EVALUATION OF LATERAL-DIRECTIONAL HANDLING QUALITIES AND ROLL-SIDESLIP COUPLING OF FIGHTER CLASS AIRPLANES

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FOREWORD

This report was prepared for the United States Air Force by Cornell Aeronautical Laboratory, Inc. (CAL), Buffalo, New York in partial fulfillment of Contract F33615-71-C-1240, Project No. 8219, Task No. 05 "Simulation of the Handling Qualities Characteristics Critical to Advanced Military Aircraft Through Use of the Variable Stability NT-33A Aircraft."

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ABSTRACT

Lateral-directional handling qualities for Class IV airplanes in Flight Phase Category A were investigated in the USAF/CAL variable stability NT-33A airplane. The primary purpose was to extend the data base for roll-sideslip coupling requirements specified by MIL-F-8785B(ASG) for this Class of airplanes. Other purposes included evaluation of the minimum Dutch roll frequency and damping requirements of MIL-F-8785B(ASG) for Class IV airplanes in Flight Phase Category A and an investigation of the applicability of MIL-F-83300 roll-sideslip requirements to airplanes in high speed flight conditions. Maneuvering tasks representative of the fighter mission and a precision bank angle tracking task were performed for evaluation. Evaluations were conducted at three Dutch roll frequencies, three roll-to-sideslip ratios and at values of Dutch roll damping on either side of the MIL-F-8785B(ASG) boundary. Satisfactory flying qualities were not obtained for any of the low Dutch roll frequency ($\omega_d \approx 1.0$ rad/sec) configurations investigated in this experiment. The Dutch roll damping requirements were found to be adequate, especially when the additional increment of damping as a function of Dutch roll frequency and roll-to-sideslip ratio is added. The roll-sideslip coupling requirements in terms of sideslip excursions were found to be conservative, especially at low to moderate values of roll-to-sideslip ratio. For the configurations evaluated, roll rate oscillations were quite small, even when sideslip excursions exceeded the specified limits, therefore the validity of the roll rate oscillations criteria boundaries was not sufficiently evaluated. The roll-sideslip coupling requirements of MIL-F-83300 were found to be generally not applicable to Class IV airplanes in Flight Phase Category A and high speed flight. Volume I of this report contains the body of the text; Volume II contains the appendices.

TABLE OF CONTENTS

TABLE OF CONTENTS
(continued)

TABLE OF CONTENTS
(continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS
(continued)

LIST OF ILLUSTRATIONS
(continued)

LIST OF ILLUSTRATIONS
(continued)

LIST OF TABLES

LIST OF SYMBOLS

F_{AS} - aileron stick force, lb

F_{ES} - elevator stick force, lb

F_{RP} - rudder pedal force, lb

g - acceleration of gravity, ft/sec^2

h - altitude, ft

I_x - moment of inertia about x axis, ft-lb sec^2

I_y - moment of inertia about y axis, ft-lb sec^2

I_z - moment of inertia about z axis, ft-lb sec^2

I_{xz} - product of inertia, ft-lb sec^2

j = $\sqrt{-1}$

k - ratio of "commanded roll performance" to "applicable roll performance" requirement of MIL-F-8785B(ASG)

L - rolling moment, ft-lb

L_β = $\frac{1}{I_x}\frac{\partial L}{\partial \beta}$, sec^{-2}

L_{δ_a} = $\frac{1}{I_x}\frac{\partial L}{\partial \delta_a}$, sec^{-2}

$L_{\delta_{AS}}$ = $\frac{1}{I_x}\frac{\partial L}{\partial \delta_{AS}}$, deg/sec^{-2} in.$^{-1}$

$L_{F_{AS}}$ = $\frac{1}{I_x}\frac{\partial L}{\partial F_{AS}}$, deg/sec^{-2} lb^{-1}

$L_{\delta_{RP}}$ = $\frac{1}{I_x}\frac{\partial L}{\partial \delta_{RP}}$, deg/sec^{-2} in.$^{-1}$

L_p = $\frac{1}{I_x}\frac{\partial L}{\partial p}$, sec^{-1}

L_r = $\frac{1}{I_x}\frac{\partial L}{\partial r}$, sec^{-1}

L'_i = $\left(1 - \frac{I_{xz}^2}{I_x I_z}\right)^{-1}\left(L_i + \frac{I_{xz}}{I_x} N_i\right)$; $i = \beta, \delta_a, \delta_{AS}, \delta_r, \delta_{RP}, p, r$

m - mass of airplane, slugs

N - yawing moment, ft-lb

N_β = $\frac{1}{I_z}\frac{\partial N}{\partial \beta}$, sec^{-2}

N_{δ_a} = $\frac{1}{I_z}\frac{\partial N}{\partial \delta_a}$, sec^{-2}

LIST OF SYMBOLS
(continued)

$N_{\delta_{AS}}$ = $\frac{1}{I_z}\frac{\partial N}{\partial \delta_{AS}}$, deg/sec^{-2} in.$^{-1}$

N_{δ_r} = $\frac{1}{I_z}\frac{\partial N}{\partial \delta_r}$, sec^{-2}

$N_{\delta_{RP}}$ = $\frac{1}{I_z}\frac{\partial N}{\partial \delta_{RP}}$, deg/sec^{-2} in.$^{-1}$

N_p = $\frac{1}{I_z}\frac{\partial N}{\partial p}$, sec^{-1}

N'_r = $\frac{1}{I_z}\frac{\partial N}{\partial r}$, sec^{-1}

N'_i = $\left(1-\frac{I_{xz}^2}{I_x I_z}\right)^{-1}\left(N_i+\frac{I_{xz}}{I_z}L_i\right)$; $i=\beta,\delta_a,\delta_{AS},\delta_r,\delta_{RP},p,r$

n_y - side acceleration, g units

n_z - normal acceleration, g units

p - roll rate, rad/sec or deg/sec

$\frac{p_{osc}}{p_{AV}}$ a measure of the ratio of the oscillatory component of roll rate to the average component of roll rate following a rudder-pedals-free step aileron control command

$$\zeta_d \le 0.2: \quad \frac{p_{osc}}{p_{AV}} = \frac{p_1 + p_3 - 2p_2}{p_1 + p_3 + 2p_2}$$

$$\zeta_d > 0.2: \quad \frac{p_{osc}}{p_{AV}} = \frac{p_1 - p_2}{p_1 + p_2}$$

where p_1 , p_2 and p_3 are roll rates at the first, second and third peaks, respectively

$\dot{p}$ - roll acceleration, rad/sec^2

p_{ss} - steady state roll rate, rad/sec or deg/sec

$\measuredangle \frac{p}{\beta}$ - phase angle between roll rate and sideslip in the free Dutch roll oscillation

$q_{\bar{c}}$ - $1/2\ \rho V^2$, dynamic pressure, lb/ft^2

r - yaw rate, rad/sec or deg/sec

$\dot{r}$ - yaw acceleration, rad/sec^2

s - Laplace transform parameter, $s = \sigma + j\omega$

S - wing area, ft^2

t - time, sec

LIST OF SYMBOLS
(continued)

t_{n_β} - time for the Dutch roll component of the sideslip response to reach the n^{th} local maximum for a right step or pulse aileron-control command, or the n^{th} local minimum for a left command. In the event a step control input cannot be accomplished, the control shall be moved as abruptly as practical and, for purposes of this definition, time shall be measured from the instant the cockpit control deflection passes through half the amplitude of the commanded value. For pulse inputs, time shall be measured from a point halfway through the duration of the pulse.

T_d - damped period of the Dutch roll, $T_d = \dfrac{2\pi}{\omega_d\sqrt{1-\zeta_d^2}}$

V - true velocity, ft/sec

Y - side force, lb

Y_β = $\dfrac{1}{mV}\dfrac{\partial Y}{\partial \beta}$, sec^{-1}

$Y_{\delta_{AS}}$ = $\dfrac{1}{mV}\dfrac{\partial Y}{\partial \delta_{AS}}$, sec^{-1} in.$^{-1}$

$Y_{\delta_{RP}}$ = $\dfrac{1}{mV}\dfrac{\partial Y}{\partial \delta_{RP}}$, sec^{-1} in.$^{-1}$

Y_p = $\dfrac{1}{mV}\dfrac{\partial Y}{\partial p}$, rad^{-1}

Y_r = $\dfrac{1}{mV}\dfrac{\partial Y}{\partial r}$, rad^{-1}

x, y, z - stability axes (i.e., a right hand orthogonal body axis system with origin at the c.g., the z axis in the plane of symmetry and the x axis aligned with the relative wind at zero sideslip trimmed flight.)

α - angle of attack, radians

α_o - trim angle of attack, radians

β - angle of sideslip, radians or degrees

β_V - angle of sideslip measured by the sideslip probe, radians or degrees

$\dot{\beta}$ - sideslip rate, rad/sec

$\Delta\beta_{max}$ - maximum sideslip excursion at the c.g., occurring within two seconds or one half-period of the Dutch roll, whichever is greater, for a step aileron-control command (MIL-F-8785B(ASG))

LIST OF SYMBOLS
(continued)

$\Delta\beta$	-	the maximum change in sideslip following an abrupt roll control pulse command within time $t_{\Delta\beta}$; where $t_{\Delta\beta}$ is the lesser of 6 seconds or one-half the Dutch roll period, and is measured from a point halfway through the duration of the pulse command ~ degrees (MIL-F-83300)
δ_a	-	aileron deflection, radians
δ_{AS}	-	aileron stick deflection, inches
δ_r	-	rudder deflection, radians
δ_{RP}	-	rudder pedal deflection, inches
ζ_β	-	damping ratio of numerator quadratic in sideslip to aileron input transfer function
ζ_{FS}	-	feel system damping ratio
ζ_ϕ	-	damping ratio of numerator quadratic in roll to aileron input transfer function
ζ_p	-	longitudinal phugoid mode damping ratio
ζ_r	-	damping ratio of numerator quadratic in yaw rate to aileron input transfer function
ζ_{sp}	-	longitudinal short period damping ratio
ζ_d	-	Dutch roll damping ratio
$\lambda_{\beta_{1,2,3}}$	-	real roots of numerator cubic in sideslip to aileron input transfer function
λ_R	-	roll mode root = $-1/\tau_R$
λ_S	-	spiral mode root = $-1/\tau_S$
τ_{r_1}	-	time constant of numerator cubic in yaw rate to aileron input transfer function
ρ	-	air density, slugs/ft^3
σ	-	real part of $s = \sigma + j\omega$
τ_R	-	roll mode time constant, seconds
τ_S	-	spiral mode time constant, seconds

LIST OF SYMBOLS
(continued)

$1/\tau_{\beta_{1,2,3}}$ - zeros of sideslip-aileron transfer function

ϕ - bank angle, radians or degrees

ϕ_t - bank angle change in time t, in response to an aileron step control deflection

$\frac{\phi_{osc}}{\phi_{AV}}$ - a measure of the ratio of the oscillatory component of bank angle to the average component of bank angle following a rudder-pedals-free impulse aileron control command

$$\zeta_d \leq 0.2: \quad \frac{\phi_{osc}}{\phi_{AV}} = \frac{\phi_1 + \phi_3 - 2\phi_2}{\phi_1 + \phi_3 + 2\phi_2}$$

$$\zeta_d > 0.2: \quad \frac{\phi_{osc}}{\phi_{AV}} = \frac{\phi_1 - \phi_2}{\phi_1 + \phi_2}$$

where ϕ_1, ϕ_2 and ϕ_3 are bank angles at the first, second and third peaks, respectively

$\left|\frac{\phi}{\beta}\right|_d$ - at any instant, the ratio of amplitudes of the bank-angle and sideslip-angle envelopes in the Dutch-roll mode

ψ_β - phase angle in a cosine representation of the Dutch roll component of sideslip - negative for a lag

$$\psi_\beta = \frac{-360}{T_d} t_{n_\beta} + (n-1)360 \quad \text{(degrees)}$$

with n as in t_{n_β} above

ψ_p - phase angle of Dutch roll oscillation in roll rate response to step aileron input, deg

ω - imaginary part of $s = \sigma + j\omega$

ω_β - undamped natural frequency of numerator quadratic in sideslip to aileron input transfer function, rad/sec

ω_ϕ - undamped natural frequency of numerator quadratic in bank angle to aileron input transfer function, rad/sec

ω_r - undamped natural frequency of numerator quadratic in yaw rate to aileron input transfer function, rad/sec

ω_d - Dutch roll undamped natural frequency, rad/sec

LIST OF SYMBOLS
(continued)

ω_{SP} - longitudinal short period undamped natural frequency, rad/sec

ω_{P} - longitudinal phugoid mode undamped natural frequency, rad/sec

ω_{FS} - feel system undamped natural frequency, rad/sec

Abbreviations

deg - degrees

IAS - indicated airspeed

in. - inches

kt - knots

lb - pounds

PR - pilot rating

R/C - rate of climb

RMI - radio magnetic indicator

rad - radians

sec - seconds

TR - turbulence effect rating

SECTION I

INTRODUCTION

The primary mission phase of flight for fighter and attack airplanes includes precision tasks such as the firing of air-to-air missiles and the firing of guns at enemy aircraft and ground targets. To successfully accomplish these tasks, the pilot must have the capability to fly his aircraft on a precise flight path and to precisely track an evasively maneuvering target aircraft. During these very demanding operations, the handling qualities of the fighter or attack airplane can directly contribute to or detract from successful mission accomplishment. The military specification for the flying qualities of piloted airplanes, MIL-F-8785B(ASG), Reference 1, attempts to provide the necessary degree of flying qualities by placing requirements on flying qualities parameters or, as in the case of roll-sideslip coupling, placing limits on unwanted responses.

During the recent revision of MIL-F-8785B(ASG) it was found necessary to base the requirements for roll-sideslip coupling of fighter and attack airplanes in their primary mission flight phase, that is, Class IV airplanes in Flight Phase Category A, almost completely on the results of one in-flight investigation, Reference 2. Also, little data were available from which to determine minimum values for Dutch roll frequency.

Therefore, an in-flight investigation to extend the data base for the roll-sideslip coupling requirements specified by MIL-F-8785B(ASG) has been conducted in the USAF/CAL variable stability NT-33A airplane. The data obtained apply only to the requirements of Class IV airplanes in Flight Phase Category A. The investigation also included the acquisition of data to evaluate the minimum Dutch roll frequency requirements of MIL-F-8785B(ASG) and to briefly investigate the adequacy of the minimum specified Dutch roll damping. The applicability of MIL-F-83300 roll-sideslip requirements to airplanes in high speed flight conditions was investigated as part of the overall program objective.

The parameters varied in this program were: the Dutch roll frequency, the Dutch roll damping and the roll-to-sideslip ratio in the Dutch roll. The roll mode and spiral mode time constants were held essentially constant throughout the investigation at values which would not degrade the pilot rating of an evaluation configuration. The amounts of aileron and rudder control inputs that must be used by the pilot are largely determined by the aileron and rudder control sensitivities $L'_{\delta_{AS}}$ and $N'_{\delta_{RP}}$ respectively. Desirable values of the control motion sensitivities have been shown, Reference 2, to be functions of the lateral-directional dynamics present in the system. The evaluation pilot was required to select for each evaluation the aileron and rudder control sensitivities at values that he considered as desirable in order to minimize the detrimental effect of these important parameters on the overall pilot rating. The aileron yaw parameter, $N'_{\delta_{AS}}/L'_{\delta_{AS}}$, was varied in order to effect changes in the bank angle to aileron input transfer function zero location in the s plane so that different degrees of roll-sideslip coupling could be evaluated for a given set of characteristic lateral-directional parameters. Longitudinal characteristics were held constant so that the evaluations of lateral-directional dynamics would not be influenced by varying longitudinal handling qualities.

The flight investigation was accomplished by having the evaluation pilot perform maneuvers representative of the fighter task. The evaluation maneuvers included a precision bank angle tracking task where the pilot was required to follow programmed bank angle commands. Part of each evaluation was performed in the presence of random disturbance inputs to the NT-33A airplane in order to assess the effects of turbulence on the pilot's ability to perform the task.

An overall pilot rating was obtained at the end of each evaluation which included the effects of the random disturbance inputs. A separate turbulence effect rating was also assigned at the completion of each evaluation.

SECTION II

FOUNDATIONS

2.1 BACKGROUND

The recently revised military specification of flying qualities of piloted airplanes, MIL-F-8785B(ASG), Reference 1, places requirements on both lateral-directional modal characteristics, and lateral-directional dynamic response characteristics as well as other lateral-directional considerations. Generally, requirements are stated in terms of response characteristics that are wanted; however, lateral-directional dynamic response requirements are based on limiting unwanted responses. An obvious and determined effort was made to specify the requirements in terms of parameters which could be relatively easily measured from flight data; that is, from time histories of airplane responses obtained using simple inputs such as rudder doublets and aileron steps. Hence there was the intent to specify parameters which could be used to assure compliance with lateral-directional requirements without having to resort to difficult analysis techniques.

In order to make the requirements of Reference 1 applicable to all airplanes, it was necessary to tailor them to the kind of airplane, the job to be accomplished and how well it must be accomplished, or more directly Class, Flight Phase Category and Level. The investigation reported herein is concerned only with Class IV airplanes in Flight Phase Category A. Class IV airplanes are defined as high maneuverability airplanes such as Fighter/Interceptor or Attack. Flight Phase Category A is a nonterminal Flight Phase that requires rapid maneuvering, precision tracking or precise flight path control.

Three Levels of flying qualities are defined and are stated in terms of three different values of the stability and control parameter being specified. Each value is a minimum condition to meet that level of acceptability. Level 1, for example, defines flying qualities which are clearly adequate for the mission Flight Phase. Level 2 flying qualities are adequate to accomplish the mission Flight Phase with some increase in pilot workload or degradation in mission effectiveness or both. Level 3 flying qualities are such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both. Complete definitions of Class, Flight Phase Category and Level are presented in Reference 1.

In the development of roll-sideslip coupling requirements of Reference 1, it was found necessary to base these requirements for Class IV airplanes in Flight Phase Category A almost completely on the results of one in-flight investigation, Reference 2. Since the publication of the revised military specification on flying qualities, no additional data have been generated to substantiate these requirements.

It is interesting to note that the study of Reference 2 did not meet Level 1 requirements for the Dutch roll damping specified in paragraph

3.3.1.1 of MIL-F-8785B(ASG); however, satisfactory pilot ratings were obtained. This may indicate that the Dutch roll damping ratio required, ζ_d = 0.19, could be somewhat relaxed provided other requirements were met. This may, however, depend on the establishment of a turbulence requirement.

Reference 3 states that little experimental data could be obtained to determine the minimum values of Dutch roll natural frequency, ω_d , and therefore the requirements were selected on the basis of characteristics of existing airplanes; hence, some investigation of the adequacy of this requirement would seem desirable.

Subsequent to the publication of MIL-F-8785B(ASG), a military specification for flying qualities of V/STOL aircraft was published, MIL-F-83300, Reference 4. This specification defines lateral-directional requirements boundaries in terms of different parameters or different combinations of parameters from those used in Reference 1. The application of MIL-F-83300 roll-sideslip coupling requirements to piloted airplanes other than V/STOL may provide further guidance toward the specification of roll-sideslip coupling parameters and the necessary test inputs required to determine specification compliance.

2.1.1 Purpose

The primary purpose of this program was to extend the data base for roll-sideslip coupling requirements specified by MIL-F-8785B(ASG) for Class IV airplanes in Flight Phase Category A. The acquisition of new experimental data to extend the understanding of this particular area of flying qualities is pertinent to the development of advanced vehicles and will serve to aid in refining the requirements boundaries of MIL-F-8785B(ASG). Other objectives of the program included: an evaluation of the minimum Dutch roll frequency and damping requirements of MIL-F-8785B(ASG) as they apply to Class IV airplanes in Flight Phase Category A, and the investigation of the applicability of MIL-F-83300 requirements to airplanes in high speed flight conditions.

2.1.2 Scope of the Investigation

Any investigation of lateral-directional dynamics must necessarily be limited in the number of parameters that can be varied and the number of variations that can be made. Therefore, it was necessary to select those parameters which were considered most important to the concepts being evaluated. It was likewise important to hold other parameters at constant values for which there was confidence that the evaluations would not be degraded. After analysis of available applicable data and a review of the rationale of Reference 3, the parameters discussed below were determined to be the most significant to the objectives of this program.

2.1.2.1 Dutch Roll Mode

The Dutch roll mode is not deliberately used by the pilot in normal maneuvering of the airplane but it strongly affects the control techniques that the pilot will employ and, under certain circumstances, it can seriously interfere with precision of control of the flight path. The Dutch roll may be excited whenever yawing moments, rolling moments or side forces are applied to the airplane. The resulting motion generally manifests itself as a coupled oscillation in sideslip and roll rate which may persist if the Dutch roll damping ratio is low. If the airplane has yaw due to aileron deflection, N'_{δ_a} , sideslip is developed with an aileron input and Dutch roll oscillations may be excited every time the pilot attempts aileron inputs for roll control, unless the yawing moments are perfectly countered with coordinated use of the rudder. Yaw due to roll rate, N'_p , will also excite the Dutch roll as the roll rate develops. It is the purpose of paragraph 3.3.2 of MIL-F-8785B(ASG) to place limits on these unwanted responses through the specification of maximum sideslip excursion, $\Delta\beta_{max}$, to an aileron step input and the specification of maximum allowable roll rate oscillations as measured by the parameter p_{osc}/p_{AV}.

Dutch roll frequency affects the pilot's ability to control heading. It can be shown that the amount of sideslip caused by yawing moments is inversely proportional to the square of the Dutch roll frequency, ω_d^2 . Hence, as ω_d is reduced, it becomes more difficult for the pilot to keep the airplane pointed in the direction that the airplane is actually going.

If the areas of Level 1 roll-sideslip requirements are mapped on an s plane plot in terms of the numerator zeros of the $p(s)/\delta_a(s)$ transfer function, it can be seen that the area of satisfactory flying qualities varies with Dutch roll frequency, being larger at high ω_d and smaller at low ω_d . Figure 1, extracted from Reference 3, illustrates the effects of changes in the Dutch roll mode on acceptable areas for $p(s)/\delta_a(s)$ transfer function zero locations. Hence, to evaluate roll-sideslip coupling phenomena it was necessary to evaluate several values of ω_d . The values selected were based on the minimum ω_d requirements of MIL-F-8785B(ASG) and the characteristics of current Class IV airplanes.

Values of Dutch roll damping ratio, ζ_d , also affect the Level 1 area in an s plane plot as shown in Figure 1. Evaluation values of ζ_d were selected so as to bracket the specified boundary of MIL-F-8785B(ASG). Testing both sides of the boundary should serve to confirm or refute the requirement, and aid in assessing the Level 1 s plane area, at least in the vertical direction.

2.1.2.2 Roll-to-Sideslip Ratio

The roll-to-sideslip ratio, $|\phi/\beta|_d$, strongly affects the manifestation of roll-sideslip coupling and the pilot technique used for bank angle and sideslip control. For very low values of $|\phi/\beta|_d$, little rolling motion

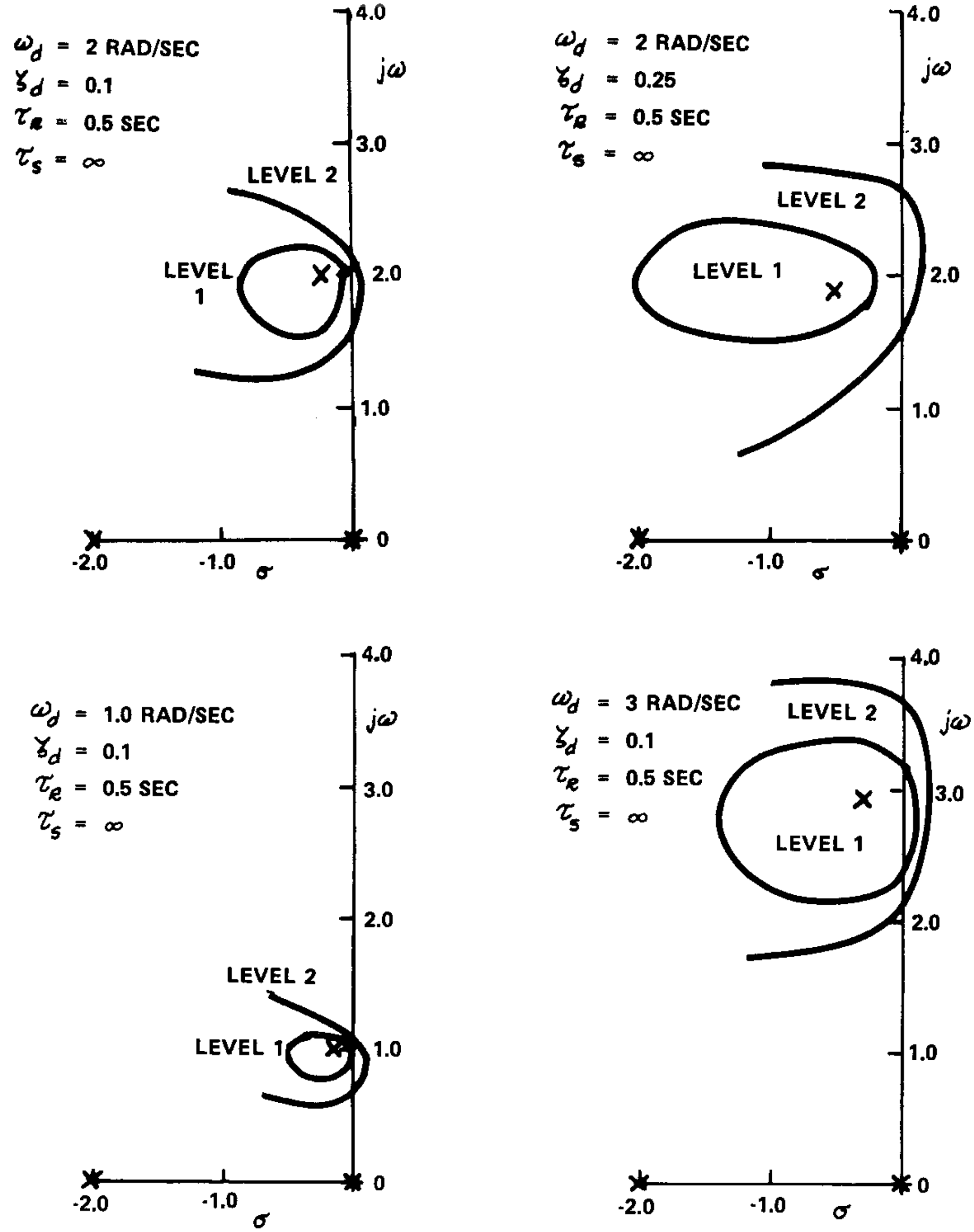

Figure 1 Areas of $\phi(s)/\delta_{AS}(s)$ Transfer Function Zero Locations for Flight Phase Categories A and C (Reference 3)

occurs as a result of sideslip disturbance; that is, the Dutch roll oscillation will occur mostly in sideslip and the pilot will tend to use little or no aileron inputs to counter the Dutch roll. He will have to use rudder inputs to suppress the Dutch roll once disturbed. At high values of $|\phi/\beta|_d$ the Dutch roll will appear more as a coupled sideslip and roll rate, or bank angle, oscillation and the pilot will use aileron inputs and attempt to coordinate rudder inputs to prevent or control the Dutch roll. The pilot may in this case find it difficult to precisely control roll rate or acquire a given bank angle. For very large values of $|\phi/\beta|_d$ the airplane may become very sensitive to turbulence disturbances and very sensitive in roll to rudder pedal inputs causing it to never be considered as a satisfactory airplane. Three values of $|\phi/\beta|_d$ were selected for evaluation; the lowest value, however, was limited to only one Dutch roll frequency and damping ratio. The specific values selected were based on the roll-sideslip coupling considerations discussed above and on values found to be applicable to current Class IV airplanes.

2.1.2.3 Lateral-Directional Parameters Held Constant

The roll mode is the lateral-directional mode most closely associated with intentional rolling maneuvers. It is usually a short term response and strongly influences the pilot's control of bank angle. The defining factor of the roll mode is the time constant τ_R. Typical variations in this parameter for Class IV airplanes are presented in Reference 6. For this experiment a representative value of τ_R was selected and maintained through the investigation. Reference 2 examined several values of τ_R, however, the basic value was $\tau_R = 0.4$ seconds. MIL-F-8785B(ASG) requires $\tau_R \leq 1.0$ seconds for Level 1 flying qualities for Class IV airplanes in Flight Phase Category A. Examination of data used as background for roll mode requirements indicates relatively little influence on pilot rating for values of τ_R between 0.3 and 1.0 seconds. Therefore the value selected for this experiment was the basic value used in Reference 2, $\tau_R = 0.4$ seconds.

The spiral mode is usually a long term response with little effect during a continuous closed-loop tracking task. For the purposes of this experiment the spiral root was held essentially at the origin of the s plane resulting in a practically neutral spiral mode.

2.1.2.4 Control Sensitivities

Aileron and rudder control sensitivities, $L'_{\delta_{AS}}$ and $N'_{\delta_{RP}}$ respectively, largely determine the amounts of aileron and rudder control inputs that must be used. Reference 2 shows that desirable values of control motion sensitivity parameters are functions of the lateral-directional dynamics present in the system. To minimize the effect of control motion gradients on the evaluation of the given airplane dynamics, and to provide additional data on the selection of these parameters in this experiment as in the study of Reference 2, the evaluation pilot was required to select both the aileron and rudder sensitivities for each evaluation.

2.2 MIL-F-8785B(ASG) LATERAL-DIRECTIONAL REQUIREMENTS

The MIL-F-8785B(ASG) requirements on lateral-directional modal characteristics are presented in terms of familiar parameters such as Dutch roll frequency, Dutch roll damping, roll mode time constant and spiral stability. These requirements are stated (Reference 1) so as to assure suitable responses to control inputs for various levels of acceptability.

Lateral-directional roll-sideslip coupling requirements, however, are presented in terms of possibly unfamiliar parameters and place limits on unwanted responses resulting from control inputs. The parameters used to specify roll-sideslip coupling requirements include, but are not necessarily limited to, p_{osc}/p_{AV} , ϕ_{osc}/ϕ_{AV}, $\Delta\beta$, ψ_β , and k . These parameters are defined in the list of symbols of this report as well as in References 1 and 3.

Roll rate oscillation limitations, p_{osc}/p_{AV} , and sideslip excursion limitations, $\Delta\beta_{max}/k$, for small aileron step inputs are specified in terms of requirements boundaries on plots of p_{osc}/p_{AV} versus ψ_β and $\Delta\beta_{max}/k$ versus ψ_β .

The plots from Reference 1 are reproduced below for the convenience of the reader.

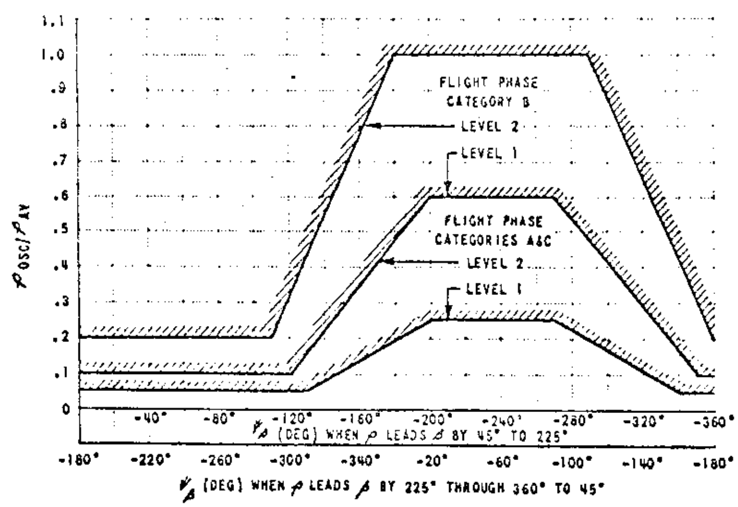

Figure 2 Roll Rate Oscillation Limitations From MIL-F-8785B(ASG)

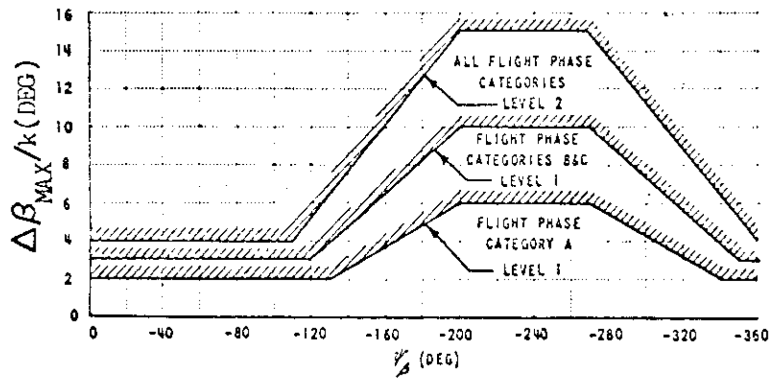

Figure 3 Sideslip Excursion Limitations
From MIL-F-8785B(ASG)

ϕ_{osc}/ϕ_{AV} versus ψ_β for an aileron pulse input may be used in lieu of p_{osc}/p_{AV} versus ψ_β for an aileron step input. The parameter ψ_β is a measure of the lag between the control input and the sideslip response, but more important, it is a measure of the difficulty of coordination. The two scales for ψ_β on Figure 2 are intended to account for positive effective dihedral effect (p leads β by 45° to 225°) and negative effective dihedral (p leads β by 225° through 360° to 45°).

