position, is used as the input parameter for this measurement. The migration of these configurations, generally up and to the left on the diagram, in many cases results in Level 1 vehicles being placed in the Level 2 areas of the plot. Since this placement contradicts the evaluation results, this discrepancy must be resolved by either limiting the use of bandwidth,τ_p criterion for control position-to-attitude bandwidth only or by somehow integrating the force derived bandwidth data into the existing plot. Clearly the interaction between stick force and stick position on handling qualities is an area which requires further investigation.

Disturbance Rejection - The bandwidth, τ_p figures also provide the opportunity to consider the effect of disturbance rejection quality on handling qualities. In general the ratings for hover and landing tasks and for the roll configuration with the best control bandwidth but worst level of disturbance rejection ((2.6,.19,poor) on the bandwidth, τ_p diagram) received mixed ratings. Of the five evaluations of this configuration, three were Level 1 (2.5's or 3's) for hover and landing tasks while the other two were Level 2 (4's or 4.5's) and comments accompanying these lower ratings described difficulties in counteracting the level of turbulence encountered. The discrepancy in ratings suggeststhat the level of disturbance for this configuration may be the critical boundary case for the roll axis. For the other task groups (sidestep/pirouette and quickstop), this disturbance environment had little influence on the handling qualities ratings or comments.

The above mentioned trend was even more pronounced for the pitch axis phase of the experiment. The poor disturbance rejection configuration located near the centre of the Level 1 region of the bandwidth, τ_p diagram, (2.1,.19,poor), regularly received Level 2 ratings for hover, landing, pirouette and quickstop tasks yet received a solid Level 1 evaluation by one pilot and primarily Level 1 ratings by a second during evaluations where the turbulence model was inadvertently left off. This degradation of rating for turbulence "on" evaluations must therefore be solely due to the disturbance environment and as such the $\delta\theta$ PSD for this configuration must be an unsatisfactory level of pitch perturbations for precision tasks.

A second pitch axis configuration which seems to contradict the suggested Level 1 boundary is the one located at (2.9,.16,medium) on the bandwidth, τ_p diagram. This configuration also received Level 2 ratings for a significant number of evaluations, however the Level 1 evaluation of another configuration with the medium disturbance rejection capability at a slightly lower bandwidth (1.8,.14,medium) suggest that the reasons for the Level 2 evaluation of (2.9,.16,medium) are other than disturbance rejection. This configuration will be discussed in more detail in a following section.

In light of these evaluations, the "poor disturbance rejection" configuration for both pitch and roll axes cases probably represent the handling qualities limits for disturbance level. Since these evaluations were done in a single axis mode, the combination of these two "limit cases" would probably assure Level 2 handling qualities for precision hover and landing tasks.

<u>Bandwidth and Gain Margin Limiting</u> - During the pitch axis portion of this experiment, two configurations were evaluated which, while often receiving Level 1 handling qualities ratings and comments, also received poorer ratings and comments from pilots who can be classed as "higher gain". These pilots, who tend to generate a higher frequency content in their control inputs, degraded the rating of these two configurations and commented regarding harshness or abruptness in pitch control response. The configurations of interest are at (2.4,.15,good) and (2.9,.16,medium) on the bandwidth, τ_p diagram for the pitch axis. Each configuration has Level 1 control bandwidth but is characterised by a gain margin rather than a phase margin limit for this measure.

The Bode plot of the pitch control transfer function for the worst example of this feature is shown in Figure 16. The noticeable "lump" in the higher frequency roll-off of this transfer function is the cause of the gain margin limit and is expected to be responsible for the variation in ratings found during the experiment. While satisfactory control of the vehicle can be made at frequencies lower than 3 rad/sec (and probably was by the majority of evaluation pilots), the use of control inputs with frequency content above this value would cause responses in angular rate at a higher sensitivity than would be expected for a pure linear roll-off. The pilots descriptions of harsh or abrupt response is attributed to this feature. It is expected that if the pilots who rated this configuration as Level 1 were given a task which required them to more tightly control the pitch axis, they too would operate in this higher frequency region and would also degrade their assessment of these configurations.

While no guidance regarding the overall effects of gain margin limiting can be made from the limited exposure this experiment had to the problem, it is clear that configurations with gain margin defined control bandwidth must be treated with extra caution.