It is not the intent here to carefully review the development of these parameters and requirements, but merely to afford the reader some familiarity. A complete analysis of the rationale and background is contained in Reference 3.

2.3 MIL-F-83300 ROLL-SIDESLIP COUPLING

MIL-F-83300 specifies limits on bank angle oscillations, ϕ_{osc}/ϕ_{AV}, as a function of ψ_β for an aileron pulse input, a requirement very similar to that presented in Reference 1. Sideslip excursion limitations, however, are presented in terms of $|\Delta\beta/\phi_1|$ versus ψ_β and $|\Delta\beta/\phi_1| \times |\phi/\beta|_d$ versus ψ_β where the applicable control input is an aileron pulse. ϕ_1 is the magnitude of the bank angle at the first peak of the bank angle time history and $\Delta\beta$ is the maximum change in sideslip within a specified time as shown in the List of Symbols of this report. ψ_β retains the definition of Reference 1. The requirement boundaries for sideslip excursion limitations from Reference 4 are reproduced below as Figures 4 and 5.

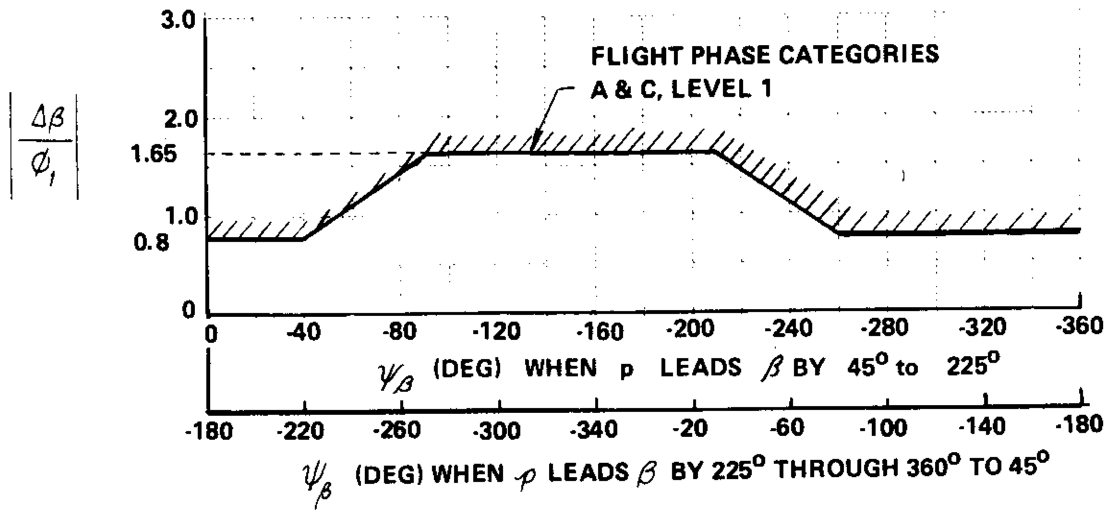

Figure 4 Sideslip Excursion Limitations (Boundary for $|\Delta\beta/\phi_1|$) From MIL-F-83300

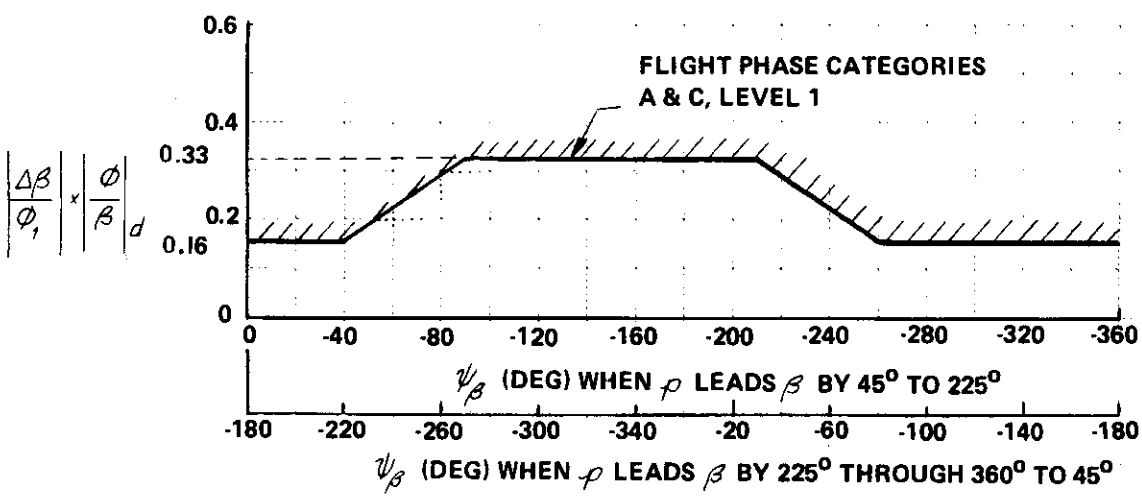

Figure 5 Sideslip Excursion Limitations (Boundary for $|\Delta\beta/\phi_1| \times |\phi/\beta|_d$) From MIL-F-83300

SECTION III

DESCRIPTION OF EXPERIMENT

3.1 TEST PROGRAM

In order to develop a test program representative of Class IV airplanes in Flight Phase Category A, the lateral-directional characteristics of current Class IV airplanes were reviewed. The range of modal parameters selected was based on both the characteristics of current airplanes and the need to extend the data base on MIL-F-8785B(ASG) roll-sideslip coupling parameters. It was also desirable to obtain data to confirm or refute the MIL-F-8785B(ASG) basic Dutch roll requirements by testing the minimum Dutch roll frequency and damping requirements in a representative fighter task.

Based on the above considerations, a matrix of basic evaluation configurations was developed as shown in Table I. It should be pointed out that the values of the modal parameters shown in Table I were target values and were not the exact values realized during the evaluations; however, they do represent nominal values. Each configuration is completely defined in Appendix IV.

TABLE I

BASIC EVALUATION CONFIGURATIONS

ω_d	1.0 rad/sec		2.5 rad/sec		4.5 rad/sec	
ζ_d	0.25	0.50	0.10	0.25	0.10	0.25
$\lvert\phi/\beta\rvert_d \approx .5$				1		
$\lvert\phi/\beta\rvert_d \approx 1.5$	2	3	4*	5, 5A** 5B, 5ND	6	7
$\lvert\phi/\beta\rvert_d \approx 5.0$	8	9	10*	11, 11A, 11B**	12	13

Numbers in each box are identification number for configurations evaluated.

* Configurations 4 and 10 were not included in the evaluations since these configurations were evaluated in the study of Reference 2.

** 5A, 5B, 11A and 11B represent configurations with the same Dutch roll root as the basic configurations 5 and 11 respectively, but with different values of the derivative N'_p . 5ND represents a configuration with essentially the Dutch roll root of the basic configuration 5 but with negative effective dihedral.

The eleven basic evaluation configurations represent five Dutch roll pole locations as shown on the s plane plot, Figure 6, and three values of the response ratio $|\phi/\beta|_d$. Each of the basic configurations was evaluated with at least five different locations of the zero of the bank angle to aileron input, $\phi(s)/\delta_{AS}(s)$, transfer function. Changes in the zero location of the $\phi(s)/\delta_{AS}(s)$ transfer function were effected by varying the aileron yaw parameter, $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ while holding all other parameters constant. Two of the medium frequency configurations, 5 and 11, were also evaluated at two additional values of the derivative N'_p and one configuration was evaluated with negative effective dihedral. These configurations were identified as 5A, 5B, 5ND, 11A and 11B and were evaluated with at least three different locations of the zero in the bank-angle to aileron-input transfer function, $\phi(s)/\delta_{AS}(s)$.

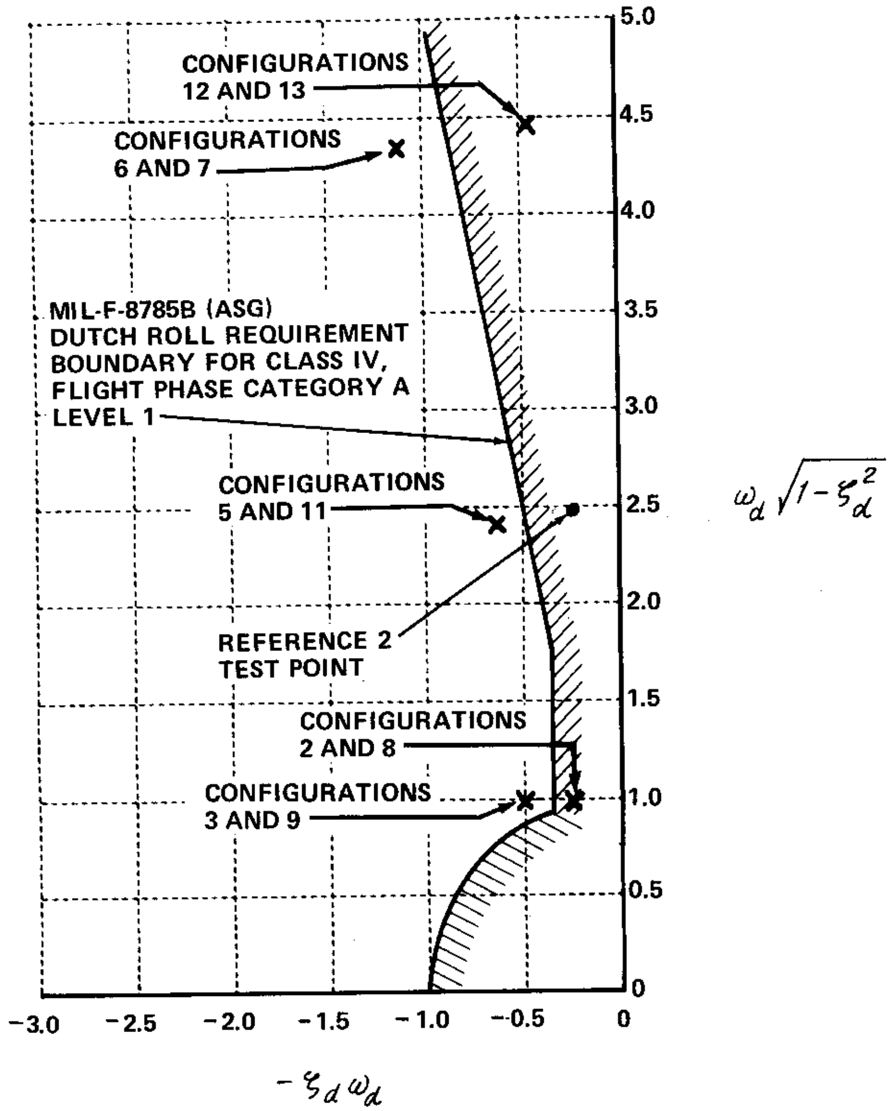

Figure 6 s Plane Plot of Dutch Roll Pole Locations Evaluated

Values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ to be evaluated were determined from computer-generated time history data compared to the p_{osc}/p_{AV} versus ψ_β or $\Delta\beta_{max}/k$ versus ψ_β requirement boundaries given in Reference 1. $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ was selected such that the requirement boundaries could be properly tested. As a result the same values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ were not necessarily evaluated for each configuration.

3.2 EQUIPMENT

Evaluations were conducted in the USAF/CAL three-axis variable stability NT-33A airplane, Figure 7, modified and operated by CAL for the AFFDL, Air Force Systems Command. A complete description of the NT-33A airplane is contained in Reference 7.

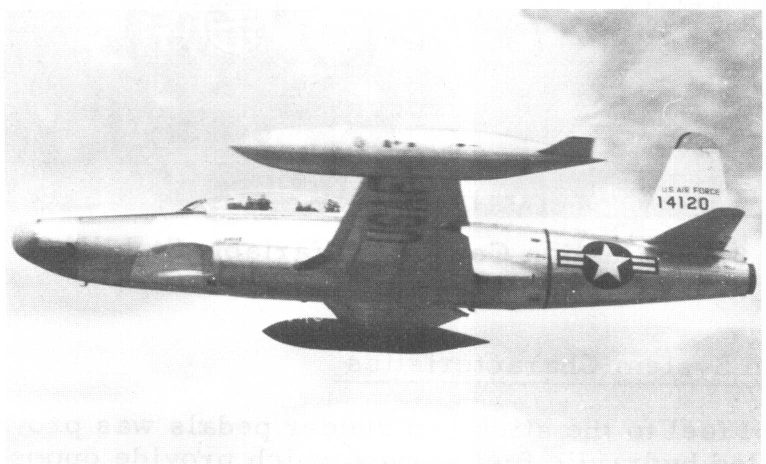

Figure 7 USAF/CAL Variable Stability NT-33A

In the NT-33A variable stability airplane, the system operator (who was also the safety pilot in the rear cockpit) altered the handling qualities about all three axes by varying the settings of the response-feedback gain controls. The evaluation pilot in the forward cockpit was unaware of the control surface motions resulting from the variable stability system signals since his controls moved only as a result of his own inputs. The front cockpit was equipped with a stick controller which is representative of Class IV or fighter type airplanes. The instrument layout of the evaluation cockpit is shown in Figure 8.

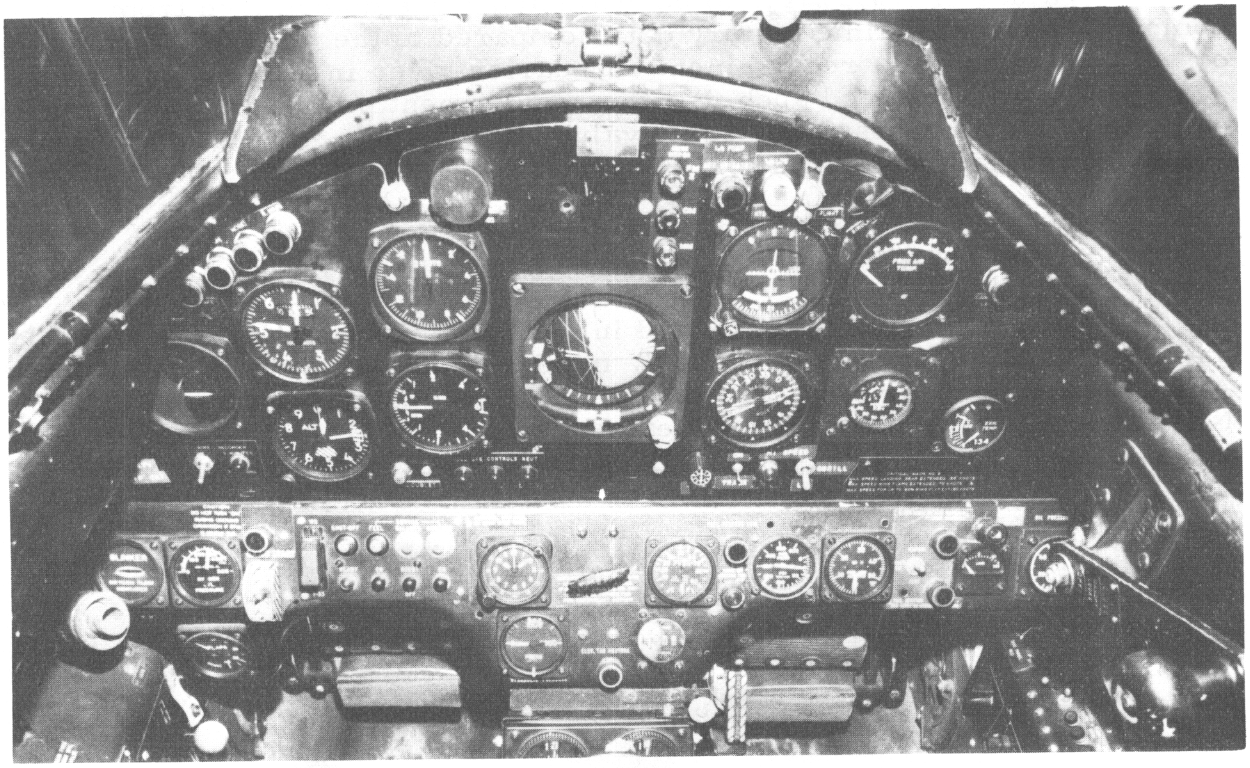

Figure 8 Evaluation Cockpit in Variable Stability NT-33A

3.2.1 Control System Characteristics

Control feel to the stick and rudder pedals was provided by electrically controlled hydraulic feel servos which provide opposing forces proportional to the control stick or rudder pedal deflections. The feel system is, in effect, a simple linear spring feel system. The dynamics of the feel systems for the aileron, rudder and elevator were held constant throughout the experiment at the values shown below:

$$\omega_{FS} = 25 \text{ rad/sec}$$

$$\zeta_{FS} = 0.70$$

Control system force gradients were maintained at the following values:

$$F_{ES}/\delta_{ES} = 22 \text{ lb/in.}$$

$$F_{AS}/\delta_{AS} = 4.0 \text{ lb/in.}$$

$$F_{RP}/\delta_{RP} = 120 \text{ lb/in.}$$

Maximum aileron stick deflection was ± 5.5 inches at the grip. Elevator stick deflection was limited to 4.5 inches forward of neutral and 5.25 inches aft. Preload types of breakout forces were provided and set at constant values of 1.5 lb for the elevator and 1.0 lb for the ailerons. Rudder breakout force was zero, however, the rudder pedals exhibited positive centering because the feel system provided an opposing force proportional to the rudder pedal deflection from center. Control friction, or hysteresis, forces were set at essentially zero for all three controls.

The control sensitivities of the aileron stick, $L'_{\delta_{AS}}$, and of the rudder pedals, $N'_{\delta_{RP}}$, were selected by the pilot during each evaluation at the values he considered suitable for that particular evaluation. This procedure was chosen so that pilot rating would not be degraded because of control sensitivity. The values so selected are presented in Section IV since they represent part of the data obtained from the experiment.

3.2.2 Longitudinal Characteristics

Since the purpose of the experiment was to investigate lateral-directional dynamics and roll-sideslip coupling, the longitudinal dynamics were held constant throughout the program at sufficiently good values so as to cause no degradation of pilot ratings. The longitudinal dynamics were as follows:

$$\omega_{SP} = 6.0 \text{ rad/sec} \qquad \zeta_{SP} = 0.85$$

$$n_z/\alpha = 18.5 \text{ g/rad} \qquad 1/T_{\theta_2} = 1.07$$

$$F_{ES}/g = 6.5 \text{ lb/g} \qquad V_{true} = 556 \text{ ft/sec}$$

The phugoid frequency and damping ratio, ω_p and ζ_p respectively, were essentially those of the T-33 airplane which has a phugoid period of $T_p \approx 65.0$ seconds and a damping ratio of the order of $\zeta_p = 0.05$.

3.2.3 Random Disturbance Inputs

In both the air-to-air and air-to-ground fighter tasks, the turbulence encountered has a bearing on the ability of the pilot-airplane system to accomplish the mission. The NT-33A does not have the capability to vary the lift response to gust-induced angle of attack changes, therefore the independent heaving motion normally associated with vertical gusts cannot be simulated. The lateral-directional responses to gusts, however, can be more realistically simulated in still air since they primarily affect the angular accelerations of the airplane. Though not an exact simulation of turbulence, random noise sources were used to provide disturbances to the airplane during the evaluations by driving the NT-33A control surface actuators with filtered random Gaussian white noise signals. The filter characteristics are shown in Appendix II.

Four independent random noise sources were used in the system. Three of the noise generators provided uncorrelated signals to the ailerons, rudder and elevator servo actuators. Signals from a fourth noise source were passed through a level sensing circuit which switched out all noise signals to the surface actuators when the signal from source No. 1 as shown in Figure 9 dropped below a predetermined level. In this way it was possible to simulate the "patchiness" of real turbulence. The amplitudes of the disturbance signals were selected at levels determined to be representative of turbulence of moderate intensity for Configuration 2 which had a Dutch roll frequency, $\omega_d \approx 1.0$ radian per second, and a roll-to-sideslip ratio, $|\phi/\beta|_d \approx 1.5$. The signals to the rudder and ailerons were varied from those selected values in proportion to the Dutch roll frequency and the roll-to-sideslip ratio respectively. For example, for a configuration with $\omega_d \approx 2.5$ radians per second and $|\phi/\beta|_d \approx 5.0$, the random disturbance gains to the rudder were increased by a factor of 2.5 and the gains to the ailerons were increased by a factor of 3.3 times those gains selected for Configuration 2. This, in effect, scaled the random noise signals making them compatible with the lateral-directional modal parameters being simulated.

A sample time history of aileron, rudder and elevator random disturbance inputs is shown in Appendix II.

3.3 EVALUATIONS

3.3.1 Mission Definition and Evaluation Tasks

The general fighter mission comprises a large variety of specific tasks including:

1. the delivery of air-to-air weapons for the destruction of enemy aircraft,

2. the delivery of air-to-ground weapons, and

3. the associated tasks such as formation flying, aerial refueling, and flight in instrument weather conditions.

It was not feasible to perform tasks of the variety and magnitude indicated above in one in-flight investigation. A set of evaluation maneuvers was chosen, therefore, which was representative of the maneuvering requirements in the fighter mission. Specifically, the tasks included up-and-away maneuvering requirements of the fighter mission in visual flight with a brief look at ground attack tracking. Table II is a list of the evaluation maneuvers in the sequence in which they were performed.

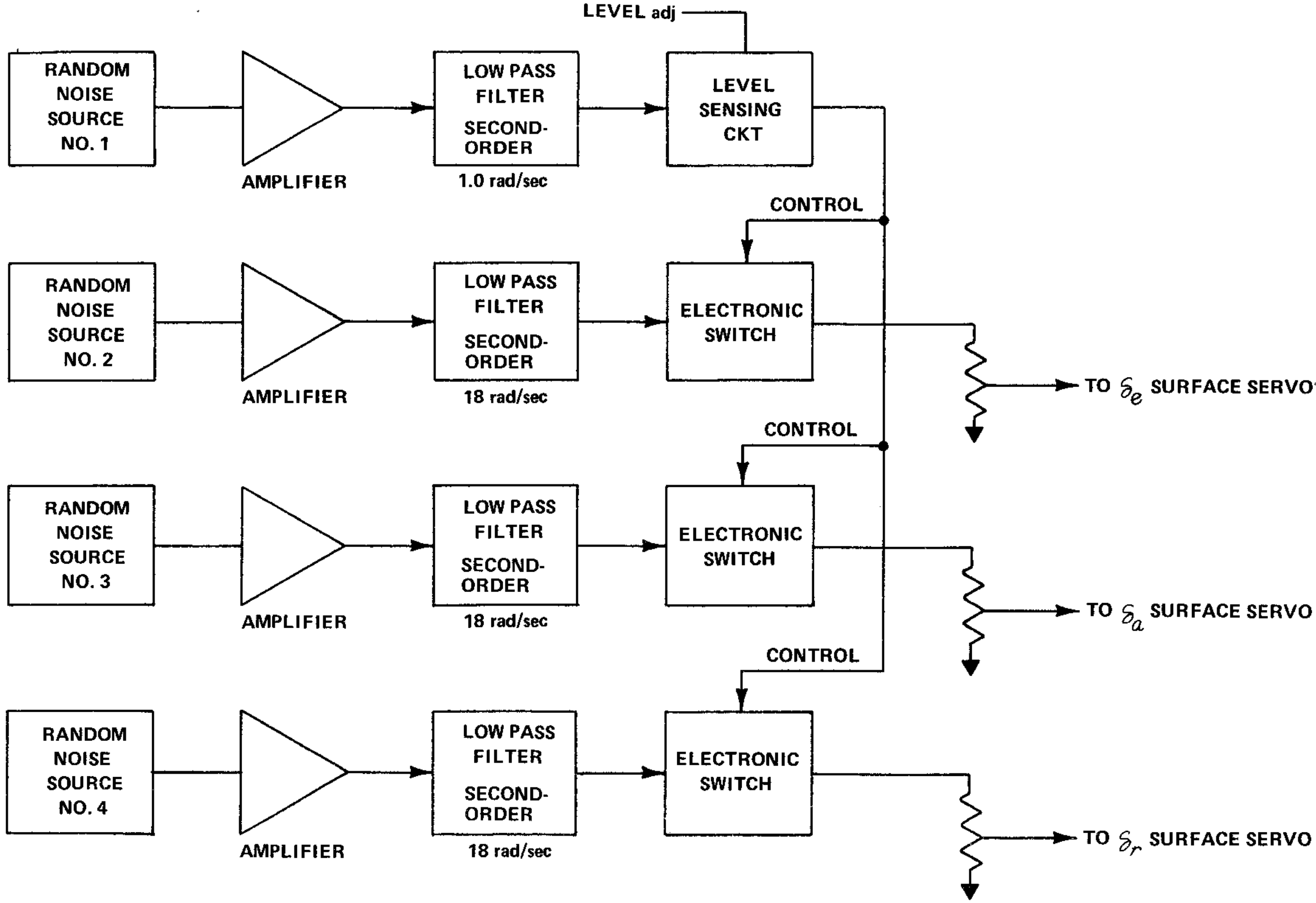

Figure 9 Artificial Turbulence (Random Noise) Circuits for NT-33A Airplane

TABLE II

EVALUATION MANEUVERS

(1) Familiarization with the configuration and selection of control sensitivities.

(2) Small maneuvers about level flight ($\phi \approx 10°$) with particular emphasis on the ability to maintain precise bank angles and to re-establish level flight on a desired heading.

(3) Precision maneuvering during 30 and 60 degree bank turns with particular emphasis on the ability to acquire and maintain precise bank angles and the ability to re-establish level flight on a desired heading or track.

(4) Rapid maneuvering with large bank angle changes with particular emphasis on the ability to acquire a given bank angle with bank angle changes of 30 to 120 degrees with n_z ranging up to + 4 g, and ability to return to level flight on a specific track.

(5) Bank angle command tracking task, using bank angle steering information programmed on the vertical command needle of the NT-33A Lear remote attitude director indicator.

(6) Ground attack (pullup, wingover, track, pullup). During this maneuver the evaluation pilot shall track a pre-selected ground target using a fixed reference on the NT-33A or a simulated reticle on the windscreen.

(7) Maneuver the airplane with random disturbance inputs in order to assess the effects of disturbance inputs on the handling qualities.

The bank angle tracking task, item (5) above, required the evaluation pilot to follow a bank angle command needle. This task is representative, in bank angle tracking, of the air-to-air intercept tracking task where radar steering information is normally displayed to the pilot. In this experiment, the center instrument in the layout shown in Figure 8 (a Lear remote attitude director indicator) was programmed so that the vertical command bar (which normally displayed sideslip angle) displayed bank angle command tracking error during the tracking task - that is, the error between the commanded bank angle and the airplane bank angle. When the airplane bank angle matched the commanded bank angle, the command bar was centered. The programmed signal commanded various bank angles of up to ± 60 degrees. The changing bank angle commands were presented to the pilot as step inputs passed through a first-order, one-radian-per-second filter. The pilot was thus required to maneuver rapidly and precisely in order to minimize the error. The duration of the task was controlled by the evaluation pilot, but the programmed signals were repeated every 3.3 minutes. The repetition period was long enough to prevent the pilot from anticipating the direction, magnitude or rapidity of the commands. Figure 10 shows one period of the bank angle step commands.

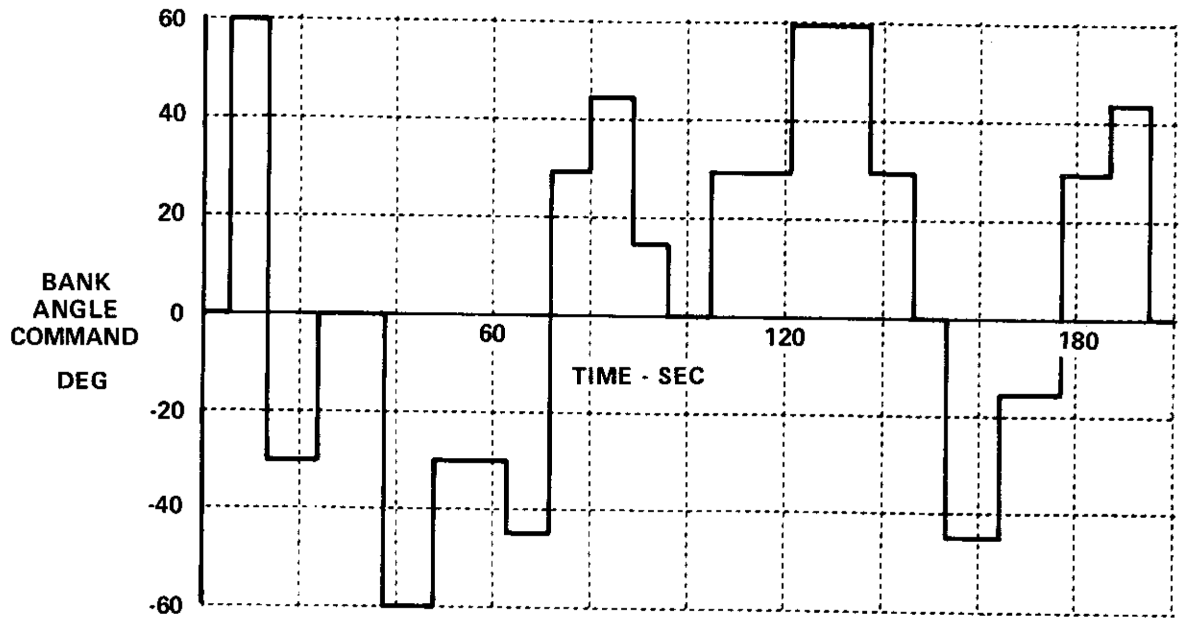

Figure 10 Bank Angle Command Tracking Task

3.3.2 Evaluation Procedure

Three configurations were evaluated on each flight. After leveling the airplane at the nominal evaluation flight condition of 17,000 feet MSL and 250 knots, the safety pilot would set the variable stability gains for the first evaluation. The evaluation pilot would then complete his evaluation. While the evaluation pilot tape recorded his comments and ratings, the safety pilot prepared the airplane for the next evaluation. This sequence was followed until the three evaluations were completed. A total of 84 evaluations were completed during the experiment.

3.3.3 Evaluation Pilot

The program was accomplished with one evaluation pilot. Of the 84 evaluations he performed, 9 were repeat evaluations. A summary of his flight experience is presented below:

CAL research pilot with over 3000 hours of diversified flying time including 2200 hours in fighter type aircraft. He has extensive experience as an evaluation pilot in handling qualities experiments employing variable stability airplanes, and has previously served as evaluation pilot in five in-flight investigations of handling qualities of fighter aircraft and several investigations of aircraft other than fighters.

3.3.4 Pilot Comment and Rating Data

Pilot comments and ratings were the primary data source. The pilot rating can only be properly interpreted and objections properly assessed if good comments are obtained. Pilot comments were encouraged at any time that the pilot felt it appropriate during the evaluation. For data consistency, it was required that the pilot comment on the items listed in Table III either during or at the completion of each evaluation. An overall pilot rating was assigned by the pilot to each configuration in accordance with the Cooper-Harper rating scale established and described in Reference 8 and shown in Figure 11. The pilot rating assigned by the evaluation pilot to each configuration included the effects that random noise disturbances may have had on the overall handling qualities.

In addition, an alphabetical turbulence effect rating was assigned which was solely an assessment of the effects on the handling qualities of random noise disturbances. These ratings were established in accordance with the turbulence effect rating scale, Figure 12.

3.3.5 Data Acquisition

Both an oscillograph recorder and a digital tape recorder were used to document the airplane responses to a rudder doublet, an aileron step and an aileron pulse prior to and immediately after each evaluation. Airplane responses, pilot control usage, and tracking task error were recorded during the bank angle tracking task. Pilot comments and ratings were recorded in flight on a voice tape recorder for later transcription. As a backup, the safety pilot manually recorded the pilot ratings on the flight card which provided the variable stability gain settings for each configuration. Control sensitivities, $L'_{\delta_{AS}}$ and $N'_{\delta_{RP}}$, that were selected by the evaluation pilot were also recorded by the safety pilot.

TABLE III

PILOT COMMENT CARD

A. Make comments at any time desired.

B. Comment on initial impressions of the configurations and the lateral-directional handling qualities in general.

C. Comment on the following specific items:

1. Ability to trim
   a) lateral-directional
   b) longitudinal
2. Selection of aileron and rudder control sensitivities
   a) explain selection
   b) compromises
   c) forces
   d) displacements
   e) harmony
3. Airplane response to pilot inputs (initial-final)
   a) aileron without rudder
   b) coordinated aileron and rudder inputs
   c) oscillatory characteristics
   d) maneuvering coordination requirements
4. Ability to achieve desired bank angle and the ease or difficulty encountered.
5. Ability to achieve desired heading and the ease or difficulty encountered.
6. Bank angle command task
   a) ease of performance
   b) problems encountered
7. Response to disturbance inputs - comment.
8. Longitudinal handling qualities, do they degrade or interfere with evaluation of the lateral-directional handling qualities?
9. How suitable are the airplane's characteristics for the fighter mission?
   a) air-to-air
   b) air-to-ground
   c) any special problems

D. Summary comments.

1. Good features.
2. Objectionable features.
3. Special piloting techniques.
4. Pilot rating and primary reason for it.
5. Turbulence rating.

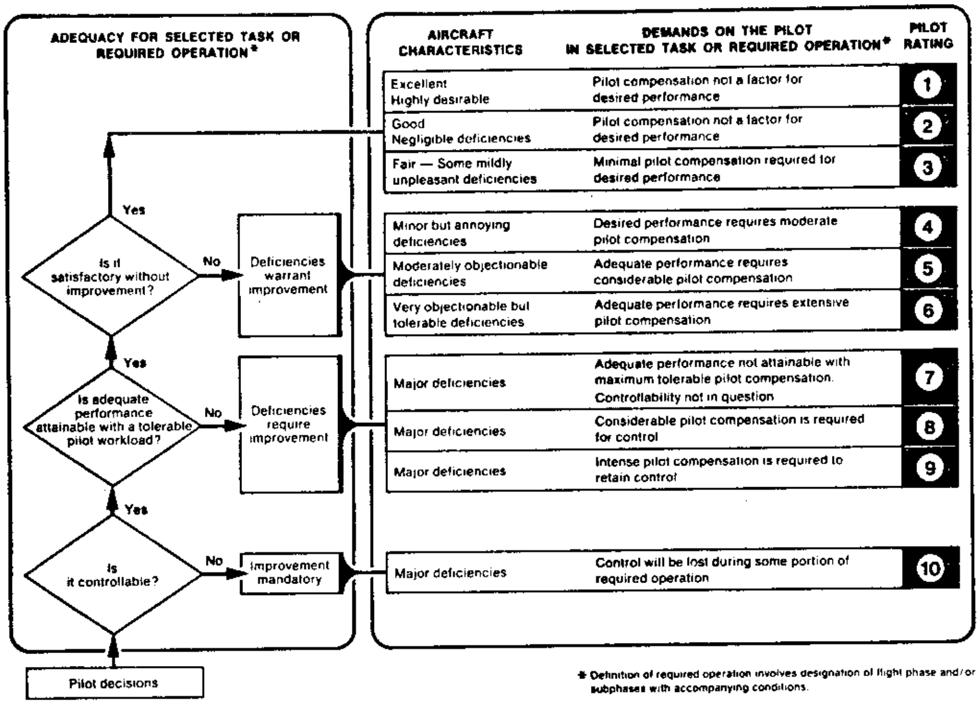

Figure 11 Cooper-Harper Handling Qualities Rating Scale

INCREASE OF PILOT EFFORT WITH TURBULENCE	DETERIORATION OF TASK PERFORMANCE WITH TURBULENCE	RATING
NO SIGNIFICANT INCREASE	NO SIGNIFICANT DETERIORATION	A
MORE EFFORT REQUIRED	NO SIGNIFICANT DETERIORATION	B
	MINOR	C
	MODERATE	D
BEST EFFORTS REQUIRED	MODERATE	E
	MAJOR (BUT EVALUATION TASKS CAN STILL BE ACCOMPLISHED)	F
	LARGE (SOME TASKS CANNOT BE PERFORMED)	G
UNABLE TO PERFORM TASKS		H

Figure 12 Turbulence Effect Rating Scale

SECTION IV

DISCUSSION OF RESULTS

4.1 EVALUATION CONFIGURATIONS

Eleven basic configurations were evaluated representing combinations of five Dutch roll pole locations and three roll-to-sideslip ratios. The evaluation matrix is shown in Table I and the Dutch roll pole locations in the s plane are shown in Figure 6. The eleven basic configurations represented variations in Dutch roll frequency and damping ratio and the magnitude of the roll-to-sideslip ratio in the Dutch roll. Each of the basic configurations was evaluated with at least five values of the aileron yaw parameter $N'_{\delta_{AS}} / L'_{\delta_{AS}}$. Further, two of these basic configurations, 5 and 11, were evaluated at two additional values each of the yawing moment due to roll rate derivative, N'_p, resulting in Configurations 5A, 5B, 11A and 11B. One configuration, 5ND, was evaluated with negative effective dihedral. These additional configurations were evaluated at a minimum of three values of the aileron yaw parameter, $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. For all of the evaluations the spiral root was held essentially at the origin and the roll mode was essentially maintained at $\tau_R \approx$ 0.40 sec.

The results are presented in three major subsections corresponding to the three values of Dutch roll frequency investigated. Since eight configurations had in common the Dutch roll frequency, $\omega_d \approx 2.5$ radians per second, these configurations are further subdivided for discussion into sets having the same value of roll-to-sideslip ratio, $|\phi/\beta|_d$. Following the discussions of pilot comment data, each set or subset of configurations is compared to the MIL-F-8785B(ASG) lateral-directional requirements. The data were also compared to MIL-F-83300 roll-sideslip coupling requirements. It was found that the sideslip excursion requirements of MIL-F-83300 were not discriminating for the data of this experiment. Therefore, a comparison with MIL-F-83300 requirements is not discussed in detail in this section, but is included in the Summary of Results, Section V of this report.

The equations defining the interactions of the stability derivatives in forming the modal characteristics are presented in Appendix I. The modal parameters listed for each configuration are the average values obtained from calibration records taken before and after each evaluation. The Dutch roll frequency and damping ratio were measured from the airplane response to a rudder doublet input. The roll and spiral mode time constants were obtained by analog-matching of the airplane response to an aileron step input using the technique presented in Reference 9. The short period longitudinal characteristics were obtained by analog-matching the airplane response to an elevator step and elevator doublet inputs by the technique explained in Reference 10.

Transient responses, configuration identification and pilot comments are presented in Appendix IV. The computer-generated transient responses were calculated using the modal characteristics obtained for each configuration. Selected transient responses obtained from actual flight records are also shown in Appendix IV.

4.2 CONFIGURATIONS WITH LOW DUTCH ROLL FREQUENCY

Four configurations were evaluated with a Dutch roll frequency near 1.0 radian per second. Configurations 2 and 3 both had the medium value of roll-to-sideslip ratio, $|\phi/\beta|_d$, evaluated in this experiment but differed mainly by their values of the Dutch roll damping ratio. The values of ζ_d were 0.23 and 0.43 respectively. Configurations 8 and 9 both had the high value of $|\phi/\beta|_d$ but differed mainly by their values of ζ_d = 0.25 and ζ_d = 0.47 respectively. The results for each configuration are discussed separately. Following the discussion of each configuration, the results for the low Dutch roll frequency configurations are compared to certain MIL-F-8785B(ASG) lateral-directional requirements.

4.2.1 Results for Low Dutch Roll Frequency, Medium $|\phi/\beta|_d$ Configurations

The $\phi(s)/\delta_{AS}(s)$ transfer function zero locations with respect to the Dutch roll poles for Configurations 2 and 3 are shown on Figure 13. The experimental results are shown on Figure 14. A detailed definition of these configurations is given in Appendix IV where the pilot comment data and transient responses are also presented.

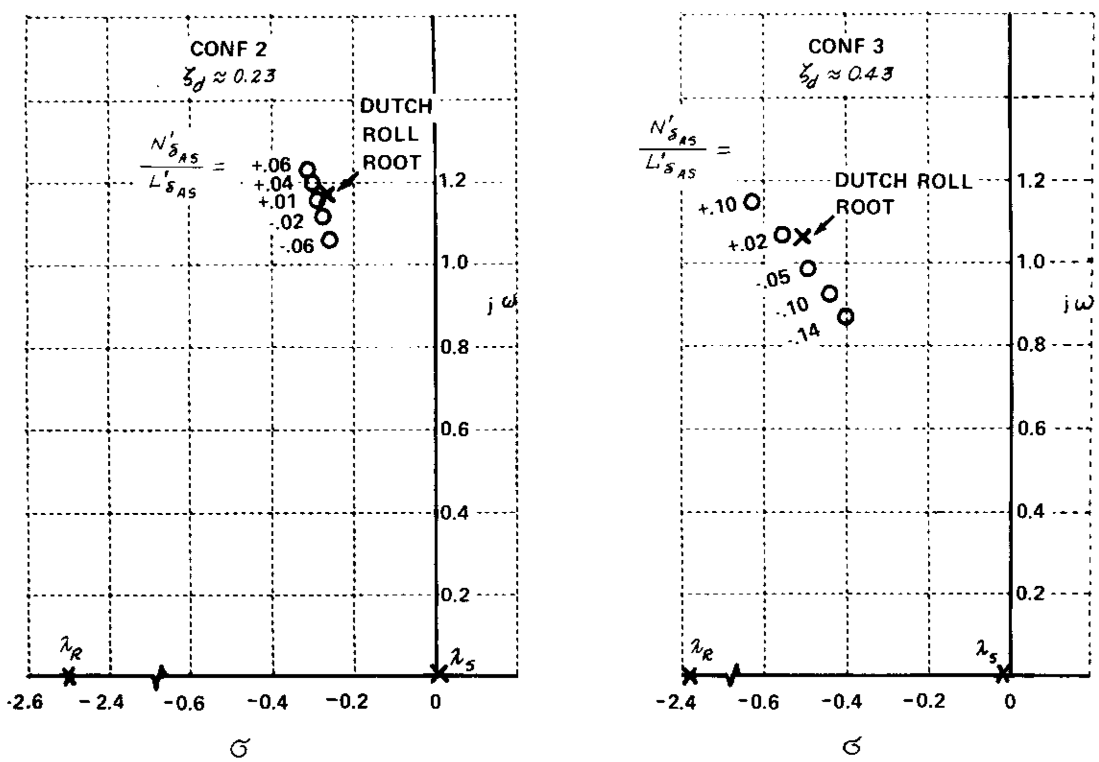

Figure 13 $\phi(s)/\delta_{AS}(s)$ Pole-Zero Locations for Low ω_d, Medium $|\phi/\beta|_d$ Configurations

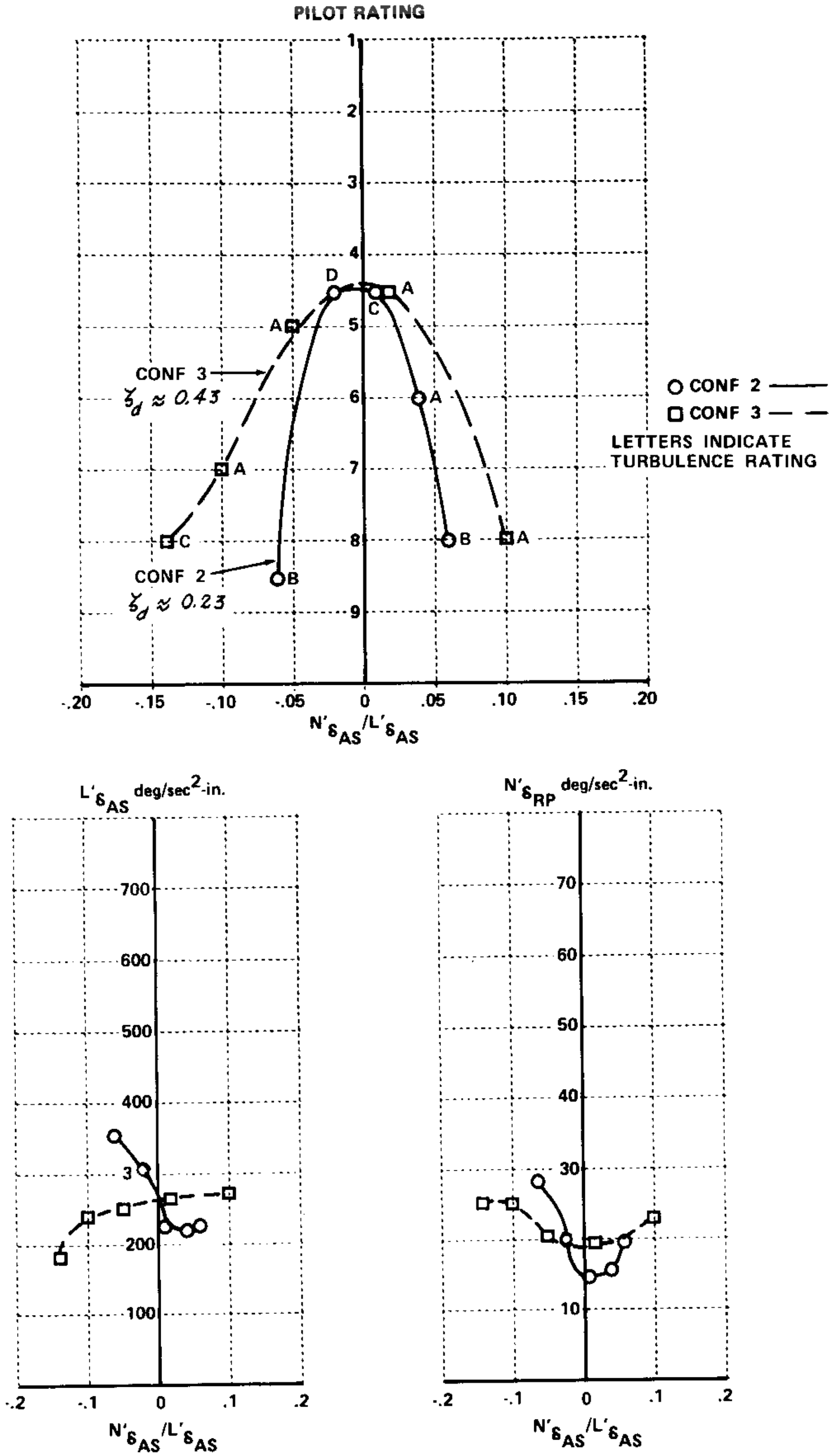

Figure 14 Pilot Ratings and Pilot Selected Control Sensitivities for Low ω_d, Medium $|\phi/\beta|_d$ Configurations

4.2.1.1 Configuration 2 - Lower Dutch Roll Damping Ratio

The lateral-directional modal characteristics for Configuration 2 were as follows:

$$\omega_d \approx 1.20 \text{ rad/sec} \qquad \tau_R \approx 0.39 \text{ sec}$$
$$\zeta_d \approx 0.23 \qquad \tau_S \approx 200 \text{ sec}$$
$$|\phi/\beta|_d \approx 1.15$$

This configuration was not rated as satisfactory without improvement at any value of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ tested. The pilot ratings, Figure 14, show a rapid degradation with increases in $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ in either the adverse or proverse directions. The best ratings, PR = 4.5, were obtained at $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.02 and + 0.01. With small adverse yaw due to aileron ($N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.02), the pilot reported the bank angle controllability quite satisfactory and the roll rate very smooth. Control of sideslip, however, was quite objectionable and sideslip was easy to excite. Attempts to arrive at and maintain a desired heading resulted in a nose oscillation about the desired heading. Rudder coordination was difficult in that as a turn was initiated there seemed to be little need for coordination but as roll rate developed the requirement for rudder coordination increased. This resulted from the adverse yawing moment due to roll rate, N'_p . Sideslip excursions in the presence of random disturbance inputs were large and difficult to control.

In the most adverse aileron yaw case ($N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = -0.06) the pilot noticed some oscillation in roll rate, but found that he could perform the bank angle tracking task reasonably well if he approached it in a very nonaggressive manner. His main objections to the airplane characteristics were the large amount of adverse yaw accompanying an aileron input and the slow directional response of the airplane. Coordination efforts resulted in overcontrol and the pilot had to direct most of his attention to the control of sideslip. His concentration on control of sideslip detracted from his ability to perform the overall task, especially the bank angle tracking task. Response to disturbance inputs was not very significant and produced much less sideslip than that caused by aileron inputs.

With small proverse aileron yaw ($N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = +0.01) the pilot had difficulties with heading control. The nose would oscillate slowly about the desired heading requiring rudder reversals for coordination. As yaw due to aileron was increased in the proverse direction, the pilot reported increased degradation in heading control. The heading control problems resulted largely from sideslip oscillations. Sideslip generated with an aileron input was in the wrong direction (nose into the turn) for normal coordination to be of any benefit. The pilot commented that both the proverse sideslip and the slowness of the oscillation contributed to his coordination difficulties. Bank angle controllability was reported as good except in the most proverse aileron yaw case where the pilot attributed bank angle control problems to the fact that most of his concentration was required to control sideslip. Response to random disturbance inputs was not noted as significant.

The pilot based his selection of aileron control sensitivity on the fact that the airplane could not be maneuvered rapidly and he selected what he considered a low value of sensitivity in the most adverse aileron yaw case. With proverse yaw due to aileron the pilot lowered his aileron control sensitivity from that selected for the adverse cases in order to eliminate overcontrol in roll. He also found that he could not fly the airplane aggressively because of the large sideslip which accompanied aileron inputs. Therefore, he accepted the heavier aileron control forces (which accompany the lower control sensitivity) in order to improve bank angle control and to slow the response of the airplane as an aid to sideslip control.

Rudder control sensitivity selection was a compromise in that the pilot would have liked lower rudder forces but found that he could easily overcontrol the sideslip. Figure 14 indicates that large values of rudder sensitivity were selected where coordination requirements were the most demanding: the most adverse and most proverse aileron yaw cases. For smaller values of aileron yaw, the rudder control sensitivity selected was significantly lower, but the pilot still reported sideslip control difficulties.

4.2.1.2 Configuration 3 - Higher Dutch Roll Damping Ratio

The lateral-directional modal characteristics for Configuration 3 were as follows:

$$\omega_d \approx 1.18 \text{ rad/sec} \qquad \tau_R \approx 0.42 \text{ sec}$$
$$\zeta_d \approx 0.43 \qquad \tau_S \approx 115 \text{ sec}$$
$$|\phi/\beta|_d \approx 1.20$$

The best pilot rating obtained was PR = 4.5 with $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.02$. The pilot expressed one dominant objection to the configuration at all values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ tested: the control of sideslip. He found coordination difficult and tended to overcontrol directionally. No problems were encountered with Dutch roll oscillations. The pilot described the sideslip as a "slow sliding maneuver." The buildup of sideslip during maneuvers was insidious, and could get to quite large values unless the pilot made a conscious and continuous effort to control it. As a result of sideslip control difficulties, heading control was poor at all values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ tested. The main difference between the adverse and proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ cases was the character of the sideslip response and the resulting differing coordination requirements.

With adverse yaw due to aileron, the pilot found that when he rolled out of a turn he had to make a determined effort to zero the sideslip and get the airplane headed in the desired direction. In doing so he often overcontrolled with the rudder. Because of the low directional stiffness and the slow response of the airplane, the pilot was not always aware of the magnitude of the sideslip unless he made direct reference to the sideslip indicator.

Thus sideslip control difficulties were compounded during the bank angle tracking task when the pilot had no cockpit sideslip indicator.*

With proverse yaw due to aileron, coordination required rudder inputs opposite to the turn direction initially, but as the turn progressed, rudder was required into the turn to the point that steady rudder was required in a steady turn. This can be noted by referring to the transient responses shown in Appendix IV. The sustained rudder input in a turn was required because of the relatively large value of the derivative N'_r that was necessary to obtain the high Dutch roll damping ratio and the essentially neutral spiral mode root. This point is discussed further in paragraph 4.2.3.1. Hence coordination was difficult and heading control was one of the poorer features of the configuration.

The pilot's selection of aileron control sensitivity was generally a compromise between light-enough forces for good maneuverability but heavy-enough to prevent overcontrol. If the pilot selected light aileron forces, he had more difficulty coordinating the large magnitude sideslips that were generated with aileron inputs. Rudder control sensitivity selection was also a compromise between heavy-enough rudder pedal forces for control of small sideslip angles about zero, but light-enough to control the large excursions that often occurred in sideslip.

4.2.2 Results for Low Dutch Roll Frequency, High $|\phi/\beta|_d$ Configurations

The $\phi(s)/\delta_{AS}(s)$ transfer function zero locations with respect to the Dutch roll poles for Configurations 8 and 9 are shown on Figure 15. The experimental results are shown in Figure 16. A detailed definition of these configurations is given in Appendix IV where the transient responses and pilot comment data are also presented.

4.2.2.1 Configuration 8 - Lower Dutch Roll Damping Ratio

The lateral-directional modal characteristics for Configuration 8 were as follows:

$\omega_d \approx 1.04$ rad/sec $\tau_R \approx 0.41$ sec

$\zeta_d \approx 0.25$ $\tau_S \approx -450$ sec

$|\phi/\beta|_d \approx 4.0$

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* The reader's attention is directed to the tiny side acceleration ball near the bottom of the attitude director indicator shown in Figure 8. The small size of that ball was the main reason that the sideslip was displayed on the vertical command needle.

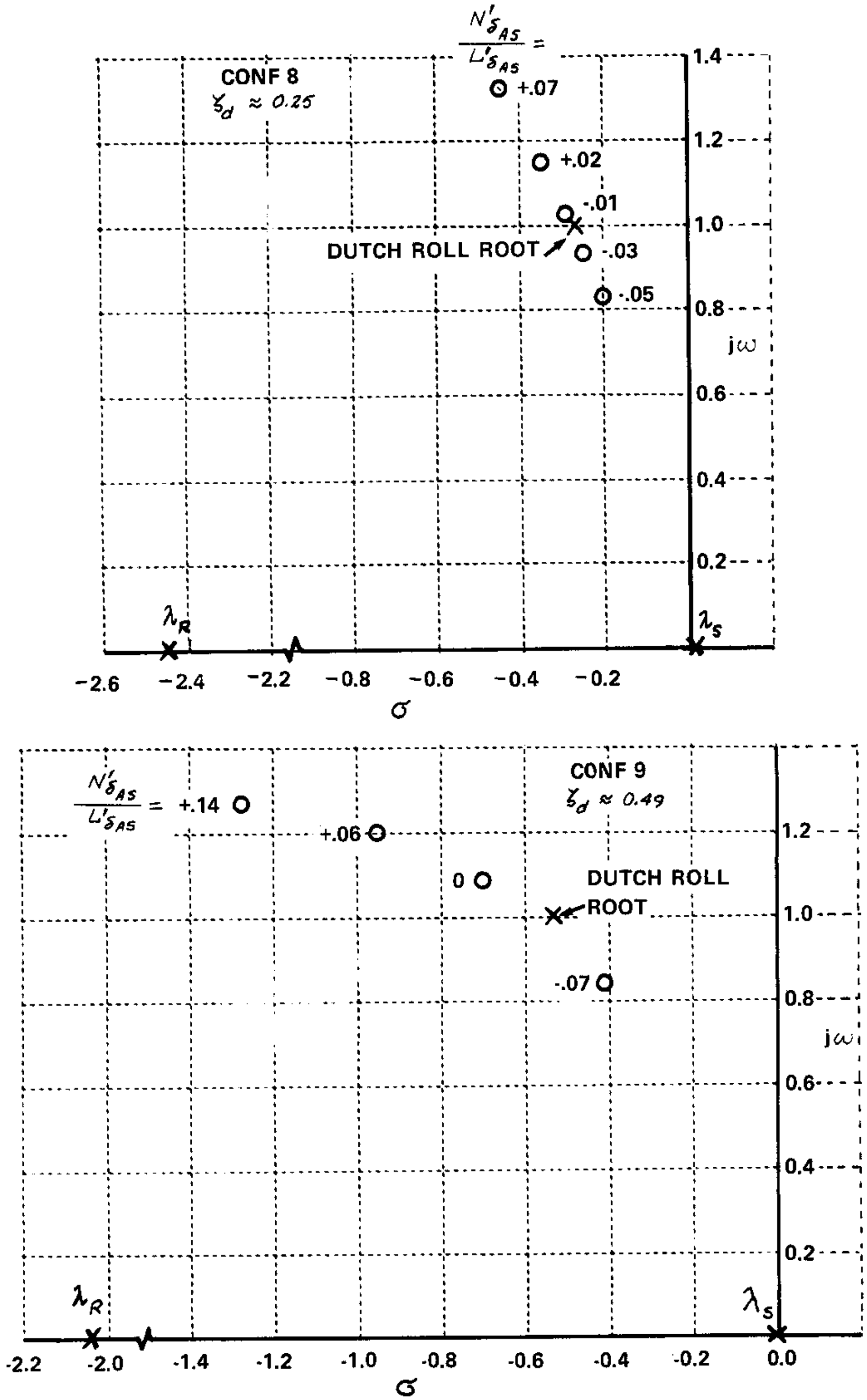


Figure 15 $\phi(s)/\delta_{AS}(s)$ Pole-Zero Locations for Low ω_d, High $|\phi/\beta|_d$ Configurations

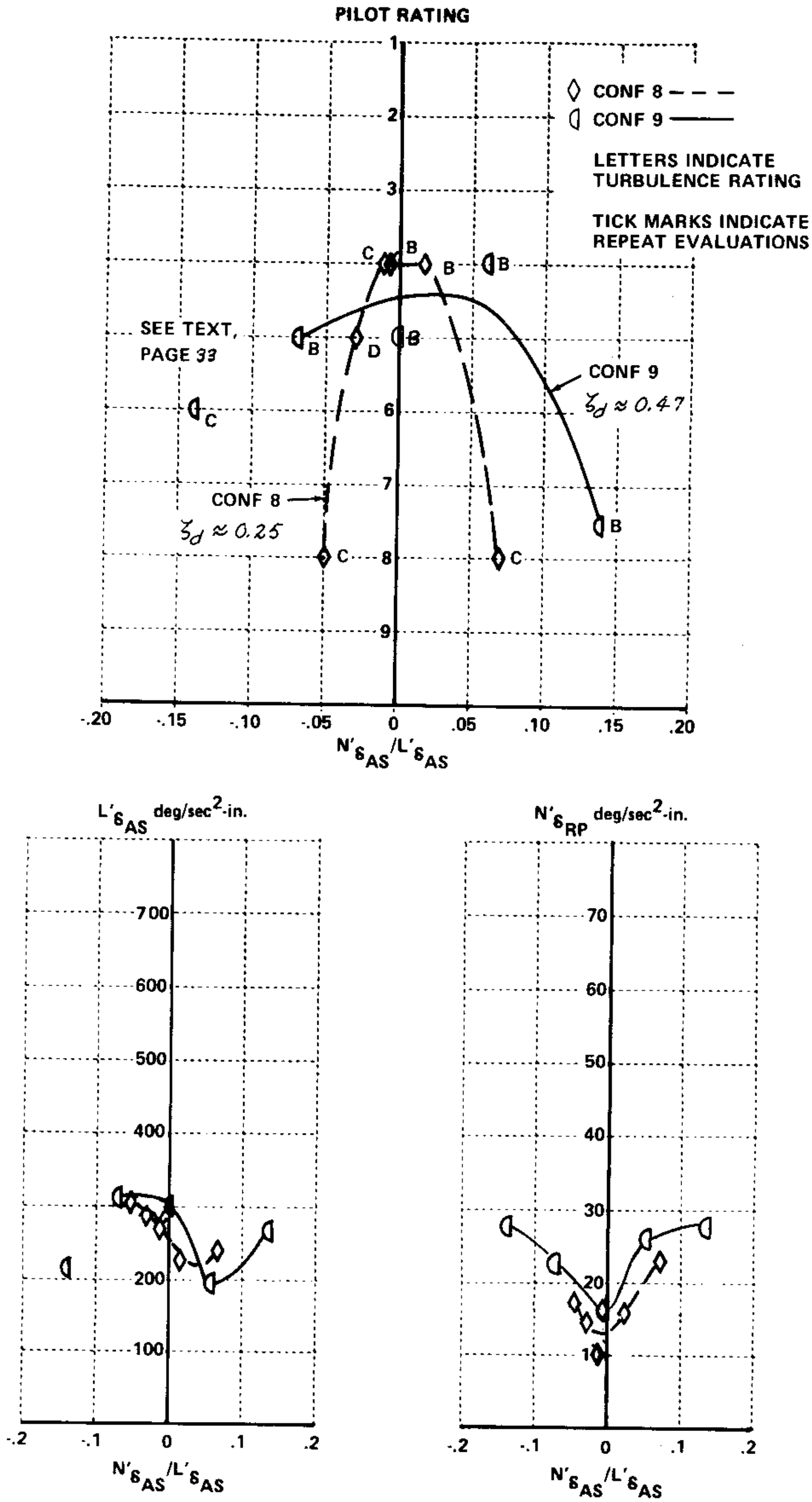


Figure 16 Pilot Ratings and Pilot Selected Control Sensitivities for Low ω_d, High $|\phi/\beta|_d$ Configurations

As shown on Figure 16 the best pilot rating received for this configuration was PR = 4 at the smallest values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ tested. The pilot reported that the bank angle controllability and the roll control were satisfactory. His objections to the configuration, and the primary reasons for not rating the configuration as satisfactory without improvement, were as follows:

1. The tendency to generate large sideslip angles when maneuvering.

2. Attempts to control the sideslip through rudder coordination often led to overcontrol and the re-excitation of sideslip.

3. The slow directional response or low directional stiffness of the airplane which interfered with the pilot's ability to control the heading and the sideslip.

The pilot described the heading control in terms of "residual sideslip and a slow oscillation of the nose." When he would attempt to attain a desired heading, he would have to position the nose of the airplane with the rudder and then wait for the airplane to slowly oscillate through one or two overshoots. Because of the low Dutch roll frequency, it took a considerable time for the oscillations to subside, too long for good performance in the air-to-air mission.

Pilot comments for the most adverse aileron yaw case ($N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.05) were lost because of a voice recorder malfunction. With $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.03, the pilot reported bank angle control problems which he attributed to the relatively high rolling moment due to sideslip. Attempts to establish a desired bank angle resulted in an overshoot of the bank angle. The major objection, however, still centered about sideslip excitation with aileron inputs and the overcontrol of sideslip when attempting to coordinate. It is of interest to note that the pilot reported the Dutch roll as being well damped and that oscillations in the Dutch roll were not a problem, even though this configuration failed to meet the MIL-F-8785B(ASG) requirement that $\zeta_d \omega_d \doteq$ 0.35. Hence, as indicated by the comments on sideslip excursions, the low directional stiffness was more of a problem than was the lower value of ζ_d.

In the most proverse aileron yaw case, $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = + 0.07, the pilot noted a significant deterioration in the roll control and noted a tendency to accelerate in roll rate. This result is expected with large effective dihedral and proverse yaw due to aileron. His ability to achieve a desired bank angle was poor, both because of the roll control characteristics and because most of his efforts were required to control sideslip. Again the major objectionable feature of the airplane was sideslip. Proverse sideslip was developed with an aileron input and it was difficult to coordinate since cross-control was required.

Response to disturbance inputs was not a major factor in the evaluation of Configuration 8 at any value of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ tested. The rating of "D" for the $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.03 case resulted from bank angle control difficulties in the presence of random disturbances. For all other points tested, random disturbance inputs resulted in no more than a minor deterioration in task performance.

The pilot's selections of aileron control sensitivity generally reflect his desire to limit the airplane's response to aileron inputs so that he could cope with the sideslip and accompanying rudder coordination problems. Hence, he selected lower sensitivities than he might otherwise choose for a Class IV airplane. The rudder control sensitivity selections were based on the need to counter sideslip excursions. They were chosen at a level to try to prevent overcontrol, while providing harmony with the aileron control.

4.2.2.2 Configuration 9 - Higher Dutch Roll Damping Ratio

The lateral-directional modal characteristics for Configuration 9 were as follows:

$$\omega_d \approx 1.14 \text{ rad/sec} \qquad \tau_R \approx 0.49 \text{ sec}$$
$$\zeta_d \approx 0.47 \qquad \tau_s \approx 83 \text{ sec}$$
$$|\phi/\beta|_d \approx 5.0$$

This configuration, like the other low Dutch roll frequency configurations discussed above, did not receive a satisfactory pilot rating at any value of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ tested. The pilot comments indicate that the major objections to the characteristics of this configuration were the control of sideslip, or coordination difficulties, and the slow directional response of the airplane.

The best pilot rating, PR = 4, was obtained with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = + 0.06, the case with the smallest value of proverse aileron yaw tested. Here the pilot reported that both bank angle and heading control were good. The airplane was well damped in the Dutch roll and no oscillatory characteristics were apparent. Coordination, however, required rudder opposite to the direction of the turn initially followed by rudder into the turn and a sustained rudder input in the direction of the turn. With direct reference to the sideslip indicator the pilot found that, with concentration, he could coordinate quite well. However, in performing the overall task, and in particular the bank angle tracking task where the sideslip indicator wasn't available to the pilot, coordination was almost invariably applied in the normal direction, i.e., into the turn. This caused acceleration in the roll rate and a tendency to overshoot the desired bank angle, resulting in a deterioration in task performance.