__Control Sensitivity__ - While variations in control sensitivity had to be limited due to configuration matrix size constraints, certain models did have enough variation during the experiment to describe desirable values of sensitivity. Unlike previous research programs which have documented sensitivity by the damping and control power derivatives (ie. L_p and L_δ), this program used the rate sensitivity at the control input frequency of 1.0 rad/sec since most pilot stabilization activity is concentrated near this frequency and since the conventional derivatives are difficult to define for highly damped or rate command systems. Consistent with other portions of the experiment, wherever a roll axis characteristic was varied, the pitch axis model was the baseline Level 1 configuration and vice versa.

Figures 17-20 describe the variation in handling qualities ratings for a range of control sensitivities for models which were evaluated enough times to consistently describe rating trends. The high bandwidth pitch model data (Figure 17) shows a limited effect of sensitivity with the most desirable sensitivity being approximately 10 deg/sec/inch. The lower bandwidth pitch model data (Figure 18) shows a much more dramatic "handling qualities cliff" at sensitivities less than 10 deg/sec/inch but otherwise is consistent with the previous figure.

The roll axis data in Figure 19 (the high bandwidth case) does not reveal a minimum but does show that sensitivities above 7 deg/sec/inch result in Level 1 handling qualities. The lower bandwidth roll model (data in Figure 20), while never attaining Level 1 handling qualities, appears to have the best handling qualities when the sensitivity is at values of close to 15 deg/sec/inch and, like the low bandwidth pitch model data, shows a more definitive sensitivity effect. In comparing the roll sensitivity results to previous research results on this topic, such as those in Reference 4, it appears the present results do conform to previous trends. These trends are displayed in Figure 21.

__Conclusions__

As the analysis of results presently stands, the in-flight experiments on control bandwidth, sensitivity and disturbance rejection have displayed the following trends for variations in roll and pitch axis characteristics:

1) The handling qualities degradation with decreasing control bandwidth has been clearly documented and the data gathered during this experiment confirms the presently proposed MilSpec handling quality Level boundaries for control bandwidth and phase delay (τ_p) when control position measurements are used for this documentation. The results also show that when plotted using force generated bandwidth and τ_p values, the current boundaries are significantly conservative. In addition to suggesting that force derived bandwidth data must be interpreted with caution, this result also suggests that further investigation should be carried out to determine the full interaction between stick force and displacement characteristics.

2) The few experiences with gain margin limited control systems over the course of this

experiment suggest that this feature is generally undesirable however no quantitative limits for this feature can be defined.

3) A limited number of evaluations demonstrated the variation of handling qualities with lateral and longitudinal control sensitivity and suggest that for heavily rate damped or rate command configurations the control sensitivity values at 1 rad/sec should be approximately 15.0 deg/sec/inch in roll and 10 deg/sec/inch in pitch. These values translate to 8.6 and 4.0 deg/sec/lb for the stick force characteristics used during this experiment. For systems with lower control bandwidth or with poor disturbance rejection characteristics, the effect of off-optimum sensitivity is far stronger than for "good" systems.

4) The results of evaluations made on vehicles with varied levels of disturbance rejection ability suggest that the handling qualities of such vehicles for precision hover and landing tasks are not strongly affected by the variation in disturbance induced vehicle perturbations however a handling qualities limit on the level of disturbance response does exist. For pitch and roll axes, the disturbance perturbation environment represented by the "poor" disturbance rejection cases appear to be the limit levels for Level 1 handling qualities.

Acknowledgement

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References

1 Hoh, Roger H., et al, "Proposed Specification for Handling Qualities of Military Rotorcraft, Volume I -- Requirements", USAAVSCOM Technical Report 87-A-4, May 1988.

2 Corliss, L.D., Carico, G. Dean, "A Flight Investigation of Roll-Control Sensitivity, Damping and Cross-Coupling in a Low-Altitude Lateral Manoeuvring Task", NASA Technical Memorandum 84376, December 1983.

3 McGregor, D.M., "The Influence of Aircraft Size on Control Power and Control Sensitivity Requirements. A Comparison of Results From Two Variable Stability Helicopters", NRC Aeronautical Report LR-459, July 1966.

4 Hoh, Roger H., Ashkenas, Irving L., " Development of VTOL Flying Qualities Criteria for Low Speed and Hover", NADC 77052-30, December 1979.

5 Bendat, Julius S., Piersol, Allan G., Random Data: Analysis and Measurement Procedures, Wiley-Interscience, New York, 1971, pp 25.