When the yaw due to aileron was made more proverse, $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = + 0.14, the bank angle control deteriorated because the pilot had to devote more of his attention to sideslip control. Most of the pilot comments for this case were lost because of a tape recorder malfunction; however, those available indicate that the major problem was the coordination requirement.

With adverse yaw due to aileron inputs, and also in the $N'_{\delta_{AS}}/L'_{\delta_{AS}} = 0.0$ case, the pilot's major objection was still the sideslip generated. Roll rate was strongly affected by the adverse sideslip and the airplane displayed a slight reversal in roll rate when attempting aileron-only turns. Coordination of the rudder with the aileron allowed the pilot to obtain what he considered a reasonable roll rate, however he commented: "Maneuvering coordination requirements are quite large." The pilot found coordination difficult, even though rudder was required in the direction of the turn. With the low directional stability of the airplane, coordination attempts frequently resulted in eliminating adverse sideslip and producing proverse sideslip because of overcontrol with the rudder. In other words, the pilot could not stop the sideslip at zero. Heading control, as a result, was poor. With $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.14$ some of the VSS gain settings were in error because the safety pilot was provided with the wrong gain settings. The resulting configuration had a Dutch roll frequency of $\omega_d = 1.3$ radians per second and a Dutch roll damping ratio of $\zeta_d = 0.34$. The roll to sideslip ratio was $|\phi/\beta|_d = 4.0$. As a result the $\phi(s)/\delta_{AS}(s)$ transfer function zero location is not shown on Figure 15, but the pilot ratings have been shown with Configuration 9. It was decided to show the data for this case because the parameters ρ_{osc}/ρ_{AV}, $\Delta\beta_{MAX}/k$ and ψ_β were measured directly from the flight data and can be shown as a valid evaluation for comparison to the MIL-F-8785B(ASG) roll-sideslip coupling requirements.

The pilot's selection of aileron control sensitivity, $L'_{\delta_{AS}}$, in the proverse aileron yaw cases was chosen so as to prevent overcontrol in bank angle which occurred with high aileron control sensitivity. With adverse aileron yaw, the pilot stated that there was no compromise in his selection of aileron control sensitivity.

The selection of rudder control sensitivity, $N'_{\delta_{RP}}$, was a compromise at all values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. Steady rudder forces were required in a constant banked turn. The pilot attempted to select $N'_{\delta_{RP}}$ so that he would have light rudder forces in the steady turn but then found that he overcontrolled sideslip around zero. With his final selections of $N'_{\delta_{RP}}$, the rudder forces were light for small bank angle turns and heavy during large bank angle turns.

4.2.3 Comparison of Low Dutch Roll Frequency Configurations With MIL-F-8785B(ASG) Lateral-Directional Requirements

In this section the low Dutch roll frequency configurations, $\omega_d \approx 1.0$ rad/sec, of this investigation are compared to the following MIL-F-8785B(ASG) requirements:

a) Dutch Roll Frequency and Damping Requirements (Reference 1, paragraph 3.3.1.1).

b) Lateral-Directional Dynamic Response Requirements Including:

1) Roll rate requirements for small inputs (Reference 1, paragraph 3.3.2.2.1)

2) Sideslip requirements for small inputs (Reference 1, paragraph 3.3.2.4.1)

4.2.3.1 Dutch Roll Frequency and Damping Ratio

For Class IV airplanes in Flight Phase Category A, MIL-F-8785B (ASG) limits the Dutch roll damping ratio, ζ_d, to a minimum value of ζ_d = 0.19 or the total Dutch roll damping, $\zeta_d \omega_d$, to a minimum value of $\zeta_d \omega_d$ = 0.35 for Level 1 flying qualities. The governing damping requirement is that yielding the larger value of ζ_d. Levels 2 and 3 flying qualities requirements specify a minimum Dutch roll damping ratio of ζ_d = 0.02. In this experiment, as shown on Figure 6, two of the $\omega_d \approx 1.0$ radian per second configurations, 3 and 9, met the Level 1 Dutch roll damping requirements of $\zeta_d \omega_d > 0.35$ with $\zeta_d \omega_d$ of 0.507 and 0.535 respectively. Configurations 2 and 8 failed to meet the $\zeta_d \omega_d > 0.35$ requirement with $\zeta_d \omega_d$ of 0.276 and 0.260 respectively. These values were chosen so as to bracket the MIL-F-8785B(ASG) Dutch roll damping requirement boundary shown in Figure 6.

The minimum Level 1 Dutch roll frequency, ω_d, required by MIL-F-8785B(ASG) for Class IV airplanes in Flight Phase Category A is 1.0 radian per second. For Levels 2 and 3 flying qualities ω_d may be as low as 0.4 radians per second.

Both the medium $|\phi/\beta|_d$ configurations, 2 and 3, received a best pilot rating of 4.5 for small values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ where the roll-sideslip coupling was minimum. However, as shown in Figure 18 and discussed in paragraph 4.2.3.2, neither of these configurations met Level 1 $\Delta\beta_{MAX}/k$ versus ψ_β requirements. The pilot ratings for Configuration 2 (ζ_d = 0.23) degrade more rapidly with increases in $|N'_{\delta_{AS}}/L'_{\delta_{AS}}|$ than do the pilot ratings of Configuration 3 (ζ_d = 0.43). This difference in pilot rating gradient can be attributed to Dutch roll damping, since the two configurations differed mainly by their values of ζ_d. The pilot comments indicate that the major problem with both configurations was the control of sideslip. With Configuration 2 the pilot noticed some oscillation in sideslip while with Configuration 3 the pilot described the sideslip as non-oscillatory and more of a steady "drift". Configuration 2, with the lower Dutch roll damping, was also more susceptible to the effects of random disturbance inputs as indicated by the turbulence effect ratings on Figure 14.

The high $|\phi/\beta|_d$ configurations, 8 and 9, both received best pilot ratings of PR = 4. The pilot ratings for Configuration 8 with ζ_d = 0.25 were in an acceptable range (Level 2) for a small range of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. The faired pilot rating curve, Figure 16, indicates that Level 2 flying qualities could be achieved in the range $-0.04 < N'_{\delta_{AS}}/L'_{\delta_{AS}} < +0.06$. Configuration 9 was found to be acceptable (PR < 6.5) over a wider range of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. As shown on Figure 13, proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ as large as $N'_{\delta_{AS}}/L'_{\delta_{AS}} \approx +.12$ could result in acceptable pilot ratings. On the adverse side, Configuration 9 is not defined to a pilot rating of PR = 6.5, as indicated on Figure 16, however, the faired curves of pilot rating show Configuration 9 with ζ_d = 0.47 to be acceptable to larger adverse values of the aileron yaw parameter than Configuration 8 with ζ_d = 0.25. As a result of random disturbance inputs, neither of the high $|\phi/\beta|_d$, low ω_d configurations showed more than a minor deterioration in task performance, with a turbulence effect rating of C.

All of the low Dutch roll frequency configurations had considerable sideslip excitation following an aileron step input even for those test values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ where the zero of the $\phi(s)/\delta_{AS}(s)$ transfer function was nearest to the Dutch roll pole. This caused a significant degradation in pilot rating. With the zero of the $\phi(s)/\delta_{AS}(s)$ transfer function near the Dutch roll pole the pilot ratings show little effect as a result of the Dutch roll damping ratio. With the zeros of the $\phi(s)/\delta_{AS}(s)$ transfer function more removed from the Dutch roll pole, the lower value of Dutch roll damping results in a more rapid degradation of pilot rating than does the higher value. In this investigation no difference could be detected between the $\zeta_d\omega_d \approx 0.27$ and $\zeta_d\omega_d \approx 0.50$ configurations at those values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ where roll-sideslip coupling was at the minimum tested, but still did not meet Level 1 requirements.

The required minimum level of total Dutch roll damping, $\zeta_d\omega_d$, for satisfactory flying qualities may be more a function of Dutch roll frequency, ω_d, than of Dutch roll damping ratio ζ_d. If the minimum required Dutch roll frequency were increased, then the time to damp would be shortened and the total damping would be increased. Further, as mentioned in Section II of this report, the Dutch roll frequency affects the pilot's ability to control heading. The amount of sideslip caused by yawing moment is inversely proportional to the square of the Dutch roll frequency, ω_d^2.

In the preceding discussions of each of the low Dutch roll frequency configurations it was noted that for both values of $|\phi/\beta|_d$ and both values of ζ_d investigated in this experiment, the pilot had difficulties with control of sideslip, and often tended to overcontrol with the rudder. Further, the pilot often objected to the slow directional response of the airplane which made it difficult to arrive at a desired heading. These objections were common to all the low ω_d configurations, but the strongest objections always centered around sideslip excursions or a slow buildup of sideslip. It was also noted that Configurations 3 and 9 with higher Dutch roll damping ratio were not oscillatory in sideslip, yet quite large sideslip was generated following an aileron input.

During the planning stages of this experiment, computer-generated time histories were run to aid in the selection of values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ to be used for evaluation. For the low Dutch roll frequency, high Dutch roll damping ratio configurations (3 and 9) none of the computer simulations met Level 1 sideslip excursion requirements for any value of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ tried. This was the case even when the zero of the $\phi(s)/\delta_{AS}(s)$ transfer function numerator was superimposed on the Dutch roll pole. To satisfy the roll-sideslip requirements of MIL-F-8785B(ASG) at low Dutch roll frequency demands very precise control over coupling derivatives such as $(N'_p - g/V)$ and $N'_{\delta_{AS}}$. Both these derivatives are notoriously difficult to identify and equally difficult for the designer to control. In addition, consideration must be given to yawing moment due to yaw rate. In this experiment, $\zeta_d \approx 0.45$ was obtained through use of N'_r. As can be seen from the numerator of the $\beta(s)/\delta_{AS}(s)$ transfer function, Appendix I, the constant term depends on $(N'_{\delta_{AS}} L'_r - L'_{\delta_{AS}} N'_r)$. For small $N'_{\delta_{AS}}$ the constant term can only be reduced by reducing N'_r. Thus, to achieve both high ζ_d and low sideslip excitation for cases with low ω_d, yawing moment due to yaw rate must be washed out at low frequencies or the ζ_d must be achieved through some other means, for example, sideslip rate feedback. The data of this investigation have shown that the computer predictions of Level 2 roll-sideslip coupling at a Dutch roll frequency of 1.0 radian per second were later borne out by in-flight evaluations.

4.2.3.2 Lateral-Directional Dynamic Response Requirements

Figure 17 shows the location of the low Dutch roll frequency configurations in the p_{osc}/p_{AV} versus ψ_β requirements plane of MIL-F-8785B(ASG), Reference 1. Each point shown was measured from oscillograph recordings of flight data and is representative of a given value of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. The pilot ratings are also presented on the figure as the number which accompanies each point.

For the medium $|\phi/\beta|_d$ configurations (2 and 3) p_{osc}/p_{AV} was well within the Level 1 boundary for all values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ evaluated. The pilot did, however, experience some difficulty with bank angle control at the extreme values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ evaluated. For the high $|\phi/\beta|_d$ configurations (8 and 9) only two points failed to meet the Level 1 p_{osc}/p_{AV} versus ψ_β requirements, Configuration 8 with $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.07$ and Configuration 9 with $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.14$. The pilot's difficulty with bank angle control often stemmed from the fact that he had to devote most of his attention to sideslip control. It would be expected that the pilot ratings would be degraded because of sideslip and therefore the pilot ratings attained for the low Dutch roll frequency configurations contribute almost no information which can be used to evaluate the p_{osc}/p_{AV} versus ψ_β requirements boundaries of MIL-F-8785B (ASG).

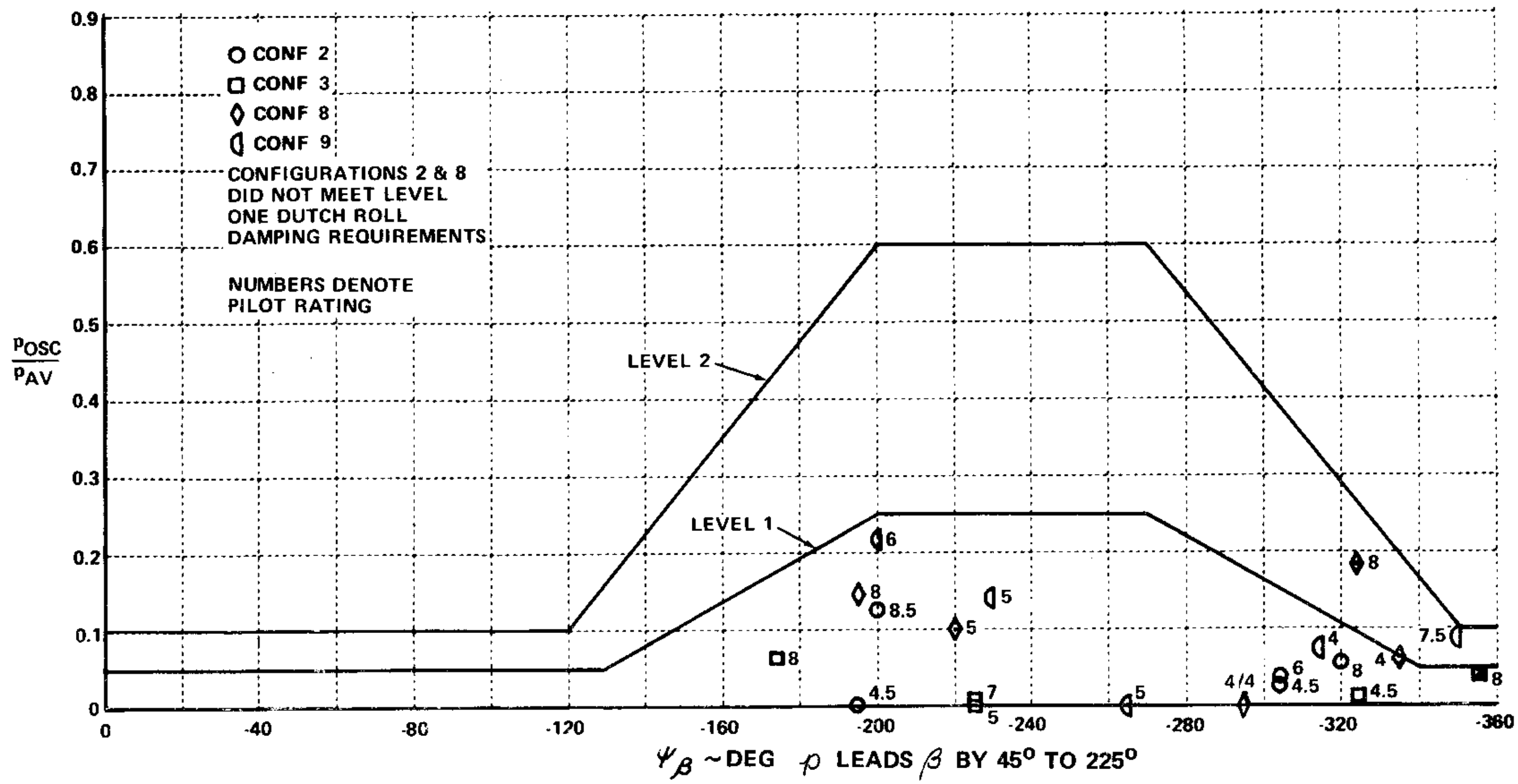


Figure 17 Low Dutch Roll Frequency Configurations Compared to p_{osc}/p_{AV} Requirements of MIL-F-8785B(ASG)

Values of $\Delta\beta_{MAX}/t$ versus ψ_β for the low Dutch roll frequency configuration are presented on Figure 18 for comparison with the Level 1 MIL-F-8785B(ASG) requirements boundary. Figure 19 presents the configurations compared to the Level 2 requirements boundary. Values of $\Delta\beta$ were measured from in-flight records as the maximum excursion in sideslip within one-half the damped Dutch roll period. Values of ψ_β were also measured from the flight records. The parameter "t" for Level 1 requirements was based on the roll performance requirements for air-to-air combat, Flight Phase CO, that is, $\phi_t = 90°$ in 1.0 second. The Level 2 "t" was based on a roll performance requirement of $\phi_t = 90°$ in 1.3 seconds. It should be noted that the Level 2 "t" for air-to-air combat is equivalent to the Level 1 "t" for ground attack without external stores.

As shown by the time histories in Appendix IV, the sideslip response to an aileron step input for the low Dutch roll frequency configurations often appears more as a ramp or first-order divergence than an oscillatory mode. This is especially true for the adverse aileron yaw cases and for values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ where the zero of the $\phi(s)/\delta_{AS}(s)$ transfer function numerator was near the Dutch roll pole. For the proverse aileron yaw cases, the sideslip appears oscillatory initially but finally ramps in the adverse direction. The sideslip response may be more in the spiral and roll modes than in the Dutch roll mode, especially when the $\phi(s)/\delta_{AS}(s)$ transfer function numerator zeros are near the Dutch roll pole. The pilot comments from this investigation reveal, however, that the pilot is sensitive to the total sideslip response and how it affects his ability to perform the overall task. The ramping sideslip response presents a problem to the analyst in the evaluation of ψ_β which, for a purely ramping sideslip time history, probably has little significance as a measure of rudder coordination difficulties. In this investigation ψ_β was determined for an aileron pulse input. The equivalent ψ_β for a step was then determined from

$$\psi_{\beta_{STEP}} + 90° + \sin^{-1}\zeta_d = \psi_{\beta_{PULSE}}$$

As has been stated, none of the low Dutch roll frequency configurations, at any value of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ evaluated, met Level 1 $\Delta\beta_{MAX}/t$ versus ψ_β requirements for Flight Phase CO. That is, all points were above the Level 1 $\Delta\beta_{MAX}/t$ versus ψ_β requirements boundary. This is in consonance with the pilot ratings since the best pilot rating for any of these points was PR = 4. Thus, the Level 1 $\Delta\beta_{MAX}/t$ versus ψ_β would properly predict that pilot ratings would fall in the less than satisfactory range, PR > 3.5.

The Level 2 requirements plane for $\Delta\beta_{MAX}/t$ versus ψ_β, Figure 19, includes three evaluation points within the boundary which received PR > 6.5 and three points outside the requirements boundary which were rated PR < 6.5.

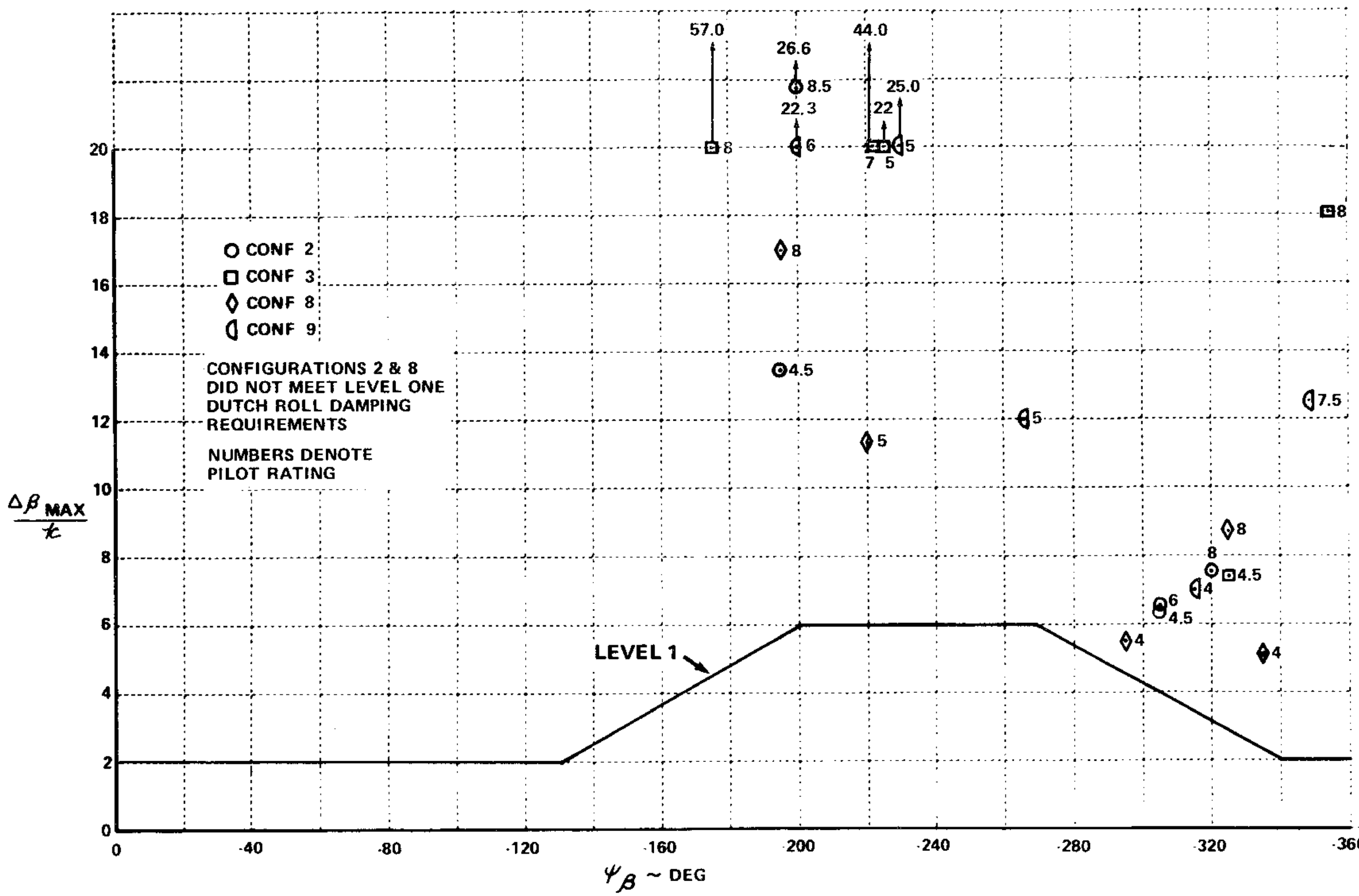


Figure 18 Low Dutch Roll Frequency Configurations Compared to Level 1 $\Delta\beta_{MAX}/\kappa$ Requirements of MIL-F-8785B(ASG)

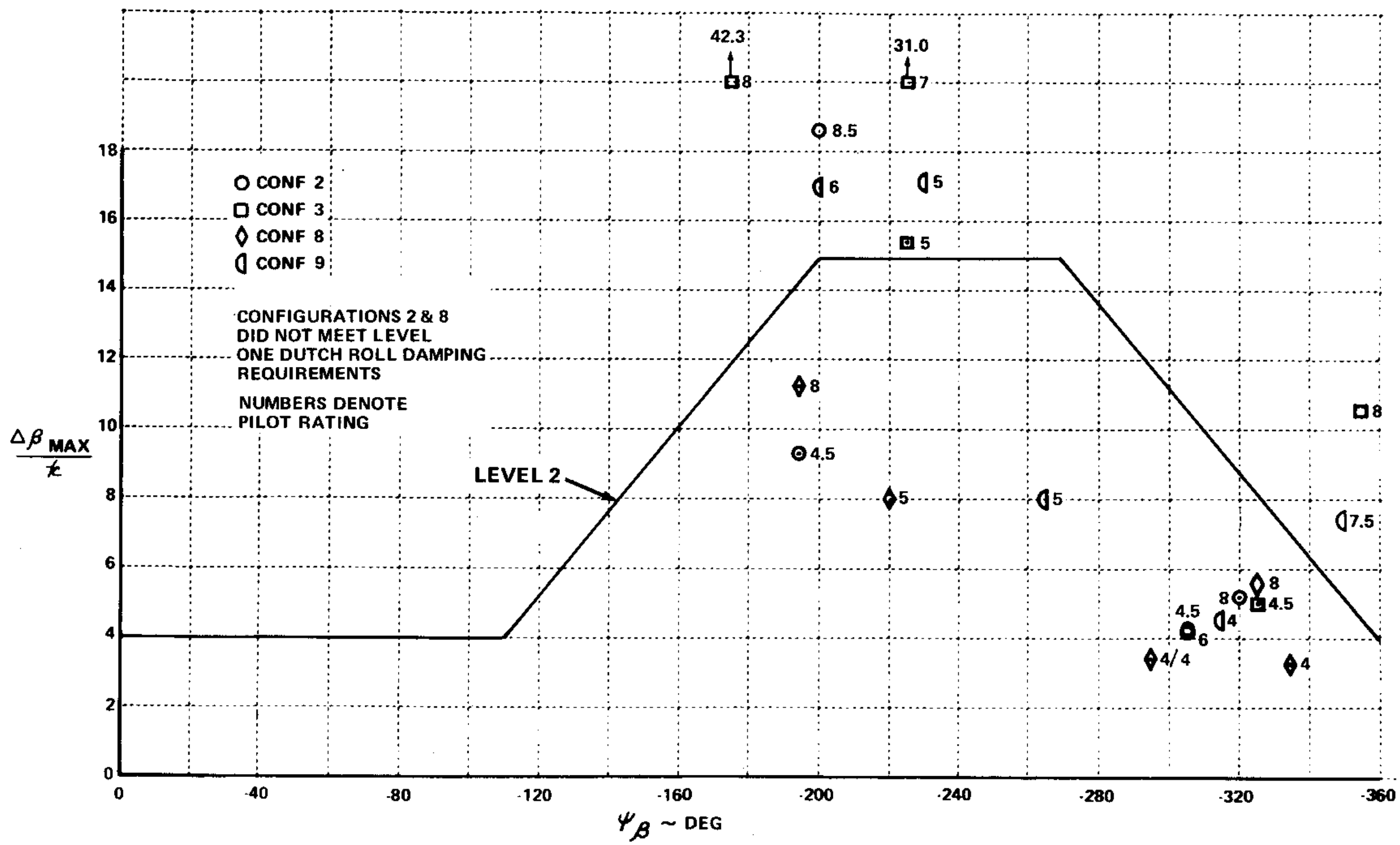


Figure 19 Low Dutch Roll Frequency Configurations That do Not Meet Level 1 $\Delta\beta_{MAX}/\not{t}$ Requirements Compared to Level 2 $\Delta\beta_{MAX}/\not{t}$ Requirements of MIL-F-8785B(ASG)

The three PR > 6.5 points which met the Level 2 requirements were for configurations which had the lower value of Dutch roll damping, Configurations 2 and 8. As pointed out in paragraph 4.2.3.1, the lower value of Dutch roll damping, $\zeta_d \omega_d \approx 0.27$, investigated in this experiment had a definite effect on degrading pilot ratings at the larger values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ evaluated. The three points in question here were as follows:

Configuration 2 with $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.06$
Configuration 8 with $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.07$
Configuration 8 with $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.05$

The faired pilot rating curves, Figures 14 and 16, show that the above values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ were the extreme values evaluated for Configurations 2 and 8 and the previous discussion of these configurations shows that the pilot ratings for these points were degraded as a result of the lower value of Dutch roll damping.

The three points which received a PR < 6.5 and fell above the Level 2 $\Delta\beta_{MAX}/k$ versus ψ_β boundary were evaluation points of Configurations 3 and 9 which had the higher value of Dutch roll damping $\zeta_d \omega_d \approx 0.50$. These three points would indicate that the Level 2 $\Delta\beta_{MAX}/k$ versus ψ_β requirements boundary may be too conservative between $\psi_\beta = -200$ degrees and $\psi_\beta = -270$ degrees. These three points suggest that the boundary could be raised from $\Delta\beta_{MAX}/k = 15$ degrees to $\Delta\beta_{MAX}/k$ on the order of 17 degrees and still be valid for Level 2 flying qualities.

In summary, none of the low Dutch roll frequency configurations of this investigation received satisfactory pilot ratings and all evaluation points were on the unacceptable side of the Level 1 $\Delta\beta_{MAX}/k$ boundary. Hence, the $\Delta\beta_{MAX}/k$ versus ψ_β criterion would successfully predict pilot ratings greater than 3.5. The data therefore substantiate the Level 1 $\Delta\beta_{MAX}/k$ boundary. The Level 2 $\Delta\beta_{MAX}/k$ versus ψ_β boundary, however, erroneously rejected three evaluation points. This suggests that the Level 2 boundary is too conservative in the $\psi_\beta = -200$ degrees to $\psi_\beta = -270$ degrees region. The p_{osc}/p_{AV} requirements boundaries did not erroneously reject any evaluation points. Since the sideslip, or perhaps the low Dutch roll frequency itself, was the reason for pilot rating degradation, the data do not substantiate the p_{osc}/p_{AV} requirement, but they do not refute it either.

4.3 CONFIGURATIONS WITH MEDIUM DUTCH ROLL FREQUENCY

A total of eight medium Dutch roll frequency configurations were evaluated for various values of the aileron yaw parameter $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. All eight configurations had in common the following nominal values of lateral-directional modal parameters.

$\omega_d = 2.5$ rad/sec $\tau_R = 0.4$ sec
$\zeta_d = 0.25$ $\tau_S = \infty$

Configuration 1 was evaluated with $|\phi/\beta|_d \approx 0.36$, Configurations 5, 5A, 5B, and 5ND with $|\phi/\beta|_d \approx 1.6$, and Configurations 11, 11A and 11B with $|\phi/\beta|_d \approx 6.0$. All configurations had positive effective dihedral except for Configuration 5ND which was evaluated specifically to test for negative effective dihedral. Configurations 5, 5A, and 5B as well as Configurations 11, 11A and 11B differ amongst themselves in their values of yaw due to roll rate (N'_p).

The discussions of the various configurations are grouped in relation to their $|\phi/\beta|_d$ while the negative dihedral configuration (5ND) will be treated as a special case at the end of Section 4.3.

4.3.1 Results for the Medium Dutch Roll Frequency, Low $|\phi/\beta|_d$ Configuration

Only one configuration, (Configuration 1) was evaluated at the low $|\phi/\beta|_d$ of this experiment. It was chosen to satisfy the Flight Phase Category A, Level 1 requirements of MIL-F-8785B(ASG) on Dutch roll frequency, Dutch roll damping ratio, and the roll and spiral mode parameters. Configuration 1 had the following values of lateral-directional modal parameters:

$$\omega_d \approx 2.36 \text{ rad/sec} \qquad \tau_R \approx 0.39 \text{ sec}$$
$$\zeta_d \approx 0.25 \qquad \tau_s \approx 504 \text{ sec}$$
$$|\phi/\beta|_d \approx 0.36$$

The $\phi(s)/\delta_{AS}(s)$ transfer function zero locations with respect to the Dutch roll pole are shown on Figure 20. The experimental results are shown on

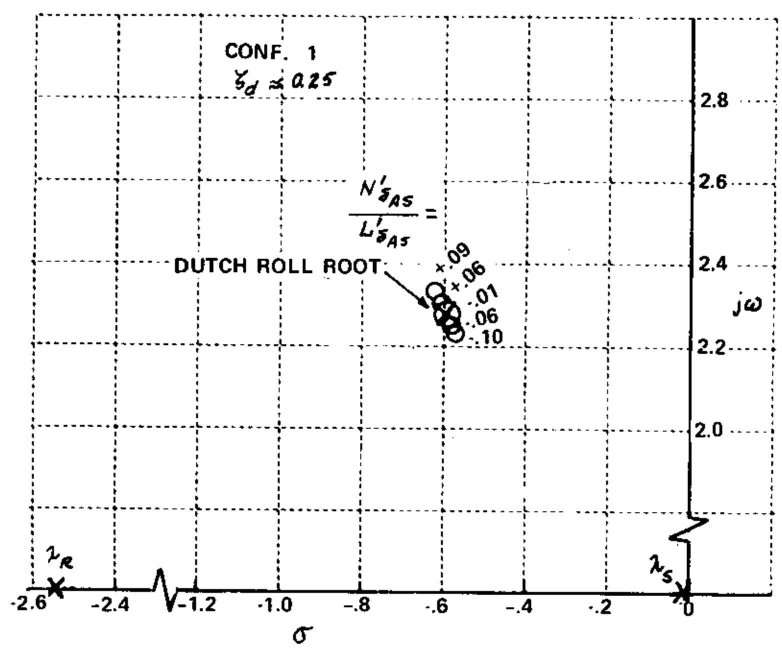


Figure 20 $\phi(s)/\delta_{AS}(s)$ Pole-Zero Locations for Medium ω_d, Low $|\phi/\beta|_d$ Configuration

Figure 21. Also shown on the pilot rating plot on Figure 21 are the data for Configuration 5 to indicate the negligible influence of the $|\phi/\beta|_d$ change in the low to medium $|\phi/\beta|_d$ range.

N'_p was chosen so that the locus of zeros of the $\phi(s)/\delta_{AS}(s)$ transfer function, with varying $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ is a curve passing through the Dutch roll pole as shown on Figure 20. A detailed definition of this configuration is given in Appendix IV where the pilot comment data and the transient responses are also presented.

With $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.01$, the numerator zero is superimposed on the Dutch roll pole and they cancel each other. As expected with the low $|\phi/\beta|_d$ the movement of the zeros is quite small with increasing $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ and this is reflected in the almost negligible values of p_{OSC}/p_{AV} for all the test points of Configuration 1. However, $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ has a strong effect on the zeros of the $\beta(s)/\delta_{AS}(s)$ transfer function and the pilot comments center on the sideslip generated for aileron inputs.

A fact that is immediately apparent from Figure 21 is that the pilot's aileron sensitivity selection did not change substantially throughout the $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ range evaluated. This however was not the case with $N'_{\delta_{RP}}$. Discounting the very low $L'_{\delta_{AS}}$ point at near zero $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ which was generated in the early practice evaluation phase, the small apparent effect of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ on the pilot's selection of $L'_{\delta_{AS}}$ suggests that whatever problems aileron yaw caused with Configuration 1, they did not strongly affect his roll control because of the low $|\phi/\beta|_d$ of 0.36. At the most adverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ of - 0.10, the pilot did report that he strove for a compromise between "having aileron forces too heavy for maneuvering" and having the aircraft too sensitive in roll. Further, large values of $L'_{\delta_{AS}}$ resulted in "very large" yaw (hence sideslip) produced by a given aileron stick deflection, but there was no mention of this sideslip affecting roll control authority. At the two less adverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ cases, the pilot reported no compromises on his selection for "nice, light forces". For the lesser proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.06$ case, on the first evaluation, the pilot had another aircraft to track and to fly formation with. He reported that he "toned down" his gearing selection from what it might have been without this reference. On the repeat evaluation, for which he did not have this reference, he chose a higher sensitivity suggesting that the task that the pilot was actually performing was slightly different between the two evaluations. Nevertheless, the latter evaluation task (without the target aircraft) is more consistent with the rest of the evaluations of this experiment and hence more weight is given to the higher $L'_{\delta_{AS}}$. The relationship between these two evaluations of the same test point might however be a factor to keep in mind, in comparing control sensitivities from this experiment with those of other experiments. On the evaluation without the other aircraft, the pilot commented that he was still limiting his sensitivity selection because of the large proverse yaw, and hence sideslip, that was generated resulting in a "scooping" in roll. Finally, for the most proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ case, the pilot still chose the same moderately high sensitivity as for the other cases despite his comment on "toning down his selection due to overcontrol tendencies in tight tracking maneuvers".

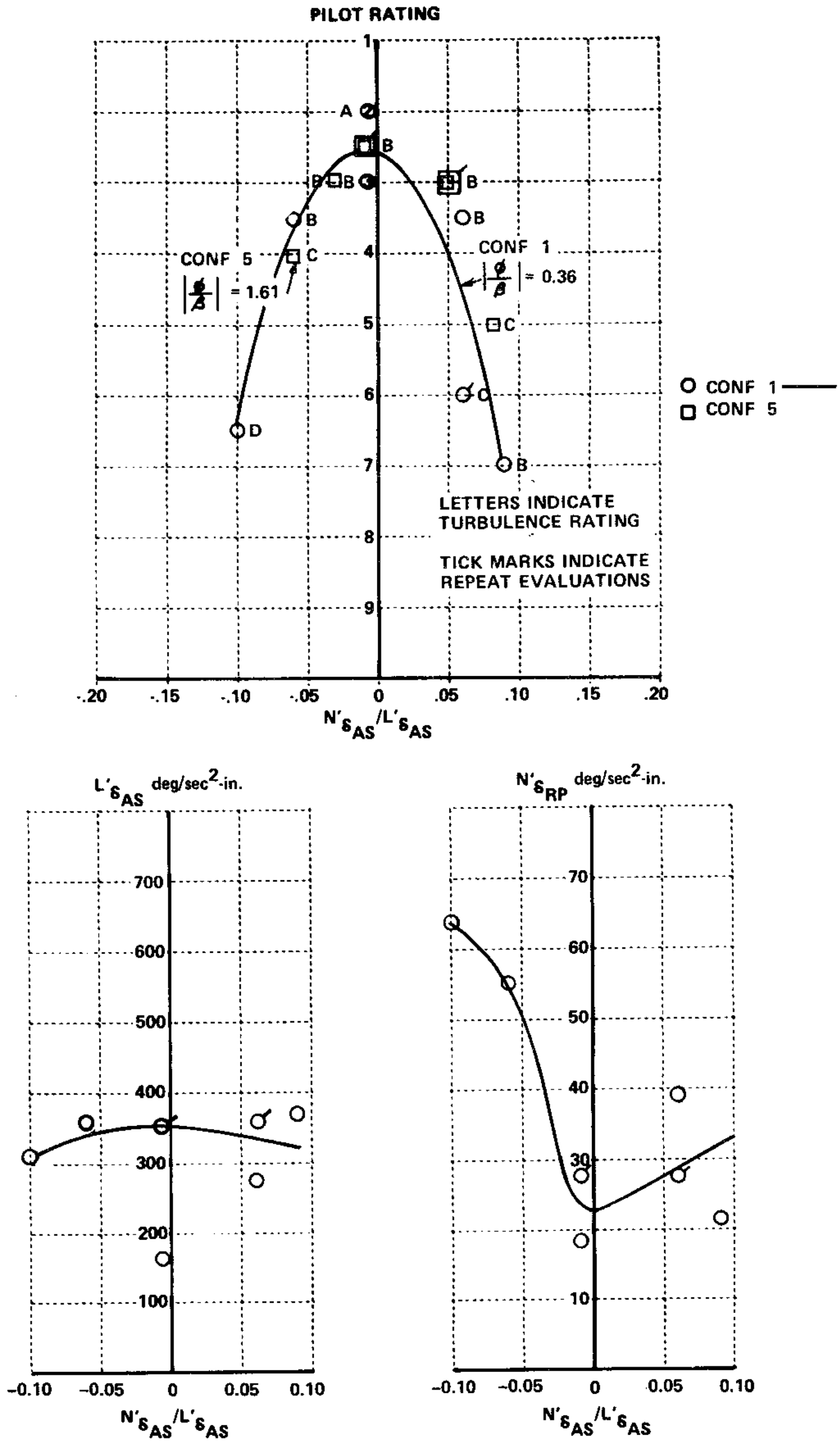


Figure 21 Pilot Ratings and Pilot Selected Control Sensitivities for the Medium ω_d , Low $|\phi/\beta|_d$ Configurations

Pilot-selected values of rudder sensitivities varied considerably with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. For the aileron yaw parameter near zero (and the small N'_p), the pilot selected a relatively low sensitivity, because he didn't need much rudder to coordinate in maneuvers. For the largest adverse case he chose a very high $N'_{\delta_{RP}}$ in order to cope with the large sideslip due to aileron inputs while still maintaining reasonable rudder forces. With the required coordination being in the normal direction and with the relatively small effect of sideslip on bank angle, there were no control difficulties associated with coordinating with such a high $N'_{\delta_{RP}}$. For $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ of -0.06, the selection was nearly as high, but less rudder was required for coordination.

For $N'_{\delta_{AS}}/L'_{\delta_{AS}} = + 0.06$, pilot selection of $N'_{\delta_{RP}}$ did not change from that at $N'_{\delta_{AS}}/L'_{\delta_{AS}} \approx 0$ for the evaluation without the target aircraft, while it increased substantially for the evaluation with the reference aircraft. The pilot comments indicate that without the target aircraft, the pilot was more conscious of the sideslip excitation because he was looking more at his instruments. Therefore he concentrated more on coordination and selected the control sensitivity so as not to overcontrol the sideslip excessively. For the other evaluation of the same test point, he stated "I didn't use rudder very much and kind of accepted the initially selected sensitivity without much iteration." In other words, by having to look at the other aircraft, he wasn't fixing his attention on the sideslip indicator and hence on the coordination problem. Finally, for the most proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ case, the pilot reported that there was such large sideslip generated by aileron inputs "that it really needed coordinating." But when he tried, the technique proved too complex in roll maneuvering with normal coordination aggravating the situation. He ended up not using rudder except to limit the sideslip "when it got too far away." The rudder control sensitivity selection was probably compromised by the tendency to overcontrol when rudder use was attempted.

Configuration 1 had a flat Dutch roll where the bulk of the response was in sideslip with very little in roll or bank angle. Therefore the pilot's problem was primarily with directional control. His complaints centered on the sideslip generated in maneuvers and the control thereof. In fact, if the pilot did complain about roll control, it was primarily due to the heavy distraction caused by directional control.

For $N'_{\delta_{AS}}/L'_{\delta_{AS}} = - 0.01$, the pilot reported no problem with roll control and associated bank angle tracking even when he performed aggressively. He was quite satisfied with the roll performance. What little sideslip was generated due to $N'_{\delta_{AS}}$ and N'_p caused no problem and coordination, when required, was in the normal direction and easy to perform. The pilot stated that yaw due to aileron was quite small, while yaw due to roll rate (N'_p) was noticeably greater. He had to feed rudder in as the roll rate increased in banking and recovery from a banked attitude, a slight coordination technique modification which he didn't like. Heading control was no problem, since even if Dutch roll was excited, time to damp ($\zeta_d \omega_d$) was short.

With $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.06$, the pilot reported that the sideslip buildup in maneuvers was quite significant without coordination. Dutch roll excitation was also more noticeable because of the larger sideslip disturbance involved but he added that with the "rapid damping" it was not objectionable. Conscientious coordination was a requirement for maneuvering and he needed to use a large amount of rudder but coordination was in the normal direction. However, because of the sources of the sideslip, the resulting shape of the β time history for aileron inputs required some complicated rudder input shaping. This occurred because $N'_{\delta_{AS}}$ produced immediate yaw while the N'_p effect came later in proportion to roll rate. Thus, in quick maneuvers, sideslip control was less than perfect.

With the more adverse aileron yaw case ($N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.10$) sideslip occupied most of the pilot's attention. In fact, he downrated bank angle control and tracking due to the diversion of attention that sideslip control caused. It is worth noting that due to the low $|\phi/\beta|_d$ coupling there exists essentially an independent two axis control requirement: aileron for roll and rudder for sideslip. Aileron cannot be used to damp the Dutch roll since there is very little Dutch roll in the roll response; besides attempts in that direction may even aggravate the situation. Furthermore, oscillations in heading make sideslip more noticeable to the pilot and the overall control problem more difficult resulting in the PR of 6.5. This movement of the nose without associated bank angle probably contributed to the pilot report of poor heading control and interfered heavily with small corrections in ground attack runs.

With $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.06$, the significant problem was again the sideslip itself. On one evaluation of this test point the pilot had the normal task references that he had for the rest of the experiment and he rated it a PR of 6. On the repeat evaluation he had another aircraft to chase and fly formation with, diverting attention from the ball or sideslip needle and he assigned a pilot rating of 3.5. He evidently did different tasks on these two occasions, since the flight data indicates that the airplane characteristics were the same. With the other aircraft to chase, the sideslip excursions bothered him less. Following aileron inputs, the sideslip went proverse and in a short time reverted to about an equal amount adverse so that coordination was indeed a complex task. The resulting sideslip did not influence the roll control and the Dutch roll that was excited was well damped. On the evaluation without the target aircraft, the sideslip in itself bothered and distracted the pilot. When he tried to coordinate while also trying to concentrate on the task, such as in the bank angle tracking task, he would revert to coordinating in the normal direction thereby aggravating the initial proverse sideslip. With the target aircraft, the pilot found that he couldn't coordinate profitably and so he accepted the sideslip generated and the resulting "annoying" Dutch roll oscillations.

For the most proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ case evaluated ($N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.09$), the large proverse yaw due to the aileron inputs dominated the generation of sideslip such that the pilot was confronted with an initially large then diminishing proverse sideslip after an aileron input. The pilot commented that flying loosely, he could maneuver aggressively. However, in a tight aggressive tracking situation, he encountered a strong tendency toward bank angle oscillations. When large abrupt aileron inputs were used, large proverse sideslip was generated. Though the positive dihedral effect was small, it was sufficient to accelerate roll rate enough to cause response predictability difficulties and a resulting mild lateral PIO. Attempts at coordinating ended up aggravating the sideslip. Hence, the pilot didn't use much rudder "except to make corrections on sideslip when it got too far away." In summarizing his objections for this case, the pilot reported specifically that the large proverse yaw was the major source of his problems. Heading control was degraded far less than bank angle control, but bank angle corrections excited a heading oscillation.

With the exception of the case for $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.10, there were no significant effects of random disturbance inputs on the evaluations of Configuration 1. With $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.10 there was a moderate deterioration in task performance in the presence of random disturbance inputs. The airplane response to the disturbance inputs was principally in sideslip, but with some bank angle or roll rate disturbance. Because of the large adverse yawing moment due to aileron inputs, when the pilot attempted to counter the rolling disturbances with ailerons, large sideslip excursions were produced. As a result the pilot had difficulty distinguishing between the directional responses to his aileron inputs and the effects of the disturbance inputs on the airplane's directional response. In either case, the large sideslip angles generated in the presence of random disturbance inputs were quite noticeable and moderately objectionable to the pilot.

4.3.1.1 Comparison of Configuration 1 (Low $|\phi/\beta|_d$) With MIL-F-8785B(ASG) Roll-Sideslip Coupling Requirements

Configuration 1 met the appropriate basic Dutch roll requirements of MIL-F-8785B(ASG) for Level 1 flying qualities of Class IV airplanes in Flight Phase Category A. Degradation in pilot rating occurred primarily as a result of the sideslip excursions. This section compares the data for Configuration 1 with the roll rate and sideslip excursions for small input requirements of MIL-F-8785B(ASG).

The various test points of Configuration 1 are compared to the MIL-F-8785B(ASG) requirements limiting roll rate oscillations (p_{osc}/p_{AV}) on Figure 22. Due to the proximity of all Configuration 1 zeros of the $\phi(s)/\delta_{AS}(s)$ transfer function to the Dutch roll pole (Figure 20), the amount of Dutch roll appearing in the roll rate response to an aileron step was small for all values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$, resulting in negligible values of p_{osc}/p_{AV} . Thus, p_{osc}/p_{AV} is not a significant handling qualities parameter in regard to Configuration 1.

The only MIL-F-8785B(ASG) requirement parameter that provided some stratification of the Configuration 1 test points in relation to pilot opinion ratings was $\Delta\beta_{MAX}/k$. The corresponding plots against Level 1 and Level 2 requirements are shown on Figures 23 and 24 respectively. The Level 1

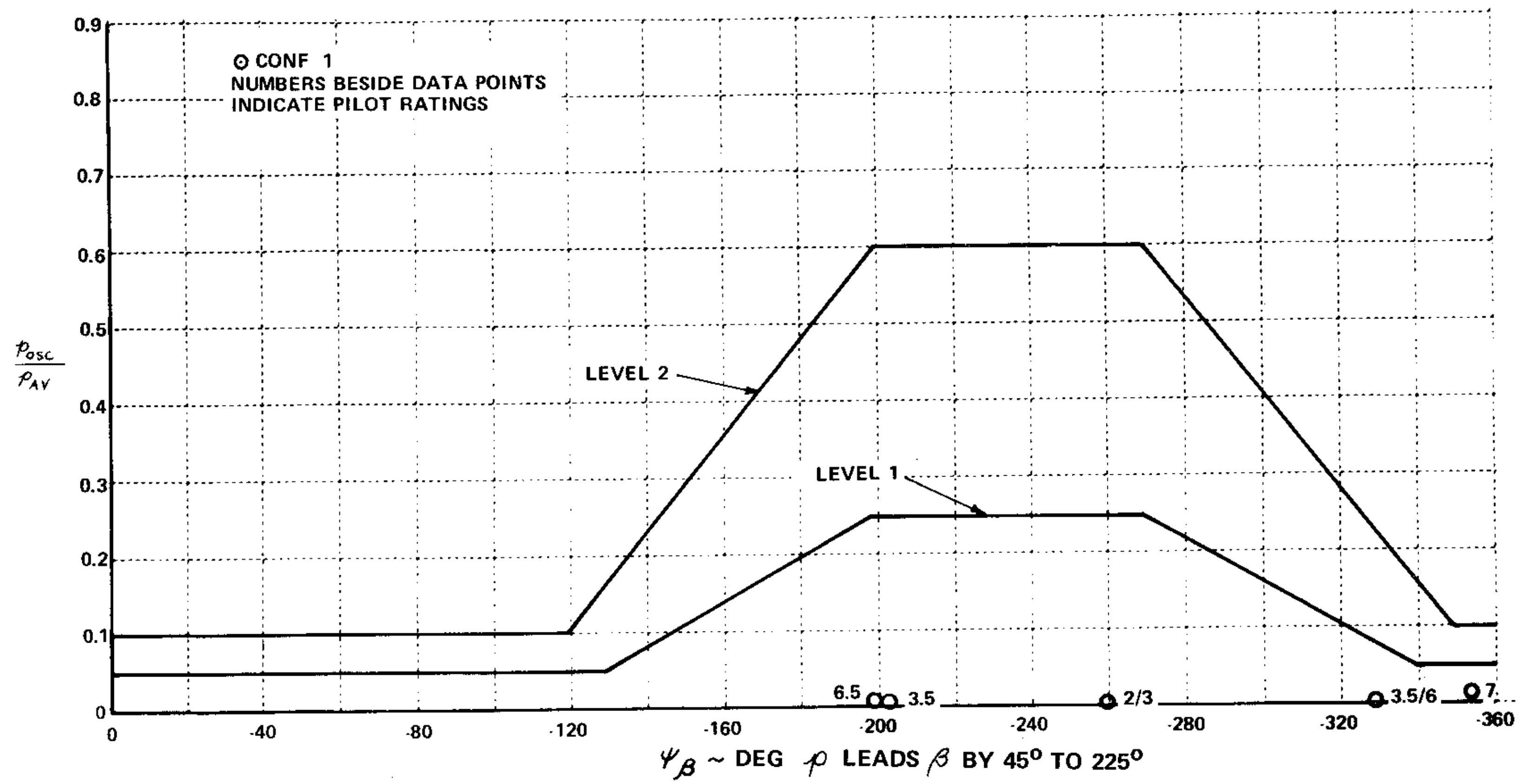


Figure 22 Medium Dutch Roll Frequency, Low $|\phi/\beta|_d$ Configuration Compared to ρ_{osc}/ρ_{AV} Requirements of MIL-F-8785B(ASG)

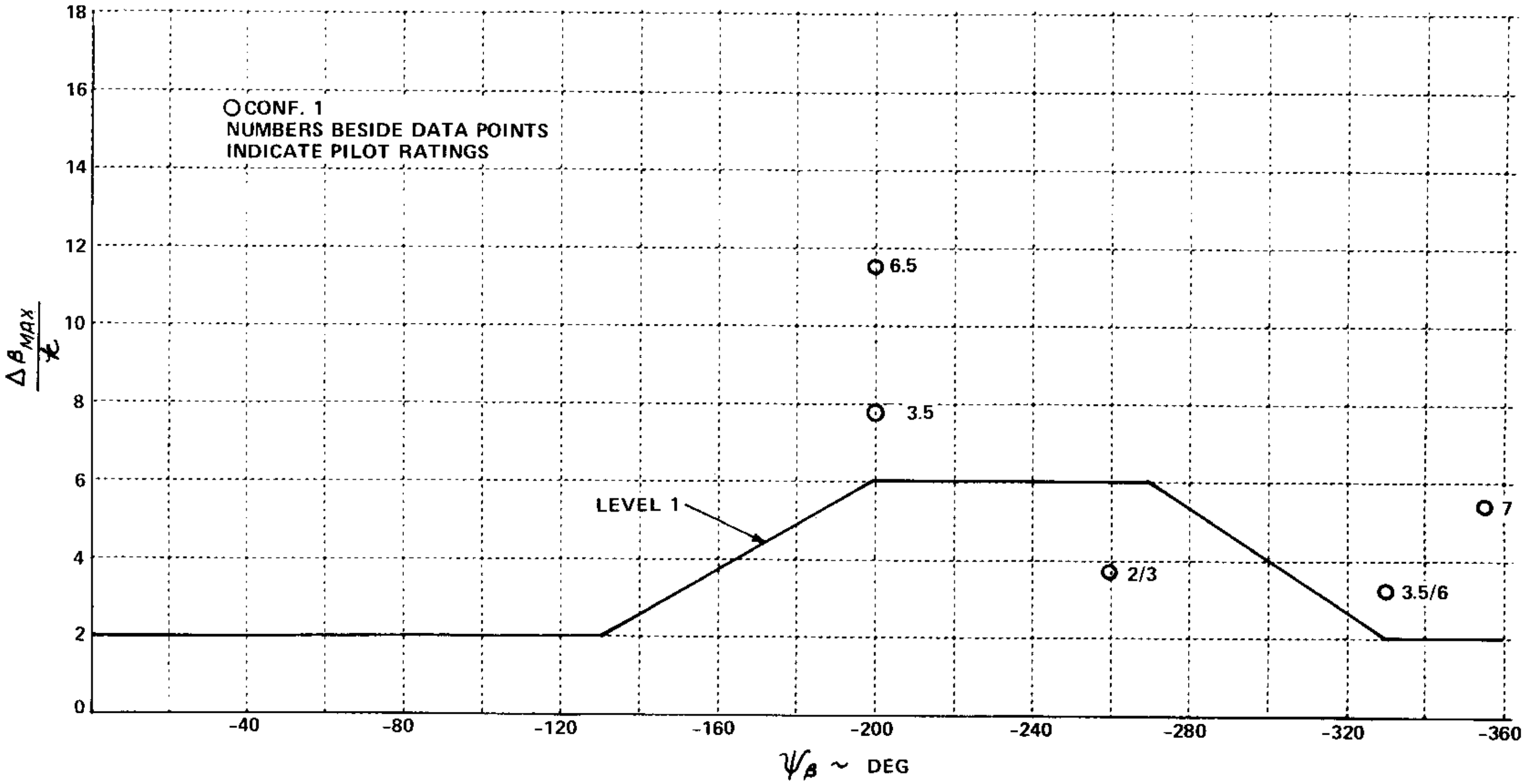


Figure 23 Medium Dutch Roll Frequency, Low $|\phi/\beta|_d$ Configurations Compared to Level 1 $\Delta\beta_{MAX}/⊄$ Requirements of MIL-F-8785B(ASG)

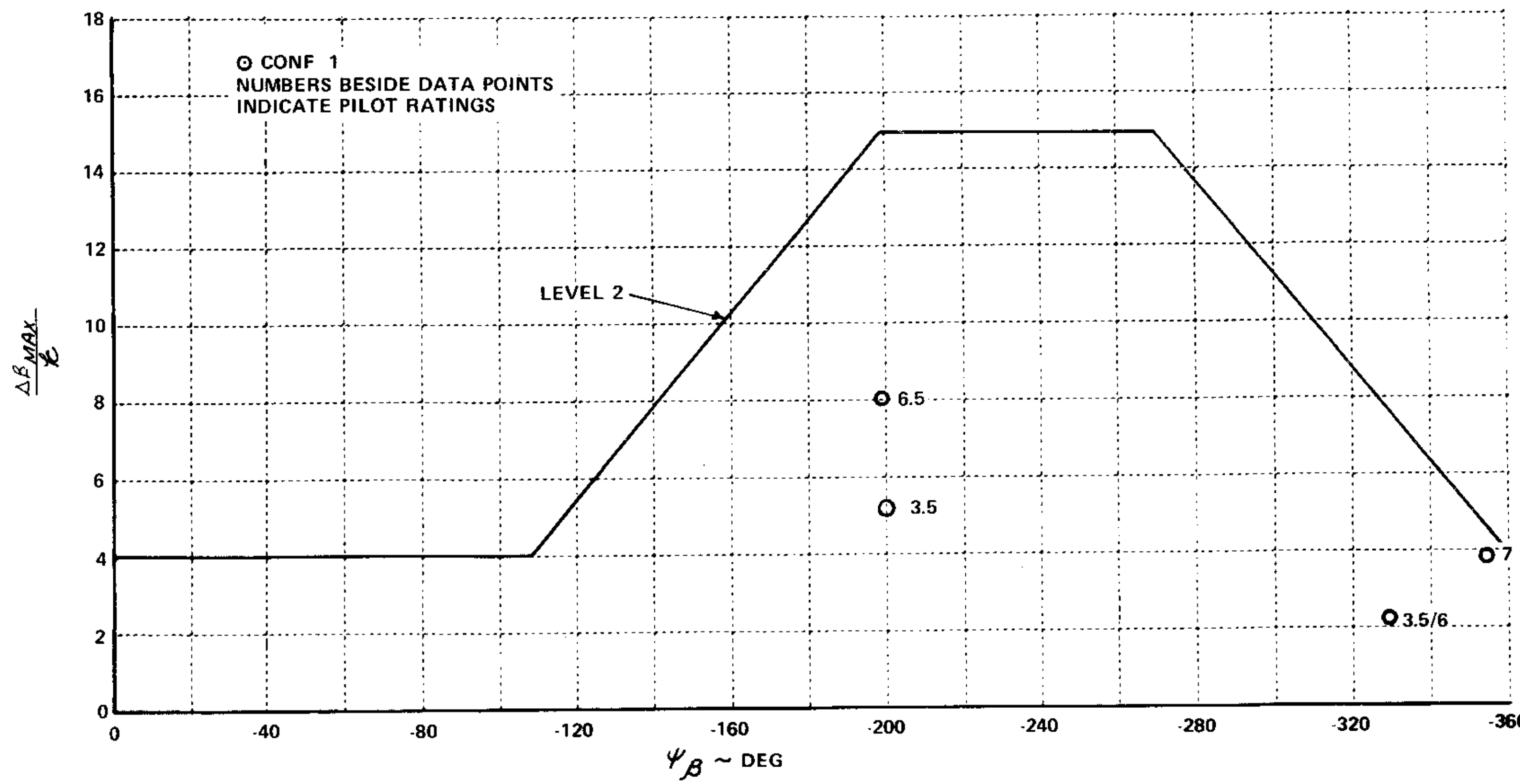


Figure 24 Medium Dutch Roll Frequency, Low $|\phi/\beta|_d$ Configurations Compared to Level 2 $\Delta\beta_{MAX}/k$ Requirements of MIL-F-8785B(ASG)

boundary does exclude all data points rated worse than 3.5. However, only the one clearly Level 1 test point falls well within the specification boundary. The point at ψ_β = - 330° had ratings of 3.5 and 6 although, as previously pointed out, the 3.5 rating was for a slightly modified task with another aircraft for reference. More weight is thrown in the direction of the clearly Level 2 rating (PR of 6 on the repeat evaluation) since the corresponding tasks were consistent with the rest of the experiment. Except for the one 3.5 rating ($\psi_\beta \approx 200°$) clearly above the boundary, the Level 1 boundary correlates with the pilot opinion. As discussions in Reference 3 state, there is more tolerance for sideslip in the range $-330° < \psi_\beta < -130°$ because this is the range of more natural coordination for turn entries and exits. The marginally satisfactory point at $\psi_\beta \approx -200°$ had $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.06 in combination with a small proverse N'_p. The pilot comments indicate that for this combination of sources of sideslip, normal coordination technique worked quite well for constraining sideslip, although it did require abundant rudder. Since the pilot was readily able to control sideslip and because what happened directionally did not affect roll appreciably, the pilot accepted a higher $\Delta\beta_{MAX}/k$ at that ψ_β than the boundary would allow. For ψ_β in the vicinity of -200°, the Level 1 boundary may be too conservative with the low $|\phi/\beta|_d$ of Configuration 1.

The Level 2 boundary on Figure 24 included all the test points of Configuration 1. The Level 3 (PR of 7) point at $\psi_\beta \approx -360°$ is close enough to the boundary that it can be said to support the existing boundary. The PR of 6.5 point at $\psi_\beta \approx -200°$ which should have been on the boundary is below the boundary to a degree unaccounted for by the accuracy of the flight data measurements. The pilot comments indicate that the aileron yaw was so large in the adverse direction that even with the low $|\phi/\beta|_d$, if he didn't coordinate, roll control was degraded. However, the dominant problem was still the large adverse yaw which caused a degradation in heading control. As a result, the pilot had to divert so much attention to control of sideslip that overall task performance suffered to the point of being marginally acceptable.

4.3.2 Results for Medium Dutch Roll Frequency, Medium $|\phi/\beta|_d$ Configurations

Three configurations were evaluated with the medium ω_d and medium $|\phi/\beta|_d$ of this investigation. The $\phi(s)/\delta_{AS}(s)$ transfer function zero locations with respect to the Dutch roll poles and the respective values of N'_p for Configurations 5, 5A and 5B are shown on Figure 25. The experimental results are shown on Figure 26. A detailed definition of these configurations is given in Appendix IV where the pilot comment data and transient responses are also presented.

4.3.2.1 Configuration 5, $N'_p = +0.068 \text{ sec}^{-1}$

Configuration 5 had the following values of the lateral-directional modal parameters:

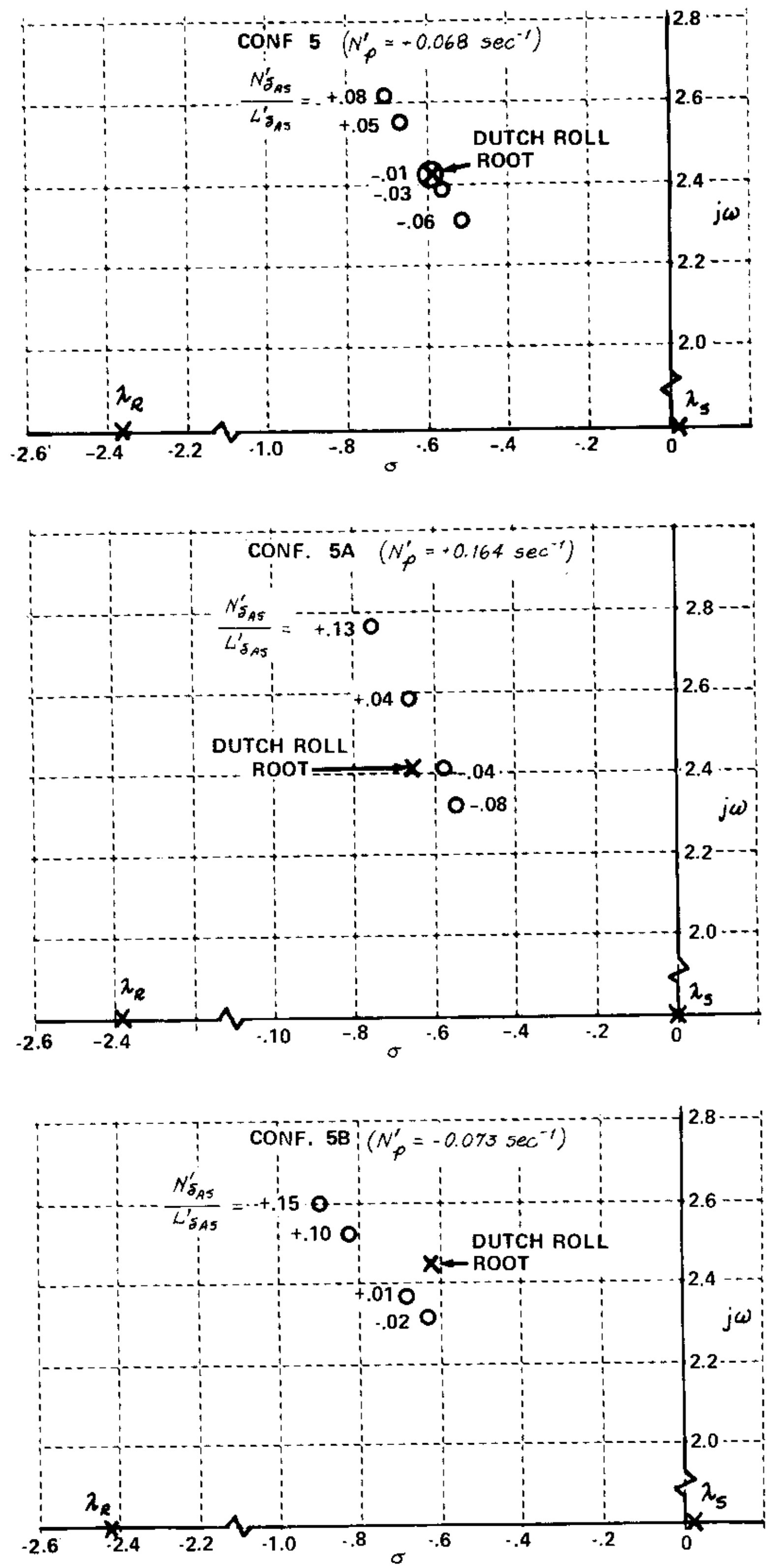


Figure 25 $\phi(s)/\delta_{AS}(s)$ Pole-Zero Locations for Medium ω_d, Medium $|\phi/\beta|_d$ Configurations

$\omega_d \approx$ 2.50 rad/sec $\qquad \tau_R \approx 0.42$ sec
$\zeta_d \approx$ 0.24 $\qquad \tau_s \approx -100$ sec
$|\phi/\beta|_d \approx$ 1.61

The control sensitivities selected by the pilot are shown in Figure 26 as a function of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. In general, the pilot's dominant goal in selecting an aileron sensitivity $L'_{\delta_{AS}}$ for any given test point was to generate "good roll performance with very light forces and very small displacement inputs." Figure 26 shows the selected $L'_{\delta_{AS}}$ to start at a moderately high value for the most proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ case decreasing monotonically towards the most proverse case. For all the adverse cases, the pilot reported no compromise on his $L'_{\delta_{AS}}$ selection due to aircraft characteristics and in fact the change in $L'_{\delta_{AS}}$ from the most adverse to the smallest negative value of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ was small. The decrease occurred because as $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ became more adverse, its effects decreased the roll performance for aileron inputs. The pilot made up for this with increased $L'_{\delta_{AS}}$. Any uncoordinated adverse yaw would result in sideslip into the turn which, when coupled with positive dihedral effect at $|\phi/\beta|_d \approx 1.6$, reduced the roll resulting from a given aileron input. However, even for the most adverse aileron yaw case, the pilot reported that the Dutch roll excited by an aileron input did not affect roll very much supporting the small change in $L'_{\delta_{AS}}$. For the proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ cases, the pilot claimed no compromise on his $L'_{\delta_{AS}}$ selection at $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.05$, but some compromise between "nice, light forces for maneuvering" and a tendency to overcontrol in roll for the most proverse case ($N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.08$). The actual sensitivity selections reflect this. The pilot selected lower values of $L'_{\delta_{AS}}$ with proverse aileron yaw because the sideslip generated in these cases augmented roll rate through the positive dihedral effect.