6 "Symposium on Vehicle Ride Quality", NASA Technical Memo,TM-X-2620, July 1972

7 Heffley, Robert K., Jewell, Wayne F., Lehman, John M., Van Winkle, Richard A., "A Compilation and Analysis of Helicopter Handling Qualities Data - Volume One: Data

Compilation", NASA Contractor Report 3144, August 1979.

8 Sattler, D.E., "The National Aeronautical Establishment Airborne Simulation Facility", National Research Council of Canada, NAE Miscellaneous Report 58, May 1984.

9 Cooper, G.E., Harper, R.P. Jr., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities", NASA Technical Note D-5153, April 1969.

10 Hoh, Roger H.,et al, "Background Information and Users Guide for Proposed Handling Qualities Requirements for Military Rotorcraft", STI Technical Report No. 1194-3

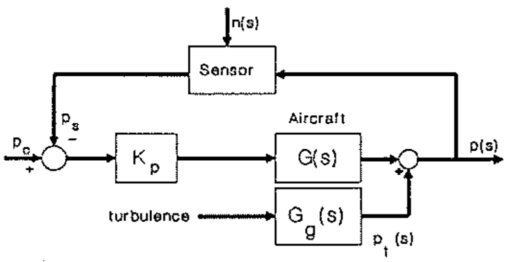

Figure 1: Simple Rate Feedback Architecture

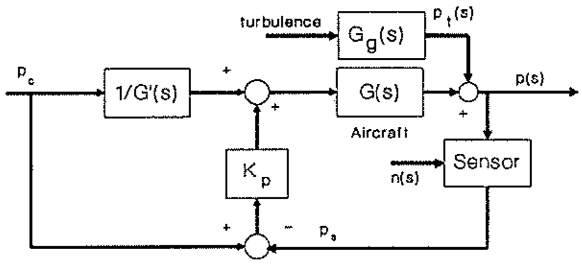

Figure 2: Advanced FeedForward/ Feedback

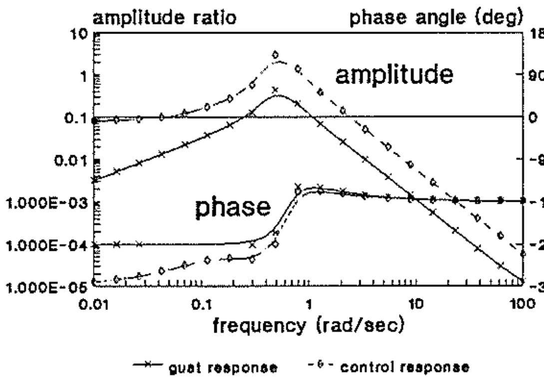

Figure 3: Roll Axis Control and Gust Response Transfer Functions

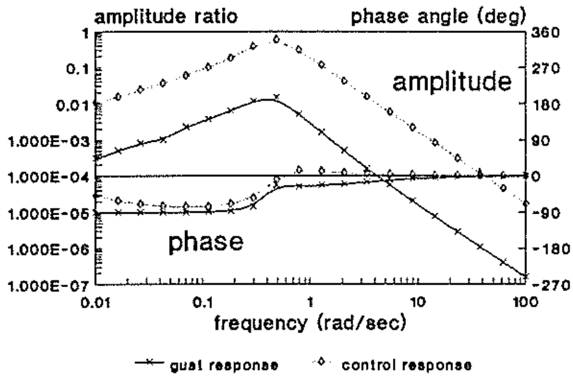

Figure 4: Pitch Axis Control and Gust Response Transfer Functions

Figure 5: The NAE Bell 205 Airborne Simulator

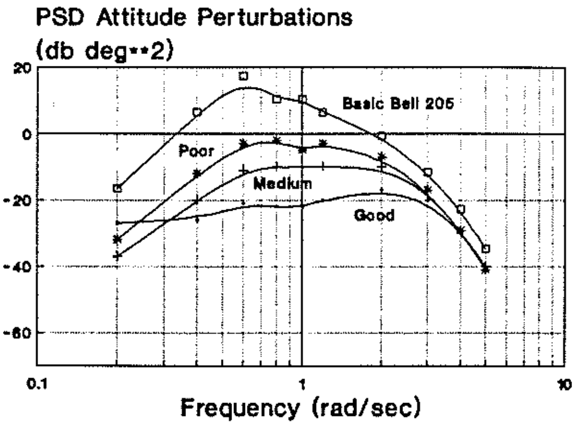

Figure 6: Roll Axis Attitude
Pertubation PSDs ($\delta\phi$)