The rudder sensitivities, $N'_{\delta_{RP}}$, selected for the various $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ cases form a shallow bucket-shaped curve as a function of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ with the adverse side steeper than the other as shown on Figure 26. Minimum sensitivity was selected for the proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ of + 0.05. The pilot comments indicate that this sensitivity selection was governed by the need to control sideslip excited by aileron inputs as balanced against his ability to do so. For $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.01$, the pilot reported a little sideslip generated with aileron inputs, however, the sideslip didn't tend to build up to large values. The pilot was willing to tolerate some uncoordinated sideslip and he didn't feel a need to control, so he picked a relatively low $N'_{\delta_{RP}}$. For a more adverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$, the sideslip generated was outside his band of acceptability, so the pilot chose a higher $N'_{\delta_{RP}}$ in order to control sideslip with acceptable rudder forces. For the most adverse case, sideslip excursions were quite large with aileron inputs. The pilot compromised his selection so as not to overcontrol the sideslip. Time histories of β response to an aileron step from trim, show β to be small initially and then to build up fairly rapidly to significant values. This type of initial to later response relationship leads to predictability problems which was apparently the source of the pilot's overcontrol tendency. In fact, he reported that the β seemed initially slightly proverse followed by sizeable adverse. With proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ ($N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.05$) the pilot reported slight amounts of proverse yaw for

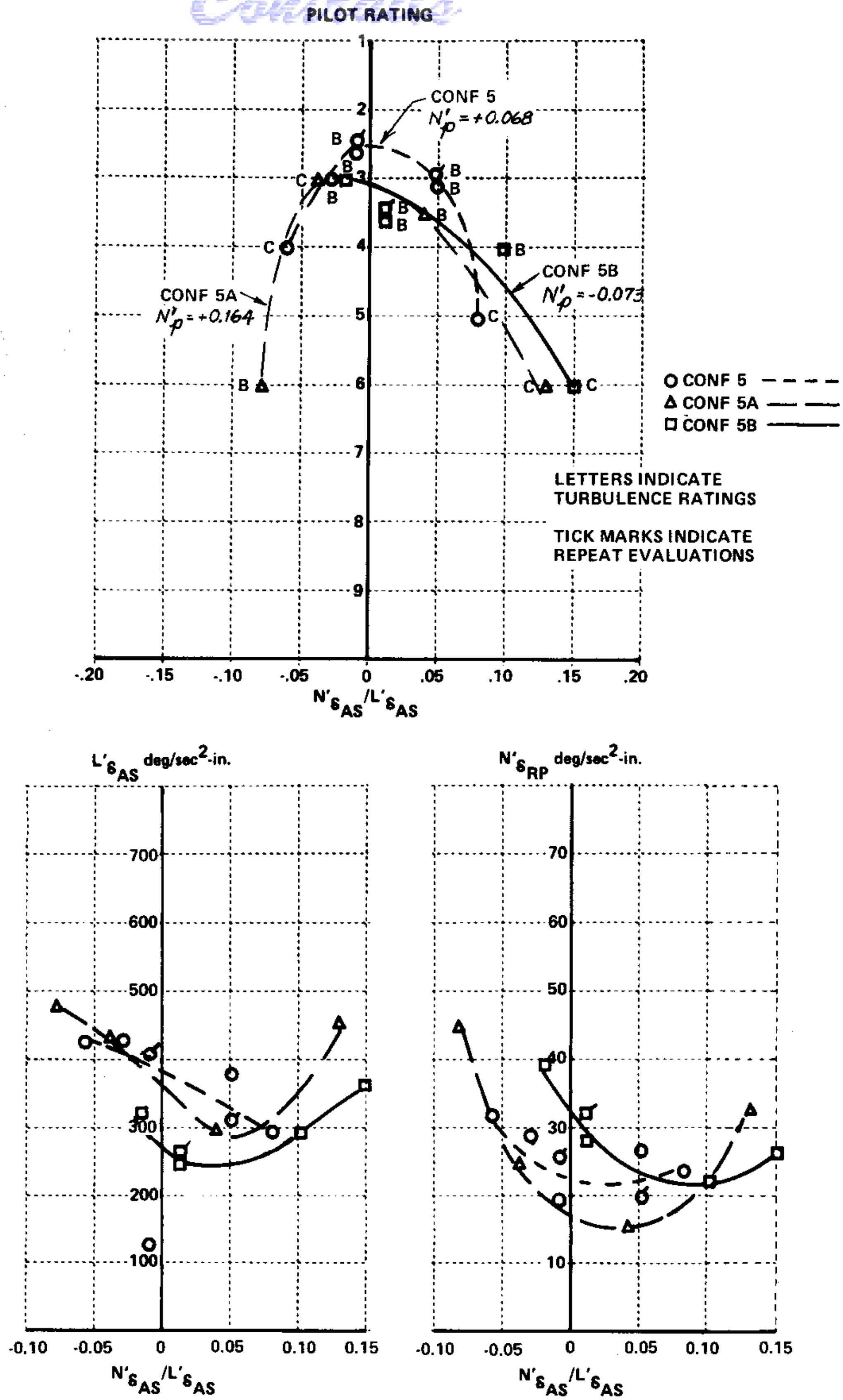


Figure 26 Pilot Ratings and Pilot Selected Control Sensitivities for Medium ω_d, Medium $|\phi/\beta|_d$ Configurations

aileron inputs but it never amounted to unacceptable sideslip. If he tried to control it (with normal rudder technique), he made things worse because of the requirement for a complicated rudder input which he couldn't do in the task. So on the balance, the pilot decided that things would be better overall if he just accepted the β that was excited since it didn't affect roll control much anyway. His corresponding choice for $N'_{\delta_{RP}}$ is essentially the same for the $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.01$ case, i.e., relatively low. For the most proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ case, he definitely felt the need to coordinate but he was faced with the requirement for an "abnormal" rudder input shape. So, although his choice for $N'_{\delta_{RP}}$ is a bit higher in this case, it was compromised by his inability to perform the coordination in the context of the task without over-controlling.

In general, pilot comments for the various Configuration 5 test points speak favorably about roll controllability in terms of roll rate response and in terms of ability to control bank angle quickly and precisely. This indicates that whatever problems were caused by $N'_{\delta_{AS}}/L'_{\delta_{AS}}$, they did not degrade the roll control to the point of producing major deficiencies. The pilot comments on the smoothness of roll rate response to aileron-only inputs were consistent with the varying amounts of roll rate distortion produced by the sideslip due to varying $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ values. The pilot's opinion of bank angle control followed a corresponding trend with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. For the aileron sensitivities he selected, the pilot repeatedly listed the roll control capability and performance under good features. Thus, it becomes evident that the primary reason for degradation of pilot opinion with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ was the amount of sideslip generated for a given input along with the pilot's ability to put in the correct rudder inputs to keep it as small as possible under the task circumstances. He had two motivations to keep sideslip down, one being its effect on roll control and the other being the desire to have the airplane pointed in the direction it is going. The first motivation was not predominant for any Configuration 5 test point. A running comment was that the "sideslip generated and permeated by the Dutch roll mode did not seem to feed into the roll response," i.e., undesirably distort the roll response via the dihedral effect. For the most adverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$, the pilot reported that the Dutch roll oscillation when excited via the sideslip "showed up almost exclusively in sideslip and very little in roll." Since $|\phi/\beta|_d$ was 1.6, there was some roll response distortion which increased with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ but never enough to be unacceptable. Furthermore, with $\zeta_d = .24$ and $\omega_d = 2.5$, the time for a given Dutch roll oscillation to damp out was sufficiently short that the distortion did not strongly interfere with roll control at any $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. Another way to put it is that the transient in the roll response did not significantly degrade the pilot's ability to predict what final response he would obtain for a given input. Consistent with all these comments, the pilot reported, "not much task performance degradation or workload increase in turbulence."

So the problems with Configuration 5 centered primarily on excitation of sideslip per se and the pilot's ability to coordinate it while performing the task. The degradation due to these problems was therefore directly related to the magnitude and sense of aileron yaw and correspondingly exhibited by the pilot rating variation with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. By habit, pilots are accustomed to manipulating rudder in what is considered normal or natural ways in order to coordinate aileron inputs. If the sideslip response requires substantial modification to these techniques then the pilot has difficulties controlling sideslip. Controlling the sideslip was clearly a predominant objection to this configuration. The pilot could not coordinate the sideslip quickly and accurately with this configuration as required in the maneuvering tasks. With the smaller adverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ case, this inability to coordinate was due to the form of sideslip development in response to aileron inputs which made it difficult for the pilot to anticipate coordination. The shape of the sideslip response required that the pilot either delay his rudder inputs a little after the aileron input or feed in rudder as a function of increasing roll rate. In the proverse aileron yaw cases, this inability to coordinate was due to the unnatural cross-control coordination requirement. Where he felt the need to coordinate to prevent the sideslip from building beyond some level of acceptability, the pilot degraded his rating for the configuration as in the most adverse and most proverse aileron yaw cases. Where he could accept the levels of uncoordinated sideslips generated without compromising task performance significantly, the pilot wouldn't coordinate since he couldn't do it well. In these cases, however, he did not degrade his pilot rating.

4.3.2.2 Configuration 5A, $N'_p = +0.164 \text{ sec}^{-1}$

Configuration 5A had the following values of the lateral-directional modal parameters:

$$\omega_d \approx 2.50 \text{ rad/sec} \qquad \tau_R \approx 0.42 \text{ sec}$$
$$\zeta_d \approx 0.26 \qquad \tau_s \to \infty$$
$$|\phi/\beta|_d \approx 1.60$$

The characterizing feature of this configuration was the moderate amount of proverse yaw due to roll rate. This caused the locus of zeros of the $\phi(s)/\delta_{AS}(s)$ transfer function to lie to the right of the Dutch roll pole as shown on Figure 25. One significant aspect of yaw due to roll rate is the phasing of the resulting sideslip in relation to an aileron input. The yawing moment, and hence sideslip, build up in proportion to roll rate. To the pilot, it appears that the initial sideslip response is delayed, following the input, and then grows with roll response. This type of sideslip response is difficult for the pilot to coordinate.

With $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ of - 0.08, there was sufficient adverse yaw due to aileron to overwhelm the proverse N'_p resulting in an adverse-only net sideslip for an aileron step input. The sideslip time history (on flight records) does clearly show the N'_p proverse contribution. The pilot apparently was not specifically aware of this proverse contribution other than to say that "coordination was more difficult than he would like." He did mention the large adverse sideslip for an aileron input and correspondingly selected relatively high $N'_{\delta_{RP}}$ to deal with it. He also chose a relatively high $L'_{\delta_{AS}}$ to overcome the roll rate reduction due to adverse sideslip in the larger, more abrupt maneuvers where he couldn't coordinate as readily. Despite this, he still complained of limiting his $L'_{\delta_{AS}}$ selection because of the large sideslip that it would excite. With $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.04$, the adverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ nearly balanced the proverse N'_p, at least enough in the longer term so that the pilot claimed no compromise on the $L'_{\delta_{AS}}$ selection. He chose the aileron control sensitivity high to maneuver the airplane aggressively with light forces. His selection of $N'_{\delta_{RP}}$ was however limited because of a problem of over-controlling sideslip. There wasn't much rudder required since the generated sideslips were quite small in the adverse direction (normal coordination) and, in fact, the pilot reported that coordination was "not absolutely necessary." However, attempts to coordinate were difficult because of the complicated rudder inputs required due to the N'_p contribution. With the proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ of + 0.04, the sideslip for an aileron step input was essentially proverse. The pilot selected the lowest $L'_{\delta_{AS}}$ of Configuration 5A for this test point, but still noted some oversensitivity and a resulting slight tendency to overshoot in roll control. Proverse sideslip if uncoordinated will augment roll rate via the positive dihedral effect. The pilot did report that he couldn't crosscontrol well, particularly in an aggressive task. This led to the selection of the low $N'_{\delta_{RP}}$ because any inattention on coordination would result in the pilot reverting to normal technique thereby aggravating the proverse sideslip. The pilot stated that, therefore, he did not use the rudder very much.

With $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ of + 0.13, the large proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ combined with the proverse N'_p produced a tendency for the airplane to accelerate in roll rate for aileron-only inputs. Nevertheless, the pilot picked a surprisingly high aileron sensitivity possibly contributing to the roll acceleration difficulties he experienced. Yet he stated that he might have selected higher aileron control sensitivities were it not necessary to limit the sideslip produced by aileron inputs. His choice of rudder sensitivity also was high in relation to the point with $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.04$ but he justified this by his need to combat the excessive proverse sideslip even though it is very difficult because of the crosscontrol requirement.

With $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.08$, there is sufficient adverse aileron yaw to more than swamp out the proverse N'_p. The pilot's complaints centered heavily on the large amount of adverse sideslip that was generated with an aileron input and the associated sideslip oscillations (Dutch roll). The oscillations damped quickly but the pilot described them as uncomfortable. Coordination was in the normal direction but required "lots of rudder." There wasn't a large effect of sideslip on roll rate, but coordination did improve the roll performance. Large rolling maneuvers definitely required heavy coordination and that was more difficult than the pilot would have liked. Abrupt maneuvers produced noticeable side acceleration which was uncomfortable. Random disturbance inputs didn't affect matters significantly.

With $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.04$, the adverse yaw due to ailerons came close, in the longer term, to balancing the proverse yaw due to roll rate. Notwithstanding the phasing of these two effects, the result was relatively small amounts of sideslip generated for aileron inputs. Coordination was in the normal direction and the pilot found it easy to accomplish since relatively small sideslip developed in maneuvering. Aileron-only roll rate was reported as very smooth (note the proximity of this test point zero to the Dutch roll pole on Figure 25). If Dutch roll was generated, it was primarily in sideslip. Hence, ability to damp this mode with ailerons only was not a consideration. The pilot suggested that any problems that arose in aggressive bank angle tracking were due to the high control sensitivities that he selected on both the rudders and ailerons.

For $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.04$, the proverse $N'_{\delta_{AS}}$ supplements the proverse N'_{p} to give an essentially all-proverse sideslip for a step aileron input. With the positive dihedral effect, the proverse yaw has an effect of augmenting roll rate. The pilot reported that for uncoordinated aileron inputs, the airplane rolled quite rapidly, but added that "the proverse yaw didn't seem to affect roll control all that much." He did admit that he was unable to coordinate by crosscontrolling; he would tend to coordinate normally, if at all, which would, of course, aggravate the situation. Dutch roll when excited damped out quite rapidly. Hence, the pilot tended to fly the bank angle tasks without using the rudder for coordination and accepting the attendant sideslip.

For $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.13$, the proverse sideslip generated for an aileron input was reported as "quite excessive." There was a tendency for the airplane to accelerate in roll rate. As a result, bank angle control was poor with a tendency for the pilot to overshoot the desired bank angle, and for the airplane to oscillate about the desired bank angle. Coordination required crosscontrol with the rudder and a conscientious effort on the part of the pilot. Therefore coordination was very difficult in a distracting, aggressive maneuvering task. The effect then of the proverse sideslip was, through augmentation of the roll rate, to cause the final bank angle to be unpredictable. The pilot stated that heading control was not difficult because the Dutch roll frequency and damping were high enough for heading oscillations to quickly subside. Response to random disturbance inputs was not a significant factor in the overall rating of this test point, but the pilot did state that the effects were noticeable.

4.3.2.3 Configuration 5B, $N'_{p} = -0.073 \text{ sec}^{-1}$

Configuration 5B had the following values of the lateral-directional modal parameters:

$\omega_d \approx 2.52$ rad/sec $\tau_R \approx 0.41$ sec
$\zeta_d \approx 0.25$ $\tau_S \approx -50$ sec
$|\phi/\beta|_d \approx 1.55$

The distinguishing feature of this configuration among the medium ω_d, medium $|\phi/\beta|_d$ configurations was a moderately adverse value of yaw due to roll rate ($N'_p = -0.073$). The locus of the $\phi(s)/\delta_{AS}(s)$ zeros with varying yaw due to aileron ($N'_{\delta_{AS}}/L'_{\delta_{AS}}$) passes to the left of the Dutch roll root as shown on Figure 25.

Figure 26 shows that with this configuration the pilot selected the lowest aileron control sensitivities in the medium ω_d, medium $|\phi/\beta|_d$ configuration series. This was a little surprising in that with the larger adverse N'_p in conjunction with adverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$, there was a reduction in roll rate with positive dihedral effect since the net residual sideslip was adverse. Hence, one might expect the pilot to select higher aileron sensitivities to maintain light forces for desired roll rates. For all evaluations of this configuration, the pilot reported no compromises on aileron sensitivity selection. Pilot-selected values of $L'_{\delta_{AS}}$ decreased from the more adverse sideslip case, as $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ became more proverse. The $L'_{\delta_{AS}}$ curve reaches a minimum expectedly where proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ counteracts adverse N'_p in the longer term and hence there is minimum reduction of roll rate by uncoordinated adverse sideslip. In the most proverse case, the pilot reported that the aileron forces were nice and light, as he liked them. No compromise was indicated.

Rudder control sensitivity ($N'_{\delta_{RP}}$) selections, also shown on Figure 26, form a shallow bucket-shaped curve with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ variation, the low point being in the region where proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ generally counteracts the adverse N'_p resulting in relatively low residual sideslip after initial transients. With proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ the pilot selected lower values of rudder control sensitivity so that during maneuvering, when he would revert to normal coordination through habit, his tendencies to aggravate the proverse sideslip situation would be reduced. For adverse aileron yaw, coordination was in the normal direction and for larger rolling maneuvers, required quite large rudder inputs. The pilot chose rudder sensitivity to provide light rudder pedal forces for large rolling maneuvers. The high sensitivity, however, resulted in overcontrol tendencies during small maneuvers about zero sideslip. Therefore, the rudder sensitivity selection became a compromise between light enough forces for large maneuvers and heavy enough forces to prevent overcontrol during small maneuvers.

Pilot ratings for this configuration varied little from a 3 at $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.02$ to a 4 at $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.10$ and then decreased to a 6 at $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.15$. The turbulence ratings also follow the same trend. The pilot's complaints for all values of aileron yaw centered on the sideslip generated by aileron inputs and his difficulties in controlling it. He repeatedly reported relatively little carryover from sideslip disturbances into the roll response.

Effects of turbulence were not very significant for any of the evaluations and were more noticeable in the sideslip response if anywhere.

For $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.02, the sideslip response to an aileron input started off in the adverse direction but then picked up considerably as roll rate developed. The pilot evidently found the rudder requirement somewhat more difficult as compared to situations where the initial sideslip is the dominant factor in coordination. The pilot reported no difficulties with roll control itself or with its associated evaluation tasks. Heading control was reported as good despite the sideslip problems. The sideslip could be coordinated well enough to point the aircraft in the desired direction and the Dutch roll was well damped. The most bothersome aspect of this test point was the pilot's inability to coordinate as well as he would have liked and the associated initial overcontrol of sideslip. More rudder was required as the roll rate increased and the pilot selected light rudder forces to be able to meet this requirement. Because of the light rudder forces, however, there was a tendency to overcontrol with the rudder during the initiation of maneuvers.

With $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = + 0.01, the predominant problem again appeared to be with the time history of the sideslip growth following an aileron input. The result is a similar difficulty with coordination as discussed above (changing requirement for rudder with roll rate) except that the pilot seemed more conscious of it here, since the sideslip stayed near zero or very slightly proverse on initial appearance and then built up as roll rate developed. Roll control was again deemed satisfactory. The Dutch roll, when excited, was mostly in sideslip and the pilot reported it as relatively well damped. The complaints for both evaluations of this test point centered on the sideslip and on the pilot's inability to coordinate. The pilot would often revert to normal rudder-aileron input phasing when distracted by a task and consequently aggravate the initial sideslip generated. Hence, he would have sideslip oscillating through small excursions about zero causing a distinct annoyance. As a result, the heading controllability was considered to be only fair. Random disturbance inputs aggravated the sideslip problems, though not significantly.

With $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = + 0.15, the sideslip generated by aileron inputs was predominantly proverse. The pilot reported coordination requirements to be excessive and in the wrong direction. Consequently coordination was difficult to accomplish. Despite the fact that the pilot indicated little effect on the roll response due to sideslip, he did report a particularly noticeable tendency to overcontrol and oscillate about a desired bank angle when he tried to acquire and hold one. These are typical problems due to oversensitivity of roll control for small bank angle corrections where the pilot probably doesn't even attempt to coordinate the proverse sideslip. Though the dihedral effect itself was fairly small, large sideslips would produce significant modification of the roll response. The bank angle control problems in turn deteriorated heading controllability as well as causing difficulty in performing the bank angle tracking task. In the more abrupt maneuvering tasks, the pilot reported that "it was easy to have the airplane pick up excessive sideslip angle" and a "tendency to lose the airplane in sideslip." These problems would strongly compromise both the air-to-air and air-to-ground fighter tasks. Response to random disturbance inputs was not very prominent other than to cause a minor deterioration from an already poor performance.

4.3.2.4 Comparison of Medium Dutch Roll Frequency, Medium $|\phi/\beta|_d$ Configurations With MIL-F-8785B(ASG) Roll-Sideslip Coupling Requirements

These configurations met the basic Dutch roll frequency and damping ratio requirements for Level 1 flying qualities of Class IV airplanes in Flight Phase Category A. Degradation in pilot rating was primarily a result of sideslip and coupling thereof into the roll response. This section compares the data for the medium ω_d, medium $|\phi/\beta|_d$ configurations with the requirements on roll rate oscillations and on sideslip excursions for small inputs of MIL-F-8785B(ASG).

Figure 27 compares the values of p_{osc}/p_{AV} obtained with the MIL-F-8785B(ASG) requirement on roll rate oscillations for small inputs. With the medium value of $|\phi/\beta|_d$ ($|\phi/\beta|_d \approx 1.6$) of this investigation, p_{osc}/p_{AV} was small for all test points, in fact well within the Level 1 boundary regardless of the associated pilot ratings. In all cases, the pilot reported relatively little effect on roll rate due to Dutch roll oscillations in sideslip. Only three points rated between 5 and 6 approached the Level 1 boundary and they were downrated primarily because of sideslip per se. Hence, these configurations do not provide sufficient information to verify the location of the p_{osc}/p_{AV} boundaries.

The Level 1 sideslip excursion parameter ($\Delta\beta_{MAX}/k$) is plotted for all the test points of the medium ω_d, medium $|\phi/\beta|_d$ configurations against the corresponding MIL-F-8785B(ASG) requirements on Figure 28. One aspect is immediately apparent; the Level 1 boundary appears too conservative in the $-240° < \psi_\beta < -360°$ range, while it appears too lenient in the vicinity of $\psi_\beta = -180°$ for the medium $|\phi/\beta|_d$ of this experiment. With all the configurations under question here, the predominant problem that the pilot reported was the sideslip that was generated by aileron inputs. There was, of course, some effect of sideslip on the roll response, but with $|\phi/\beta|_d \approx 1.6$, this was small. Hence, it would be expected that the sideslip excursion requirement of MIL-F-8785B(ASG) would stratify the test points in accordance with the ratings. This test does in fact do that but in a manner which suggests some boundary shifting. The 5ND test points are discounted from this discussion; they will be handled in a separate section.

The data points which received pilot ratings of 3.5 or less and fell outside the Level 1 boundary in the $300° < \psi_\beta < 360°$ region represent situations where the pilot had a slight amount of proverse aileron yaw ($+.01 < N'_{\delta_{AS}}/L'_{\delta_{AS}} < +.05$) in combination with various values of N'_p. The sideslip generated in each of these cases for aileron inputs was reported "not to be too large", evidently within the pilot's band of tolerance. Since there was little effect of these relatively small amounts of sideslip on roll rate, the pilot was satisfied not to coordinate at all or apply little coordination effort

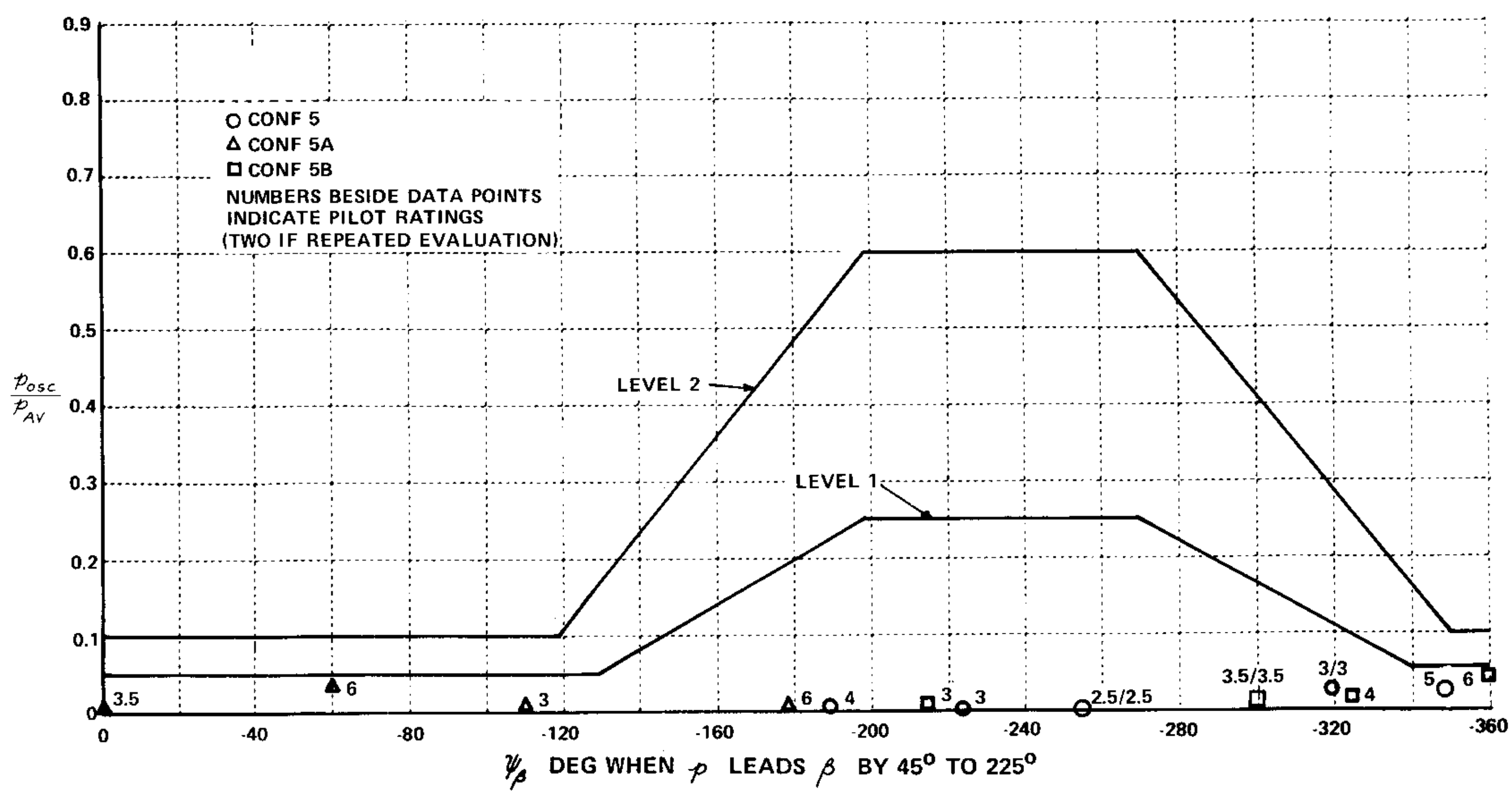


Figure 27 Medium Dutch Roll Frequency, Medium $|\phi/\beta|_d$ Configurations Compared to p_{osc}/p_{AV} Requirements of MIL-F-8785B(ASG)

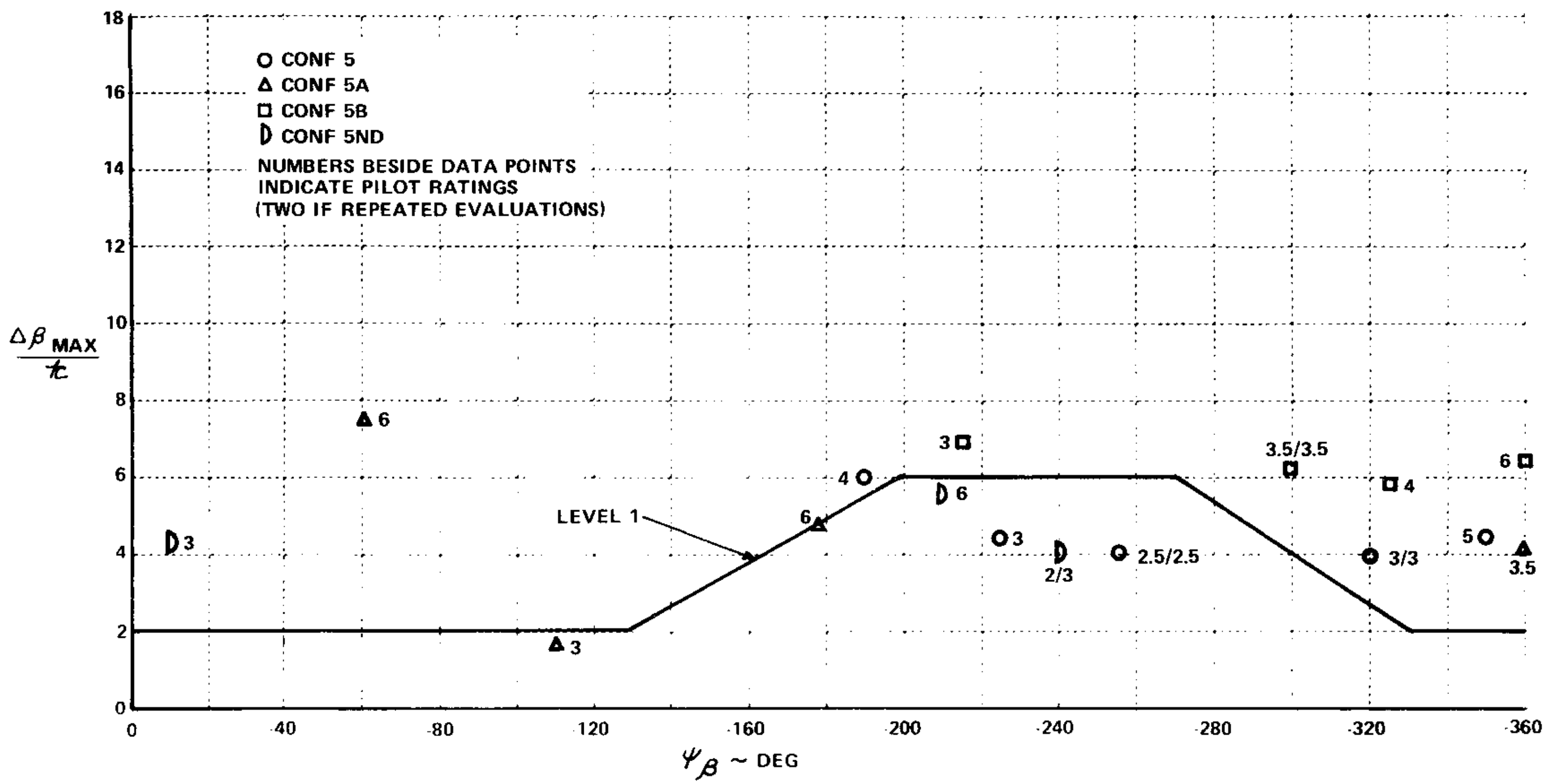


Figure 28 Medium Dutch Roll Frequency, Medium $|\phi/\beta|_d$ Configurations Compared to Level 1 $\Delta\beta_{MAX}/t$ Requirements of MIL-F-8785B(ASG)

since unnatural rudder inputs were required. Hence, these points correctly fall outside the easier to coordinate hat section of the boundary. These evaluation points do, however, have a common characteristic in that in all three cases, the sideslip went initially proverse then reversed through zero and ramped off slowly in the adverse sense. A problem with using $\Delta\beta_{MAX}$ as an indicator of pilot tolerance of sideslip is that the pilot may be more tolerant of a given magnitude of sideslip excursion if that excursion has a mean value near $\beta = 0$ than if it is all on one side of $\beta = 0$. Furthermore, he might be more tolerant of a given $\Delta\beta_{MAX}$ if he knows that it will reverse and go or cross through $\beta = 0$ in a short time. The pilot ratings, in this case, show that despite the fact that the pilot is unable (technique-wise by habit) to coordinate the sideslip, he tolerated more sideslip than the Level 1 boundary permits for the specific ψ_β range where small proverse aileron yaw exists. This may be because soon after the aileron input, the sideslip crosses through zero and the pilot would likely notice this directly or indirectly on the larger amplitude roll maneuvers where he waits a longer time after inputs before the next input. The effect of this initial proverse sideslip on small corrections where the pilot would likely operate on the initial portion of response to aileron input would be to affect preciseness by reducing predictability of response to input (proverse sideslip with positive dihedral accelerates the roll), thereby causing mild overcontrol for the test points in question. However, this overcontrol was small enough not to compromise satisfactory task performance.

There were two Level 2 data points which fell on or within the Level 1 $\Delta\beta_{MAX}/k$ boundary in the $\psi_\beta \approx 180°$ to $210°$ region. The Configuration 5ND point will be discussed in a separate section on that configuration. For the Configuration 5A point, rated PR = 6, and lying on the boundary, the pilot's difficulties were focused on the large adverse sideslip for aileron inputs that caused noticeable side accelerations for abrupt maneuvering and which "were uncomfortable." This test point had $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -.08$, causing the substantial adverse sideslip very shortly after the roll input which was compensated some time later by proverse yaw due to roll rate if the pilot waited that long. The large aileron yaw impeded the pilot's ability for making small bank angle corrections where roll rates did not develop enough to show the effects of N'_p. Either ψ_β did not account for this factor or the accuracy with which ψ_β could be measured from in-flight data was such that the data point is too far to the right on Figure 28.

The medium ω_d, medium $|\phi/\beta|_d$ configurations are compared to the Level 2 ($\Delta\beta_{MAX}/k$) requirement in Figure 29. The Level 2 boundary for the air-to-air fighter task predicts quite well the goodness of flying qualities for situations where sideslip is the dominant problem. Generally the location of points in relation to the boundary corresponds with the associated pilot rating. The two exceptions are the points with PR of 6, one on and one slightly above the boundary. The point on the boundary can be considered to support the boundary when the accuracy with which $\Delta\beta_{MAX}/k$ can be measured from flight data is considered. For the other PR = 6 point, the pilot stated that adequate performance was very marginal but he thought he could attain adequate performance if he could learn to control the "miscoordinations." Because of the marginal character of this point, it is not considered to refute the boundary.

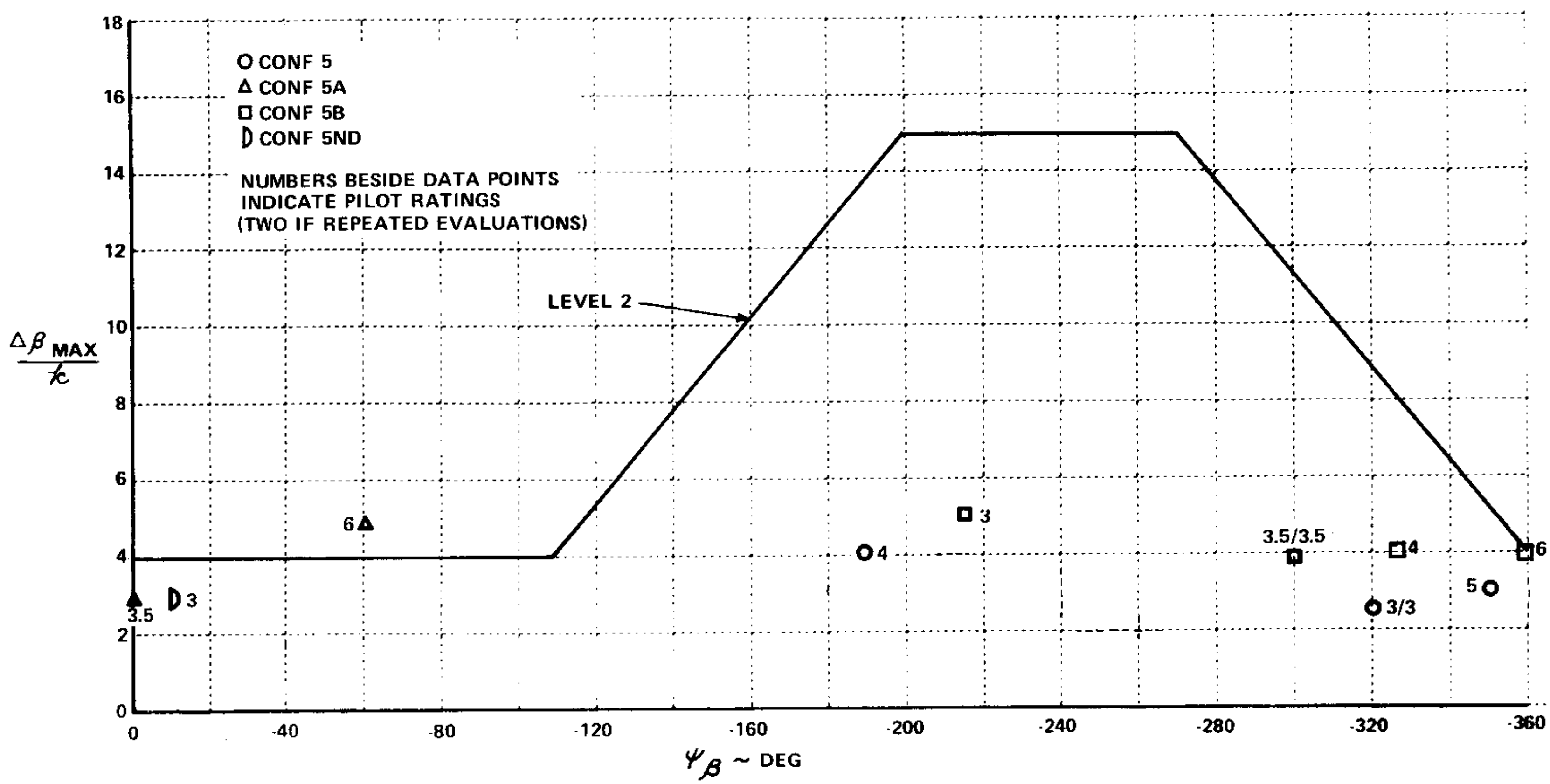


Figure 29 Medium Dutch Roll Frequency, Medium $|\phi/\beta|_d$ Evaluation Points That Do Not Meet Level 1 $\Delta\beta_{MAX}/k$ Requirements Compared to Level 2 $\Delta\beta_{MAX}/k$ Requirements of MIL-F-8785B(ASG)

4.3.3 Results for Medium Dutch Roll Frequency, High $|\phi/\beta|_d$ Configurations

Three configurations were evaluated with the medium ω_d and high $|\phi/\beta|_d$ of this investigation. The $\phi(s)/\delta_{AS}(s)$ transfer function zero locations with respect to the Dutch roll poles and the respective values of N'_p for Configurations 11, 11A and 11B are shown on Figure 30. The experimental results are shown on Figure 31. A detailed definition of these configurations is given in Appendix IV where the pilot comment data and transient responses are also presented.

4.3.3.1 Configuration 11, $N'_p = +0.013 \text{ sec}^{-1}$

Configuration 11 had the following values of the lateral-directional modal parameters:

$$\omega_d \approx 2.44 \text{ rad/sec} \qquad \tau_R \approx 0.42 \text{ sec}$$
$$\zeta_d \approx 0.22 \qquad \tau_S \rightarrow \infty \text{ sec}$$
$$|\phi/\beta|_d \approx 5.7$$

The pilot selected aileron and rudder control sensitivities for Configuration 11 are shown on Figure 31 as a function of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. The plot of $L'_{\delta_{AS}}$ reveals relative invariance with aileron yaw for negative values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. With adverse aileron yaw, the pilot reported choosing sensitivities that did not excite excessive sideslip with aileron inputs. The adverse sideslip, however, if not coordinated would decrease the roll rates attainable with aileron inputs. The pilot therefore compromised his selection of aileron sensitivity so that aileron forces were light in coordinated rolling maneuvers but not so light as to easily excite large sideslip excursions with aileron only inputs. With proverse aileron yaw, the pilot clearly reported a compromise in selecting aileron control sensitivity. With aileron inputs, proverse sideslip was excited, which in turn modified the roll response to result in closed-loop control difficulties when tracking bank angles. The pilot commented on tendencies to both overshoot the desired bank angle and to develop an oscillation about the desired bank angle. Some of the oscillatory tendency was alleviated by the selection of a lower aileron control sensitivity but this resulted in higher than desired aileron stick forces in maneuvering.

The rudder control sensitivities ($N'_{\delta_{RP}}$ on Figure 31) varied considerably with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ on the adverse aileron yaw side and not at all on the proverse aileron yaw side. The specific values of $N'_{\delta_{RP}}$ selected by the pilot were tied strongly to the requirement to coordinate sideslip and augment the roll response from ailerons in cases where he was able to do this. With $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.06$ the need for rudder to get adequate roll performance from the ailerons was strong and since coordination could be accomplished with the normal or natural technique, the pilot picked a high value of $N'_{\delta_{RP}}$. With $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.03$, coordination was again easy to do but the requirement was reduced from that above and so the pilot chose less sensitive rudders. With zero aileron yaw, $N'_{\delta_{RP}}$ was the minimum value selected for this configuration because coordination requirements were not strong but in

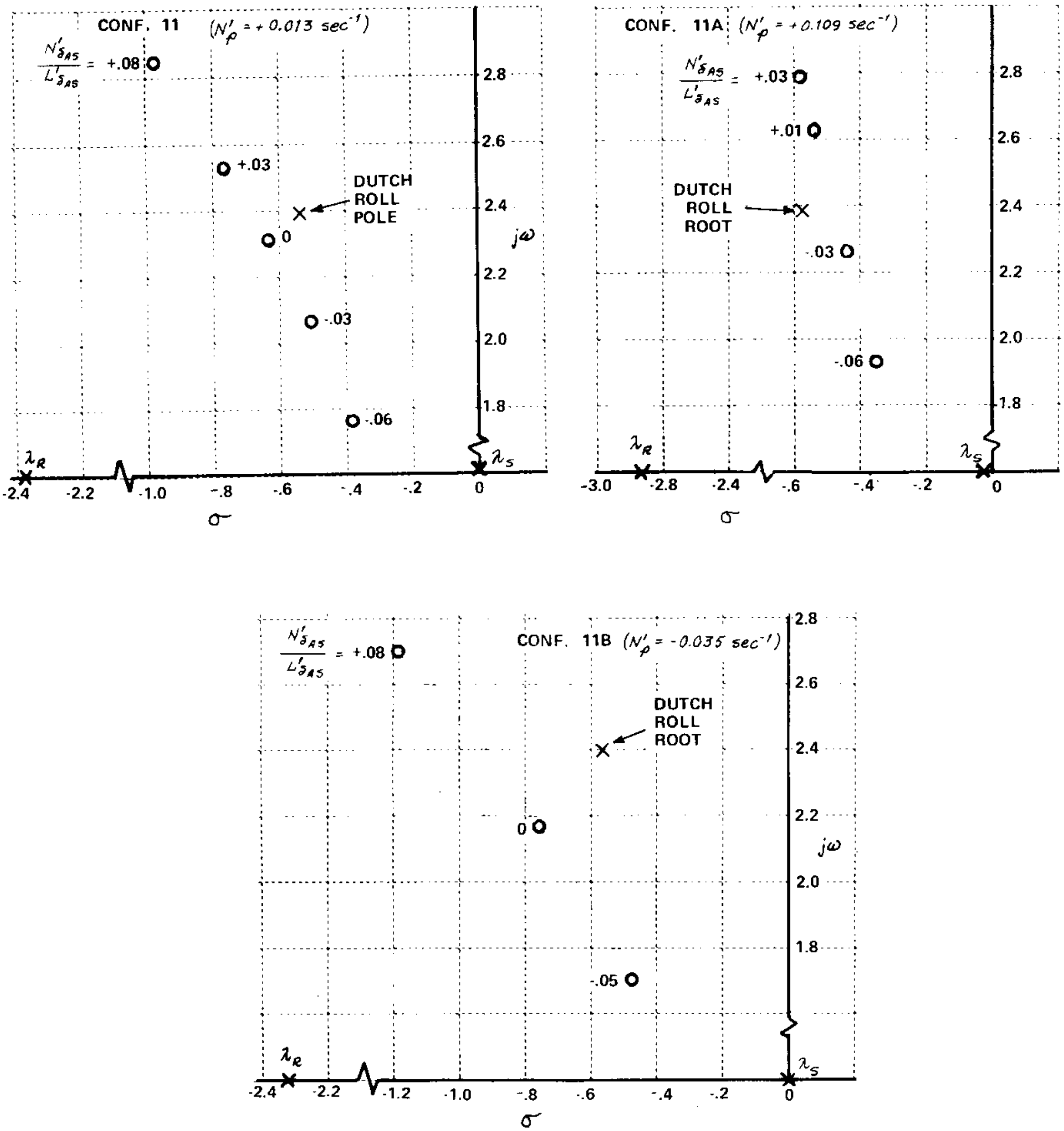


Figure 30 $\phi(s)/\delta_{AS}(s)$ Pole-Zero Locations for Medium ω_d, High $|\phi/\beta|_d$ Configurations

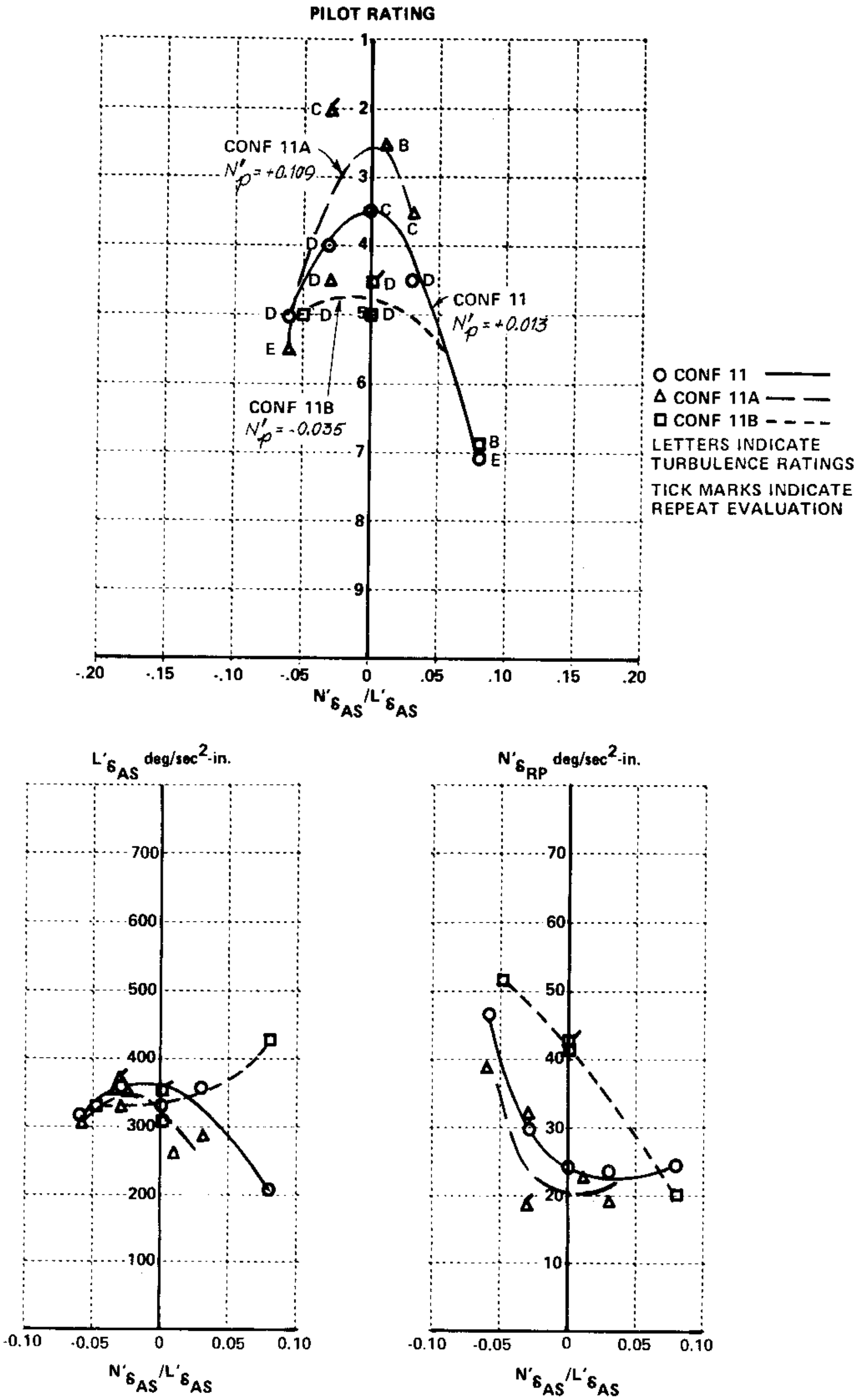


Figure 31 Pilot Ratings and Pilot Selected Control Sensitivities for Medium ω_d, High $|\phi/\beta|_d$ Configurations

addition because the delayed appearance of sideslip due to N'_p following an aileron input made coordination slightly more difficult. As $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ increased positively from zero, $N'_{\delta_{RP}}$ did not change from the value with zero aileron yaw despite the fact that the need for coordination increased. The reason is that the pilot can't coordinate since coordination requires an abnormal rudder technique which he can't learn to apply when he is concentrating on a demanding task. The more proverse aileron yaw became, the more detrimental to the overall control task were the effects of not coordinating perfectly with the abnormal technique. The pilot therefore chose to simply not coordinate, particularly in the larger roll maneuvers. Hence the pilot settled on low values of $N'_{\delta_{RP}}$, resulting in heavier rudder forces but minimizing the detrimental effects of miscoordination.

The curve fitted through the pilot ratings for Configuration 11, Figure 31, falls roughly halfway in "goodness" of handling qualities between Configuration 11A (more proverse N'_p) and Configuration 11B (adverse N'_p) in the $N'_{\delta_{AS}}/L'_{\delta_{AS}} = 0$ region. The three pilot rating curves tend to coalesce as $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ increases on both sides of zero. Except for one point (PR = 7 on Configuration 11B), these trends hold generally for both numerical ratings and turbulence ratings. The best rating for Configuration 11(at $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = 0) was on the borderline between satisfactory and unsatisfactory (PR = 3.5). Since the Dutch roll characteristics remained constant for the various test points, the open-loop effects of random disturbance inputs also remained constant. However, pilot opinion of random disturbance input effects was heavily swayed by his ability to counteract these effects in a closed-loop situation primarily through the ailerons. As that ability was impaired both overall pilot ratings and turbulence ratings were degraded.

With the moderately large value of the coupling between sideslip and roll, $|\phi/\beta|_d$, certain predominant aspects emerge from all the Configuration 11 evaluations. First of all, anything that happens in β has a large effect on the bank angle response and hence on roll control. The pilot seldom complained about sideslip in itself. In fact, he commented favorably about heading controllability for all values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$, adding that the generated sideslip was not excessive while maneuvering in the first place, but also one mechanism whereby sideslip might linger on, namely the Dutch roll mode, was of sufficiently high frequency and damping ratio that the time to damp ($\zeta_d \omega_d$) was acceptable in his time scale of control. Only with the most proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$, where he had particularly big problems with bank angle, did he allude to minor heading control difficulties. So, the problems with this configuration were not in the directional control per se but in what difficulties any imprecision in yaw control caused in the roll or bank angle control due to the large coupling $|\phi/\beta|_d$ in the Dutch roll. For even a small amount of sideslip, there was a large corresponding bank angle response through the Dutch roll mode. This sideslip could be excited in many different fashions: from yaw due to aileron ($N'_{\delta_{AS}}$), from yaw due to roll rate (N'_p), from yaw due to rudder inputs, from yaw due to side gusts. The pilot's inability to keep sideslip precisely zero under all conditions was the source of his problems.

Not surprisingly, therefore, the most prominent effects of the high $|\phi/\beta|_d$ were felt in the bank angle control and the associated ability to track bank angle, roll performance, and turbulence response. The bulk of these detrimental effects are transient ones associated with the Dutch roll. However, what causes a large $|\phi/\beta|_d$ when the Dutch roll frequency is of moderate value is the large positive dihedral effect (L'_β). What this means is that the rudder becomes very effective at producing rolling moments, and conversely any sideslip that goes unchecked produces rolling moments that either augment or detract from aileron authority.

Unfortunately, the comments for $N'_{\delta_{AS}}/L'_{\delta_{AS}} = 0$ were lost due to a recorder malfunction. The pilot rating was on the borderline of being unsatisfactory. Likely, an important downgrading factor was the roll response to turbulence and the pilot's inability to help that situation as evidenced by a TR of C.

With the adverse $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.03$ case, the pilot reported a noticeable amount of roll rate distortion for uncoordinated aileron inputs. Hence, he called it a definite advantage to coordinate with rudder, both to augment roll rate (note that both initial and longer term sideslip are adverse) and for smoothing it out. Unfortunately, he had trouble controlling the sideslip precisely to zero and the dihedral effect would then cause an undesirable modification to bank angle response. As a result the pilot reported the bank angle control and tracking as only fair to good. Also, he reported a slight oscillatory tendency trying to settle on a bank angle, probably because he couldn't coordinate on small bank angle corrections. Turbulence bothered him more in this case (TR = D) because in trying to suppress its effects, he induced some additional sideslip with ailerons. Again, as mentioned earlier, the above factors evidently did not downgrade his heading control. However, besides bank angle control problems for the air-to-air task, the pilot claimed that the turbulence problems "would tend to degrade air-to-ground capabilities quite noticeably."

For the most adverse aileron yaw case, ($N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.06$) the pilot voiced one of his few complaints about directional trim, because of its large effect on the lateral trim (via L'_β). He commented, however, that when he had achieved good directional trim, the lateral trim was easy. There also was sufficient adverse yaw due to ailerons that he had to coordinate to get roll rates that he considered to be compatible with input size, otherwise the adverse sideslip would significantly reduce roll performance. The pilot reported that, although the Dutch roll itself damped out reasonably quickly he would still set up some bank angle oscillation going from one bank to another simply because he couldn't coordinate well enough on both roll entry and recovery. In the bank angle tracking task, he claimed good performance, suggesting when he didn't try too hard (lower gain), he coordinated better. Examination of the flight record subjectively confirmed the pilot's tracking task comments. RMS tracking task error was not, however, computed for this particular case. Again, heading control was no problem. Any situation where the pilot was required to control bank angle in an unprogrammed manner, such as in air-to-air tracking or in turbulence, coordination requiring a precise combination of aileron and rudder inputs was too difficult and he would have problems. In the higher lead time ground attack situation, these problems would be less severe. In summary, this situation was clearly unsatisfactory to the pilot. In turbulence, the combination of direct effects of sideslip disturbances and the additional problems caused by the pilot fighting these effects caused the turbulence effect rating of D.

For the smaller proverse aileron yaw case ($N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = + 0.03), the sideslips generated were never large enough that the pilot couldn't accept them in terms of their effect on roll control. This, coupled with an inability to coordinate properly led the pilot to fly essentially with his feet on the floor. The consequences were not too harsh because as the pilot stated, " the Dutch roll was reasonably well damped and fast enough." There was a slight tendency to overcontrol and to overshoot bank angle. There were no difficulties with heading control. However, trying to track or control the bank angle in the presence of random disturbance inputs merited a rating of D and would compromise the pilot's ability to do the job even in ground attack.

With the most proverse aileron yaw case ($N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = + 0.08), the pilot reported a "quite dramatic tendency to overshoot, overcontrol and oscillate in bank angle." In maneuvering, he would overcontrol when trying to coordinate normally making things worse than if he maneuvered with his feet on the floor. In fact, the pilot reported that he couldn't coordinate and therefore, he had to accept the roll rate distortions caused by the sideslip. This impaired his ability to predict input size or shape to achieve a desired goal and led to lateral pilot-induced oscillations. So bank angle control and tracking were both poor since the pilot could not perform aggressively (high pilot gain) or precisely without having an unacceptable situation (PR of 7). Heading control deteriorated only insofar as it was tied to bank angle. Dutch roll oscillations in β had little effect on heading. Random disturbance inputs were detrimental (TR = E) in that when the pilot attempted to suppress the effects, lateral pilot-induced oscillations were developed. The pilot reiterated that trying to coordinate the sideslip "only made things worse."

4.3.3.2 Configuration 11A, N'_{p} = + 0.109 sec^{-1}

Configuration 11A had the following values of the lateral-directional modal parameters:

$$\omega_d \approx 2.46 \text{ rad/sec} \qquad \tau_R \approx 0.37 \text{ sec}$$
$$\zeta_d \approx 0.23 \qquad \tau_s \approx 29 \text{ sec}$$
$$|\phi/\beta|_d \approx 5.7$$

Looking at the $L'_{\delta_{AS}}$ selections on Figure 31, there is remarkably little change in aileron sensitivity with varying $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. The pilot comments associated with the selections do, however, change. For $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.06, aileron only inputs generated a lot of adverse yaw which, coupled with the large positive dihedral effect, caused a reduction in net roll rate for the given aileron input. The pilot stated that the aileron forces were a little higher than he liked but were still satisfactory. For $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.03$, the pilot reported that he chose the aileron control sensitivity to give him the aileron stick forces that he liked. He reported no compromise with aircraft characteristics for $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.01$. For $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.03$, he referred to his final $L'_{\delta_{AS}}$ selection as a definite compromise between a real strong tendency to overcontrol on bank angle and just having uncomfortably heavy ailerons to maneuver in roll.

Rudder control sensitivity selections, $N'_{\delta_{RP}}$, (Figure 31) varied considerably with the changes in yaw due to aileron, particularly for the adverse or negative values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. With $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.06$ in combination with the proverse N'_p, aileron inputs produced adverse yaw which the N'_p merely limited in amplitude. The sideslip was such that the pilot could coordinate it with normal technique. The high rudder control sensitivity he selected was undoubtedly to maintain reasonable rudder pedal forces for maneuvering coordination requirements but it was compromised by a tendency to overcontrol on small sideslip corrections if $N'_{\delta_{RP}}$ was too high. Coordination here also served to significantly increase and smooth out roll rate due to ailerons. For $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.03$, the pilot selected a considerably lower $N'_{\delta_{RP}}$, giving him sufficiently light rudders to coordinate the small amount of adverse sideslip in roll maneuvers and yet sufficiently heavy to alleviate the tendency to overcontrol on small sideslip corrections about zero. With $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.01$, the net sideslip generated by aileron inputs is initially proverse but of small amplitude and later crossed back through zero to a small adverse value. The pilot noted the initial sideslip but the longer term quantity was undistinguishably small. Consequently, he didn't really need to coordinate. In any case, if he tried, the initial crosscontrol requirement was difficult to satisfy and he would tend to overcontrol. Hence, his choice of $N'_{\delta_{RP}}$ was not very consequential other than being low to alleviate the overcontrol. With $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.04$, the sideslip was again proverse initially but then settled at a small adverse value; it didn't cause much problem in roll. Because of the difficulty in accomplishing crosscontrol coordination, the pilot simply did not coordinate; he did not use the rudder. The gearing selection was therefore again inconsequential.

Inspection of the pilot rating vs. $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ relationship on Figure 31 reveals that this configuration received higher pilot ratings within a small band of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ about zero (approximately -0.03 to + 0.03) than either of the other two high $|\phi/\beta|_d$ configurations (11 or 11B). Although not clearly defined, the optimum rating would appear to correspond to aileron yaw parameter values near zero and ratings drop fairly quickly with increasing aileron yaw on both sides of zero.

For $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.06$, the pilot objected to the large amount of adverse yaw generated by aileron inputs. Every excitation of sideslip occurring with aileron input in turn resulted in Dutch roll with the high roll to yaw ratio which modulated roll rate response ("roll rate was noticeably ratchety"). Being adverse in the steady state, this sideslip further caused a significant reduction in roll rate for the aileron input. These characteristics made coordination with rudder essential for the fighter tasks. However, when the pilot coordinated, he had a tendency to overcontrol the sideslip, which caused him to report "a funny sashaying feeling" about the airplane, and that it was in a "combination of roll and sideslip most of the time when maneuvering." As a result of all this, bank angle control and the associated tracking task were compromised. Instead of being able to roll right up and stop on a bank angle he had to either work up to it or back down to it from an overcontrol with rudder. He would, of course, use rudder to augment roll rate from ailerons, which actually meant cancelling out the adverse sideslip that caused the roll rate to be reduced or creating proverse sideslip which would augment roll rate through the positive dihedral effect. With the given damping in Dutch roll, heading control was not much of a problem. The actual sideslip excursions which would affect heading control were in themselves not large. Most of the problems arose from the large effect on roll of small sideslip. Random disturbance inputs produced quite noticeable roll response requiring "almost continually fighting the ailerons" (Turbulence Rating of E). Using ailerons to quell turbulence effects on bank angle would compound Dutch roll problems because of the aileron yaw which would further induce roll response because of the dihedral effect.

With the reduced aileron yaw at $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.03, there was only a small amount of net adverse yaw generated by aileron inputs with its attendant smaller Dutch roll oscillation. Dutch roll modulation of the roll rate response was, therefore, also small and the pilot reported the roll rate response to be smooth. The pilot evaluated this test point twice, in one case rating it a 2 and in the other, a 4.5. For the rating of 2 the pilot reported that the bank angle controllability was quite good. He could roll to, and stop on, a desired bank angle quite well. Roll control was listed as a good feature of the airplane. For the rating of 4.5, bank angle controllability was reported to be less predictable. There was a tendency to overshoot bank angle and for the airplane to oscillate for one or two overshoots about the desired bank angle. In both cases, the pilot complained about the "marked or crisp" roll response to turbulence. Coordination was not required for roll rate smoothness but could be used to noticeably augment roll rate from ailerons in the larger roll maneuvers. Thus, there appears to be an advantageous effect of the proverse N'_p in limiting the longer term adverse sideslip buildup. The fact that the pilot could use rudder effectively to help roll performance allowed him to select less sensitive aileron control; this was an advantage for small bank angle corrections. Even then, on small bank angle corrections with ailerons, such as alleviating the effects of random disturbance inputs, the pilot reported some tendency to "couple with the response every now and then." In general, as was remarked earlier, the comments for the two evaluations were similar in nature, but differed in degree consistent with the pilot ratings.

With $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = + 0.01, very little sideslip was excited and what little there was seemed to be initially proverse and unnoticeable to the pilot in the steady state. The pilot reported "doing just as well or better keeping his feet off the rudders and simply not coordinating" than trying to crosscontrol to cancel the initially proverse sideslip. Except for a slight tendency to overcontrol on bank angle, he commented quite favorably about bank angle control tasks. With the given damping in the Dutch roll, heading control was good. The most prominent objection was some "roll rate nonlinearity" on large amplitude rapid roll reversals. These are the situations where large roll rates will, in fact, produce proverse sideslip via N'_p and result in a tendency "for the airplane to take off a little bit right in the middle of the roll." Hence, when $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ is near zero, the effect of N'_p becomes more noticeable in large amplitude maneuvers. The pilot did not mention effects of random disturbance inputs on roll response and this was somewhat surprising, since one would expect open-loop turbulence response to be the same as for other test points. The pilot comments on that, however, in relation to his ability to alleviate its effects with ailerons. With $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.01$, that task, namely, small corrections with ailerons, was not a problem.

With $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.04$, the pilot commented that "a fair amount of proverse yaw was generated for each aileron input." The resulting sideslip would result in "a noticeable speeding up effect in the middle of an aileron roll." The combination of proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ and proverse N'_p had its maximum effect on roll rate sometime after the aileron input and, therefore, was particularly pronounced in the larger amplitude rapid roll reversals using large aileron inputs. The aileron yaw was, however, now sufficiently large in the proverse sense as to cause a noticeable tendency to overshoot (overcontrol) on bank angle. In small bank angle corrections with ailerons where the pilot operates more on the initial roll rate and sideslip response to aileron inputs, he commands relatively low roll rates and hence is more affected by $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ than by N'_p. Random disturbance inputs aggravated the bank angle control problems. The pilot did suggest that the severity of these problems was a function of his aggressiveness (pilot gain). With the given Dutch roll damping ($\zeta_d \omega_d$), heading control was again no problem.