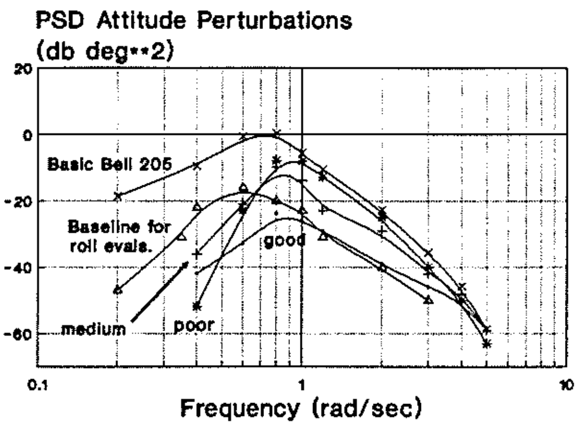

Figure 7: Pitch Axis Attitude
Pertubation PSDs ($\delta\theta$)

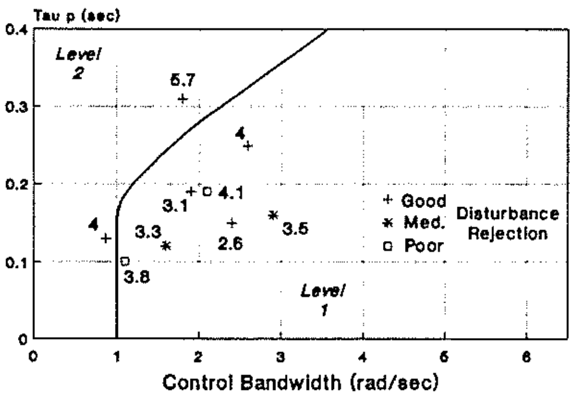

Figure 8: Pitch Axis Results
Hover & Landing Tasks

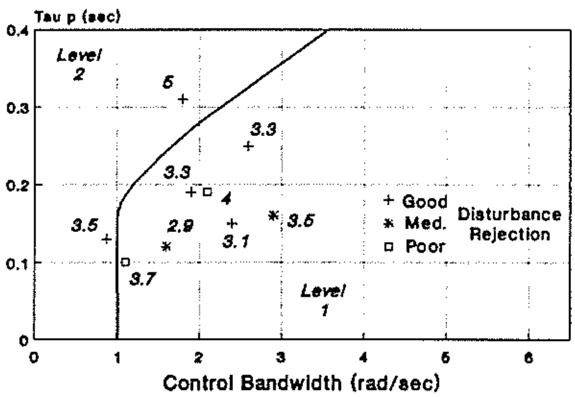

Figure 9: Pitch Axis Results
Sidestep & Pirouette Tasks

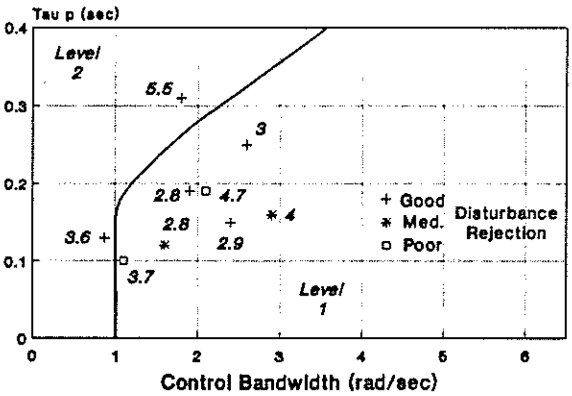

Figure 10: Pitch Axis Results
Quickstop Task

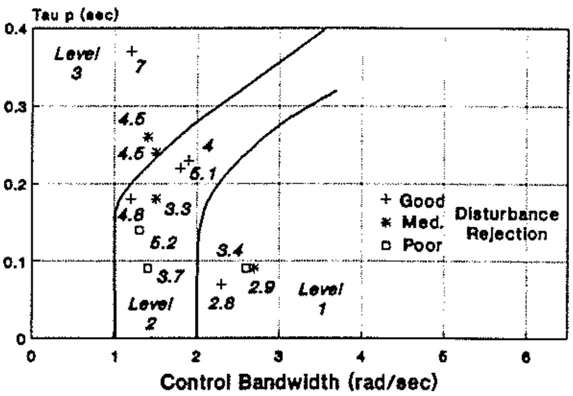

Figure 11: Roll Axis Results
Hover & Landing Tasks

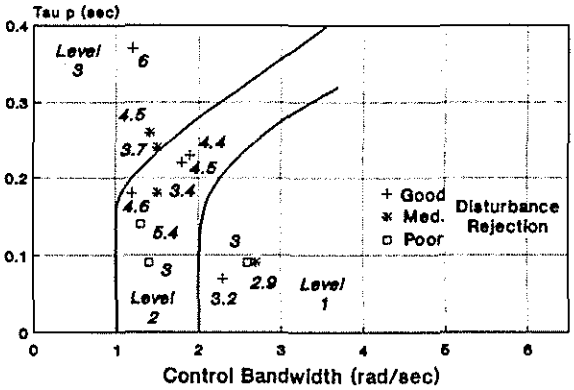

Figure 12: Roll Axis Results
Sidestep & Piroutte Tasks

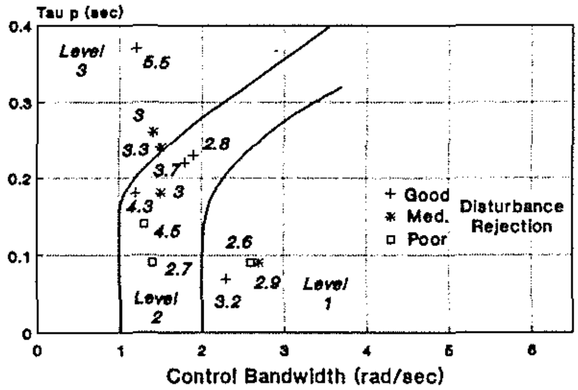

Figure 13: Roll Axis Results
Quickstop Task

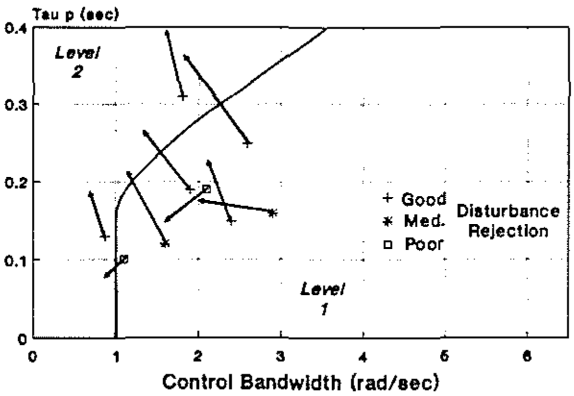

Figure 14: Relocation of Pitch Axis Configurations when Control Force used as Input for Bandwidth Measurement

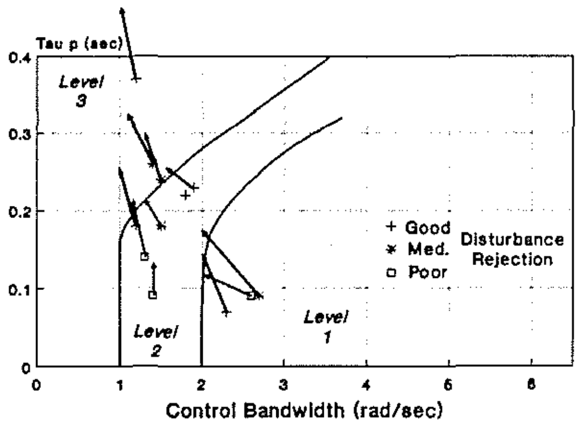

Figure 15: Relocation of Roll Axis Configurations when Control Force used as Input for Bandwidth Measurement

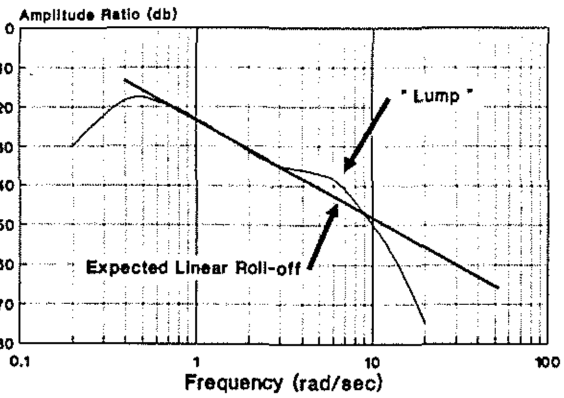

Figure 16: Amplitude Distribution of Control Force to Pitch Attitude for a Gain Margin Limited Configuration

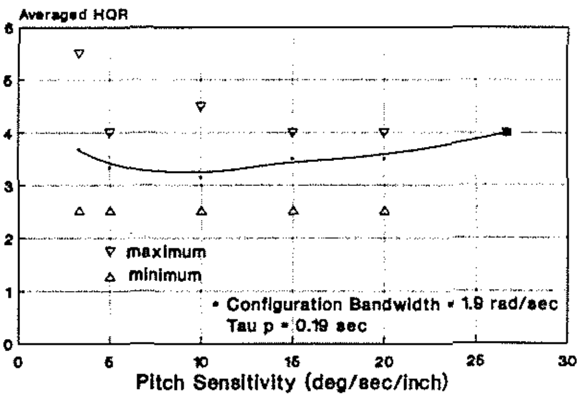

Figure 17: Effect of Sensitivity on High Bandwidth Pitch Model Handling Qualities

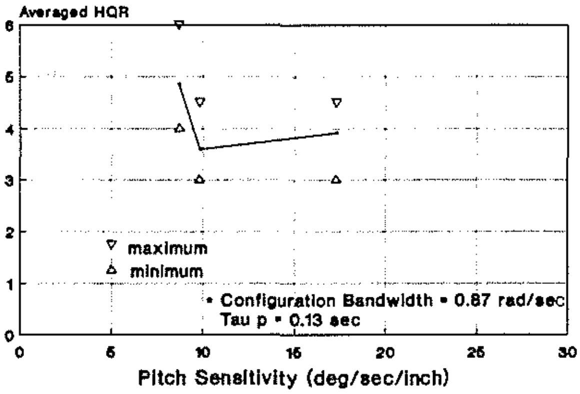

Figure 18: Effect of Sensitivity on Low Bandwidth Pitch Model Handling Qualities

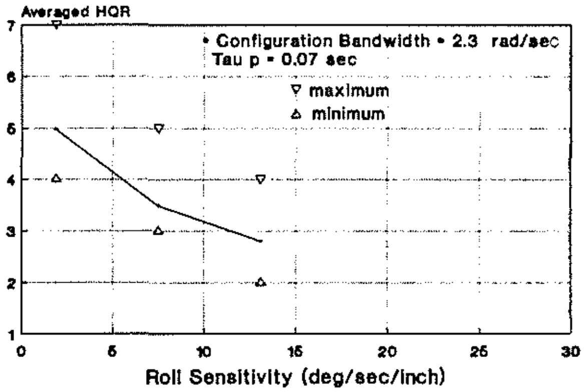

Figure 19: Effect on Sensitivity on High Bandwidth Pitch Model Handling Qualities

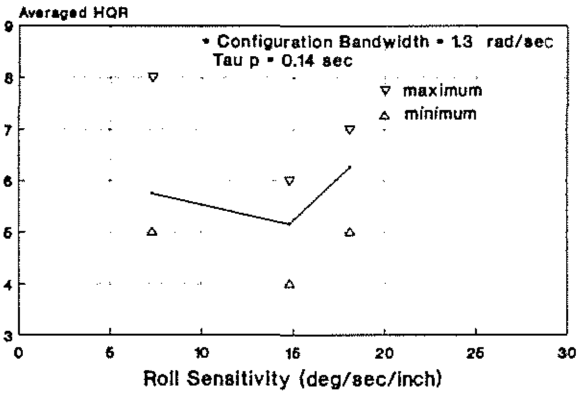

Figure 20: Effect on Sensitivity on Low Bandwidth Roll Model Handling

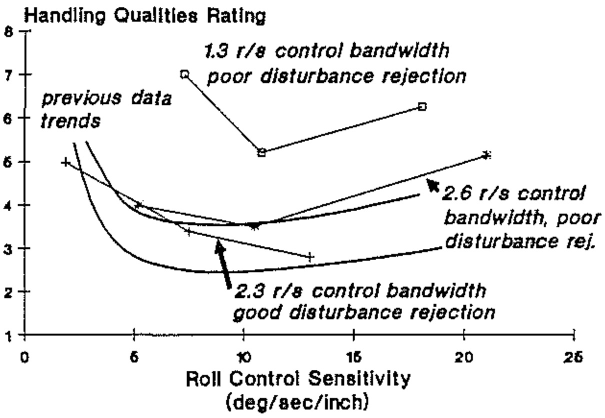

Figure 21: Roll Sensitivity Data vs Previous Research Trends