4.3.3.3 Configuration 11 B, $N'_p = -0.035 \text{ sec}^{-1}$

Configuration 11 B had the following values of the lateral-directional modal parameters:

$$\omega_d \approx 2.46 \text{ rad/sec} \qquad \tau_R \approx 0.43 \text{ sec}$$
$$\zeta_d \approx .23 \qquad \tau_S \approx 100 \text{ sec}$$
$$|\phi/\beta|_d \approx 6.2$$

Pilot ratings and lateral-directional control sensitivity selections ($L'_{\delta_{AS}}$ and $N'_{\delta_{RP}}$) are presented on Figure 31. Aileron sensitivity ($L'_{\delta_{AS}}$) selection followed the patterns of Configurations 11 and 11A for adverse aileron yaw in that they were all of about the same value numerically and relatively invariant with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. For the proverse aileron yaw case with

Configuration 11B, the pilot chose a significantly higher $L'_{\delta_{AS}}$. For $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = 0, the pilot reported a compromise between sufficient sensitivity to overcome the high aileron forces for longer rolling maneuvers, and oversensitivity which would cause noticeable overcontrol and oscillatory tendencies on small bank angle corrections. The heavy aileron stick forces were due to the significant adverse sideslip produced proportional to roll rate which through the large dihedral effect (L'_{β}) reduced the net roll rate commanded by an aileron input. This occurred in the large amplitude maneuvers for which the pilot both utilizes large roll rates and waits sufficiently long for this effect to take place. It would appear that the pilot was forced into a similar compromise on $L'_{\delta_{AS}}$ selection for $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.05. However, pilot comments were lost for this case due to a voice recorder malfunction. With $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = + 0.08, the pilot selected a relatively high $L'_{\delta_{AS}}$ which he claimed to have done with no real compromises involved, however, he commented that perhaps the lightness of the aileron stick forces created some of the bank angle tracking problems that occurred with the evaluation of this particular test point.

Rudder sensitivity ($N'_{\delta_{RP}}$) selections (Figure 31) decrease almost linearly with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ from a relatively high value at $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.05 to a quite low value at $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = + 0.08. In the former case, the adverse aileron yaw combined with adverse yaw due to roll rate to produce a large adverse sideslip buildup for aileron inputs, but one that the pilot could coordinate. The pilot could, with rudder, significantly augment the roll rate from the ailerons. In order to do the above and keep pedal forces reasonable for large maneuvers, he selected a high $N'_{\delta_{RP}}$. With $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = 0.0, the pilot reported that for aileron inputs, the sideslip response seemed initially proverse then became a significant amount in the adverse sense. What he really had was essentially zero sideslip initially followed after some time by the large adverse amount. He reported some difficulty in coordinating this sideslip because when he used "normal" aileron-rudder technique he would overcontrol the initial sideslip, in fact, producing some in the proverse sense. This imprecision in coordination had large effects on the roll control. These problems, therefore, compromised selection of a higher $N'_{\delta_{RP}}$ which he would have preferred to counteract the longer term adverse sideslip due to N'_{p}. At $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = + 0.08, the proverse aileron yaw may help to reduce the effect of the adverse N'_{p} in the longer term but it produces a more nonlinear buildup of sideslip, being proverse initially and then coming back in the adverse direction. This caused the pilot considerable coordination difficulty. In fact, when he reverted to "normal coordination" he would aggravate the initial proverse sideslip. So he chose a low $N'_{\delta_{RP}}$ to minimize this problem.

Inspection of the pilot ratings for the various test points of Configuration 11B (Figure 31) shows that in the vicinity of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = 0.0, this configuration received the lowest ratings of the high $|\phi/\beta|_d$ series. In fact, they were rated unsatisfactory (PR = 4.5 or 5) at best, which was at $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = 0.0, and unacceptable (PR of 7) at $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = + 0.08. There was essentially no degradation in overall flying qualities with the given sizeable adverse N'_{p}

going from zero aileron yaw to adverse aileron yaw at $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.05$. However, there was a significant degradation going to proverse aileron yaw at $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.08$.

As already mentioned, the pilot comments for $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.05$ were lost, but, based on the pilot's numerical and turbulence ratings and on knowledge of the characteristics simulated, it is probable that the nature of the pilot's difficulties for this test point were similar to those at the aileron yaw value of zero. In the latter case, the pilot complained about a rudder requirement to coordinate sideslip which was difficult to satisfy because the situation warranted abnormal rudder technique. With adverse aileron yaw ($N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.05$), the adverse sideslip buildup probably lent itself better to normal coordination technique but this advantage was likely offset by the requirement to use sensitive rudders in order to cancel the large longer term sideslip in large rolling maneuvers. This would, in turn, lead to overcontrol on initial sideslip or about zero sideslip. For the $N'_{\delta_{AS}}/L'_{\delta_{AS}} = 0.0$ case, the pilot's complaints focused on problems with bank angle control caused either by what he did with the ailerons directly, or by the effects of imprecision in coordinating the sideslip, which through the large dihedral effect would alter the roll response. He complained of a tendency to overcontrol and overshoot on bank angle tracking which was aggravated in the presence of random disturbance inputs. This tendency was also a function of aggressiveness or pilot gain in the bank angle to aileron closed-loop task. The comments suggest that some of these overcontrol tendencies were due in part to overcontrol of sideslip when the pilot tried to coordinate. These bank angle control difficulties also appeared when the pilot attempted to abruptly acquire a given bank angle. "Abruptness" implies large roll rate changes in a short time which, with the considerable adverse N'_p, would excite the Dutch roll. In fact, the pilot said that the oscillatory tendencies appeared to be more due to Dutch roll rather than being pilot induced.

At $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.08$, the bank angle control problems resulting from the pilot's previously discussed difficulty with coordination were further increased by the proverse aileron yaw. This additional factor compounded the oscillatory bank angle problems, which were primarily from Dutch roll for the other test points of 11B, with definite PIO tendencies. This resulted in a situation making bank angle control and the associated tracking task very difficult for the pilot and also in turn degraded the heading control. The proverse aileron yaw directly affected the pilot's difficulties in the closed-loop bank angle tracking loop with ailerons. He could not really utilize his rudders to help, because the required input time history was too complicated for the pilot to be able to do consistently. If he inadvertently reverted to normal rudder technique, the pilot aggravated his bank angle control problems. Hence, the initial proverse sideslip generated each time he put in aileron inputs so modified the roll rate response as to lead to PIO's on small bank angle corrections or when attempting to acquire and hold a bank angle. The severity of the PIO's were, as expected, a function of aggressiveness (closed-loop pilot gain), an aspect unacceptable for the air-to-air fighter tasks. The only good feature that the pilot reported for this test point with PR of 7 was that the airplane was "really maneuverable in roll." With the proverse aileron yaw to offset some of the adverse yaw due to roll rate, on the larger roll maneuvers, uncoordinated ailerons would give better roll performance. Perhaps, for gross maneuvering, the additional initial roll accelerations from proverse aileron yaw might even be an asset. Although the pilot commented that more effort was required in the presence of random disturbance inputs, he did not consider this to increase the difficulty of the task.

4.3.3.4 Comparison of Medium Dutch Roll Frequency, High $|\phi/\beta|_d$ Configurations With Roll-Sideslip Coupling Requirements of MIL-F-8785B(ASG).

These configurations met the Dutch roll frequency and basic Dutch roll damping ratio ($\zeta_d > 0.19$) requirements of MIL-F-8785B(ASG) for Class IV airplanes in Flight Phase Category A. However, since $\omega_d^2 |\phi/\beta|_d = 37$, there is an additional Level 1 requirement for $\zeta_d \omega_d$ to be $0.47 + .014(\omega_d^2|\phi/\beta|_d - 20)$ or 0.71 rad/sec resulting in a required $\zeta_d = 0.28$. The ζ_d's for the three configurations were indeed very close to this Level 1 boundary damping ratio. For the test points that received Level 1 pilot ratings (PR$\leq$ 3.5) as well as for others in the medium ω_d, high $|\phi/\beta|_d$ series, the pilot reported the Dutch roll to be reasonably well damped. Furthermore, there appeared to be no direct indication of unsatisfactory Dutch roll damping from the pilot's comments on the effects of random disturbance inputs. However, there is a suggestion from such comments as "it really moved around in roll in the turbulence," that additional damping might certainly have been beneficial. This implies support for the existing requirement for additional damping ($\Delta\zeta_d \omega_d$) over the basic Dutch roll ζ_d requirements for airplanes with high $|\phi/\beta|_d$. $\omega_d \zeta_d$ relates to the time for a Dutch roll excitation to damp. The larger that $\omega_d \zeta_d$ is, the shorter the time period over which the Dutch roll modulates roll response to an aileron input, especially for airplanes with large roll-sideslip coupling, and directly affects such tasks as heading control.

Figure 32 compares the test points for the medium ω_d, high $|\phi/\beta|_d$ configurations to the p_{osc}/p_{AV} versus ψ_β requirement of MIL-F-8785B(ASG). With the high $|\phi/\beta|_d$, these configurations possess a substantial value of p_{osc}/p_{AV} in relation to the other medium frequency configurations. As seen from the plot, the Level 1 boundary encloses the bulk of the test points including many rated worse than 3.5. There is one Level 1 point (PR = 3.5) outside the Level 1 boundary. If a given test point was not downrated for reasons other than, or in addition to, p_{osc}/p_{AV}, the Level 1 boundary appears to be too liberal. Hence, one has to look at all characteristics of a test point before judging suitability of a given requirement.

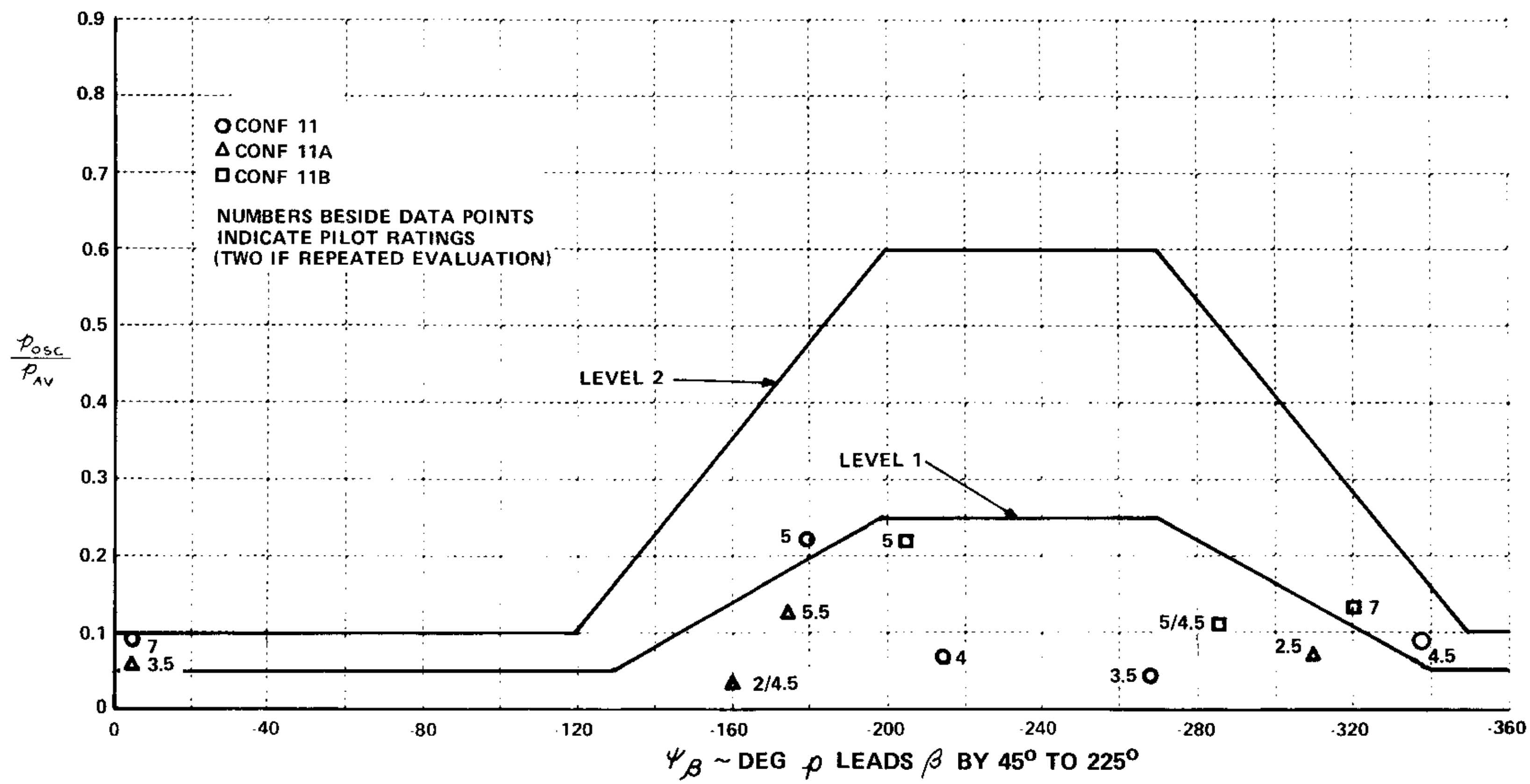


Figure 32 Medium Dutch Roll Frequency, High $|\phi/\beta|_d$ Configurations Compared to ρ_{osc}/ρ_{AV} Requirements of MIL-F-8785B(ASG)

The sideslip parameter ($\Delta\beta_{MAX}/k$) for Level 1 and Level 2 was computed and plotted against the corresponding requirements of MIL-F-8785B(ASG) on Figures 33 and 34 respectively. Starting with the Level 2 plot, the boundary is seen to contain all test points including two Level 3 points (PR = 7). One of these Level 3 points, that for Configuration 11, was downrated because of strong PIO tendencies which were significantly aggravated in the presence of random disturbance inputs (TR of E). The other point (for Configuration 11B) was also downrated due to substantial PIO tendencies although here random disturbances did not affect matters much (TR of B). Looking at the Level 1 $\Delta\beta_{MAX}/k$ plot, the boundary is seen to contain all Level 1 points but one (a 3.5 rating for Configuration 11A). The Level 3 point for Configuration 11B lies well above the boundary while the Level 3 Configuration 11 point also lies above but by a much smaller margin, perhaps due to the turbulence effects on that test point. It is generally true that Level 2 points within the Level 1 $\varphi_{osc}/\varphi_{AV}$ boundary were accounted for by not meeting Level 1 $\Delta\beta_{MAX}/k$ requirements and were downrated due to the heavy coordination requirements. The two Level 3 points (PR of 7) are within the Level 2 $\varphi_{osc}/\varphi_{AV}$ boundary as also they are within the Level 2 $\Delta\beta_{MAX}/k$ boundary. Perhaps one explanation is the fact that being Level 2 on two counts caused them to be rated Level 3. One data point, Configuration 11A with PR = 3.5 was Level 2 in both the $\varphi_{osc}/\varphi_{AV}$ and the $\Delta\beta_{MAX}/k$ requirements planes. This point had a small amount of proverse aileron yaw with substantial proverse yaw due to roll rate. The pilot complained of tendencies to overcontrol and overshoot in bank angle. Evidently the phasing of the proverse sideslip effects on the short term roll response to ailerons has a strong influence on their severity in terms of closed-loop control. The $\varphi_{osc}/\varphi_{AV}$ vs. ψ_β and the $\Delta\beta_{MAX}/k$ vs. ψ_β plots evidently did not stratify this phasing difference.

4.3.4 Results for the Medium Dutch Roll Frequency Configuration With Negative Effective Dihedral (5ND)

Configuration 5ND had the following values of lateral-directional modal parameters:

$$\omega_d \approx 2.40 \text{ rad/sec} \qquad \tau_R \approx .48 \text{ sec}$$
$$\zeta_d \approx .25 \qquad \tau_s \approx 100 \text{ sec}$$
$$|\phi/\beta|_d \approx 2.14$$

This configuration possessed negative effective dihedral as shown by the value of $\measuredangle \phi/\beta$ = - 132° in addition to the signs of L_β (now positive) and L_r (now negative) (see Appendix IV). The $\phi(s)/\delta_{AS}(s)$ transfer function zero locations with respect to the Dutch roll pole are shown on Figure 35. The experimental results are shown on Figure 36 along with the results for Configuration 5 for comparison. Configuration 5ND differs from Configuration 5 essentially in the sense of dihedral effect only. The small difference in $|\phi/\beta|_d$ is not very significant for this comparison. A more detailed definition of this configuration is presented in Appendix IV along with the pilot comments and transient responses.

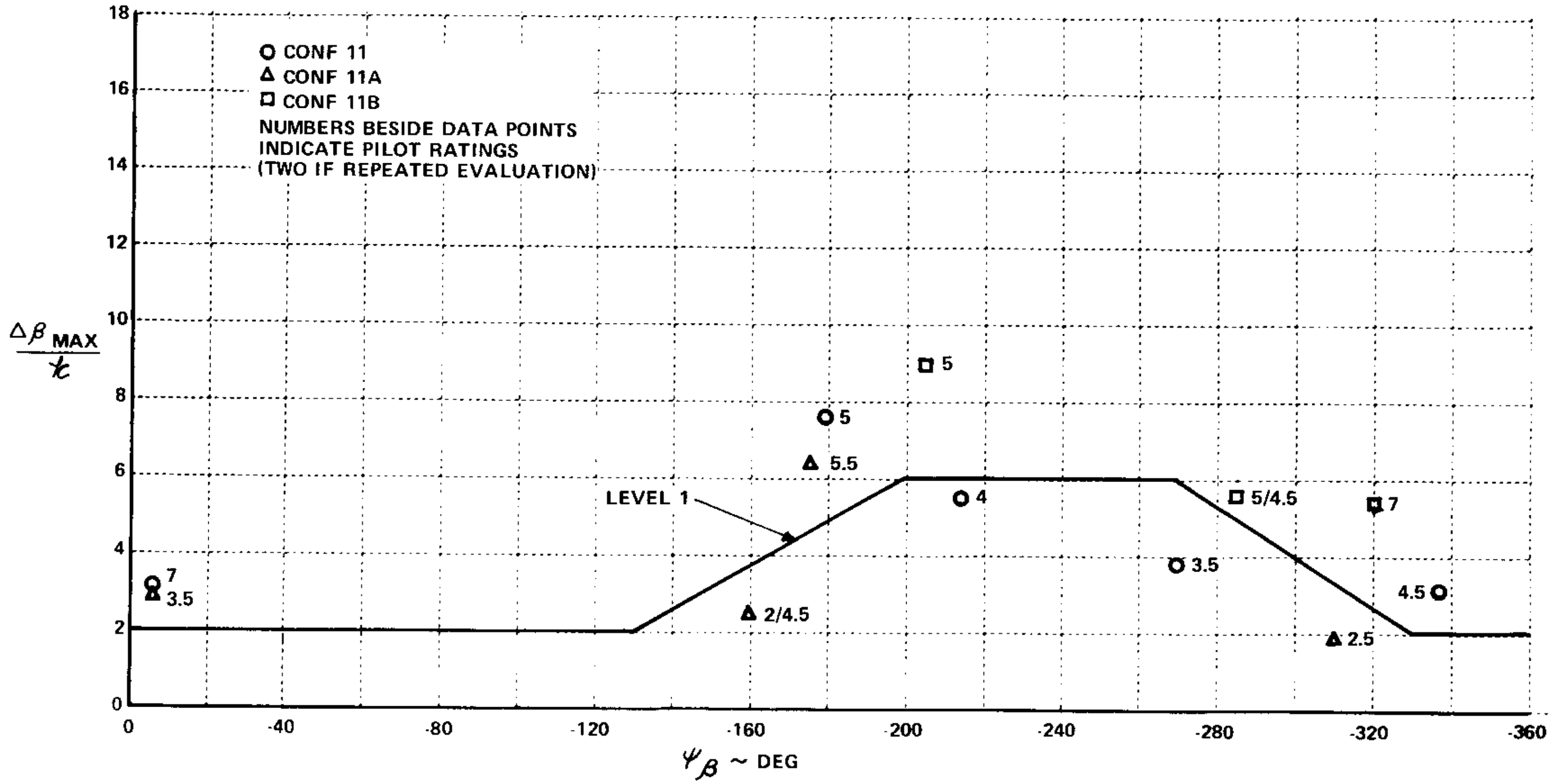


Figure 33 Medium Dutch Roll Frequency, High $|\phi/\beta|_d$ Configurations Compared to Level 1 $\Delta\beta_{MAX}/k$ Requirements of MIL-F-8785B(ASG)

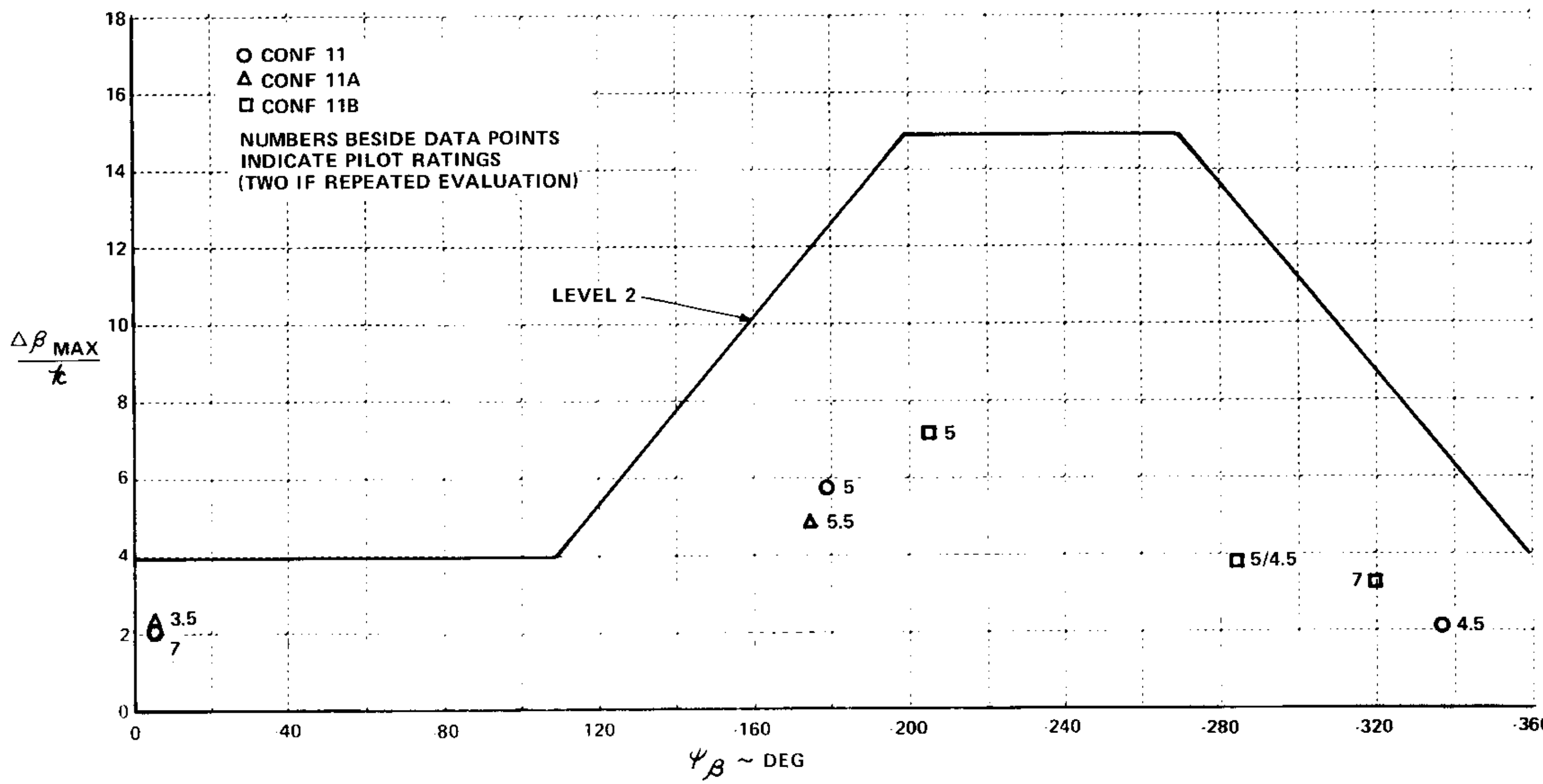


Figure 34 Medium Dutch Roll Frequency, High $|\phi/\beta|_d$ Configurations That Do Not Meet Level 1 $\Delta\beta_{MAX}/k$ Requirements Compared to Level 2 $\Delta\beta_{MAX}/k$ Requirements of MIL-F-8785B(ASG)

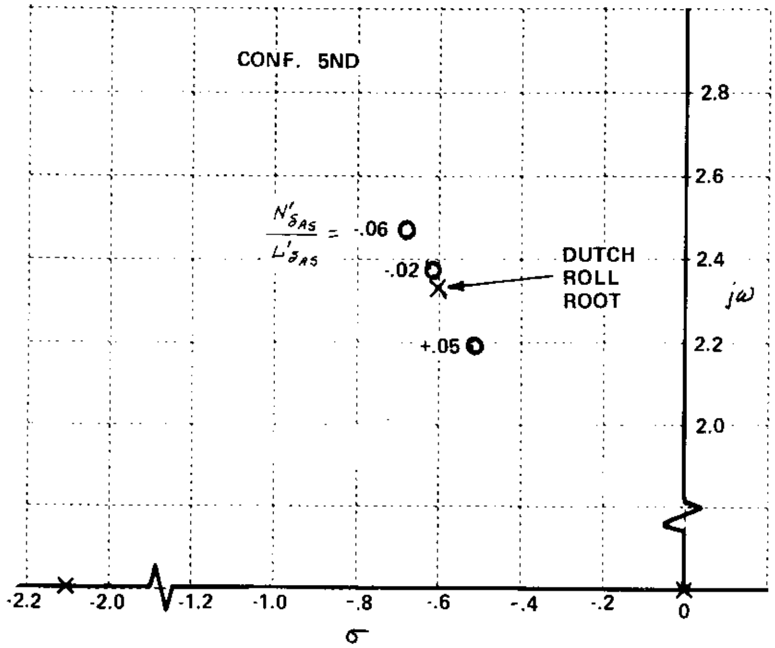


Figure 35 $\phi(s)/\delta_{AS}(s)$ Pole-Zero Locations for the Medium ω_d, Medium $|\phi/\beta|_d$, Negative Effective Dihedral Configurations

Unfortunately, the overall scope of this experiment permitted testing of this configuration at only three values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$= + 0.05, - 0.02, and -0.06 in combination with a constant value of N'_p (+ 0.055) which put the locus of zeros of $\phi(s)/\delta_{AS}(s)$ with varying $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ through the Dutch roll pole (Figure 35). It is immediately noted that the shift in the sense of dihedral effect has changed the phase of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ effects on the zeros of $\phi(s)/\delta_{AS}(s)$ by 180° i.e., adverse aileron yaw puts the zeros above the Dutch roll root and vice versa.

From Figure 36 it can be seen that pilot opinion sensitivity to the aileron yaw parameter does not differ significantly between Configuration 5 and Configuration 5ND. In fact in both cases pilot opinion sensitivity is relatively small in a small region about $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = 0 and increases very quickly as aileron yaw increases beyond this range on both sides of zero. However, for $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.06, Configuration 5 was barely unsatisfactory (PR = 4) while Configuration 5ND was almost unacceptable (PR = 6). Pilot selection of aileron sensitivity, $L'_{\delta_{AS}}$, and of rudder sensitivity, $N'_{\delta_{RP}}$, follows similar trends of changes with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ although the changes in $N'_{\delta_{RP}}$ are slightly more pronounced for Configuration 5ND. At the relatively low $|\phi/\beta|_d$, although the coupling between β and ϕ was reversed, the effect itself was small enough at the tested $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ values so as not to strongly influence the control sensitivity.

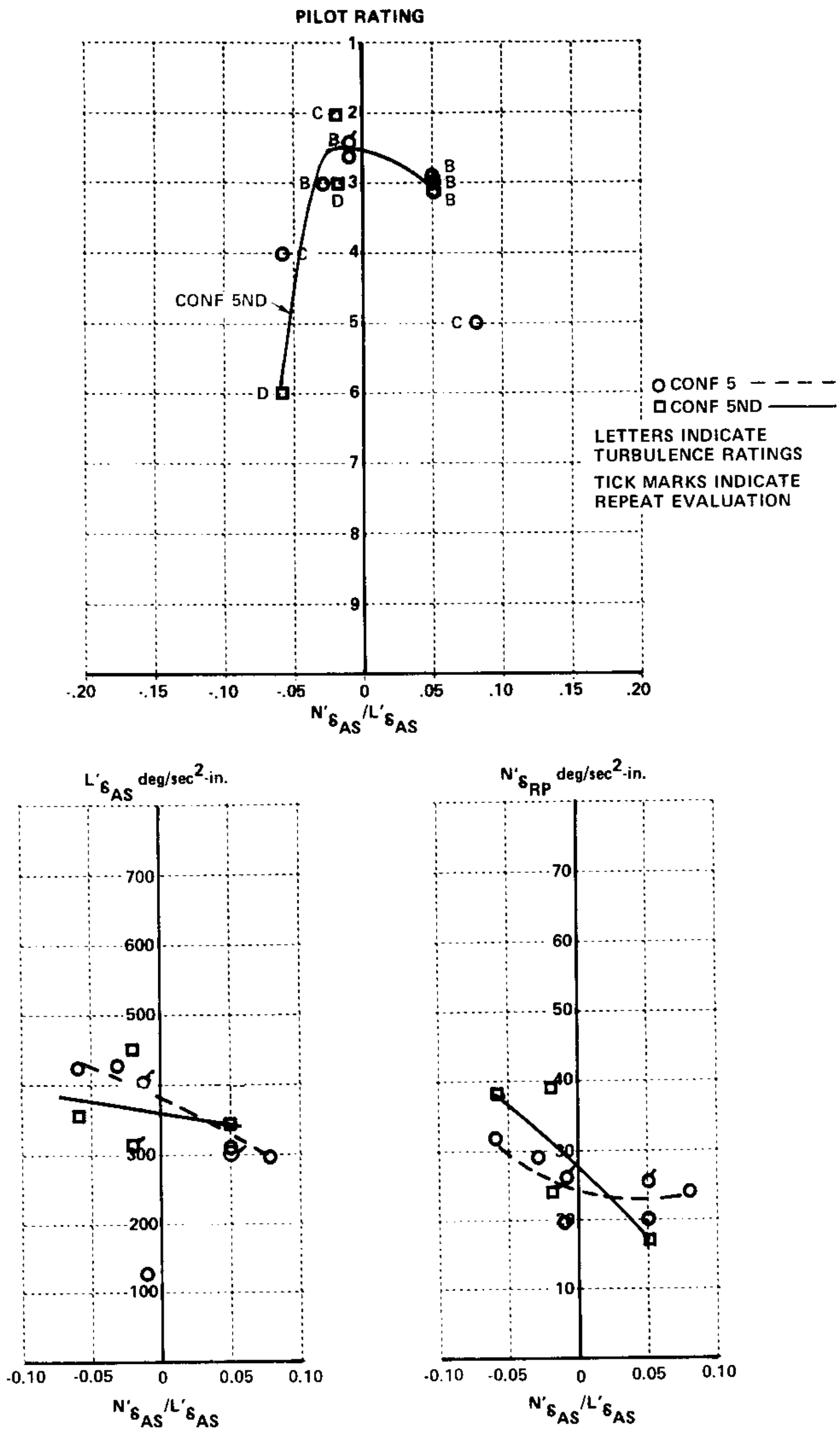


Figure 36 Pilot Ratings and Pilot Selected Control Sensitivities for Medium ω_d, Medium $|\phi/\beta|_d$ Negative Effective Dihedral Configuration and Positive Effective Dihedral Configuration

The faired curve through the pilot selected values of aileron sensitivity $L'_{\delta_{AS}}$ on Figure 36, indicates relative indifference of aileron sensitivity with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ variation for this negative dihedral configuration. In fact, the variation is significantly less than for Configuration 5, the positive dihedral counterpart. For the larger adverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$, the pilot reported a definite compromise between light forces to generate large roll rates for larger maneuvers, where he tended to coordinate with rudder, and the tendency to overcontrol in roll on small corrections, where he didn't coordinate. The $L'_{\delta_{AS}}$ he finally chose still gave him aileron forces that were "a little heavy for large maneuvers and a little light for small bank angle corrections." For the smaller adverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$, the pilot comments suggested a problem similar to that above but to a far lesser degree. However, on a repeat evaluation of the same test point, he reported no compromise. For the proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ condition, the pilot reported picking aileron forces as light as he wanted.

The rudder sensitivity selection $N'_{\delta_{RP}}$ (Figure 36) was, however, a different story. It varied from a relatively high value on the adverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ side to a relatively low value on the proverse side. For sizeable adverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ in combination with small proverse N'_p, coordination was in the normal direction. The pilot reported a definite requirement to coordinate, particularly on large maneuvers, otherwise a large sideslip angle would develop. Of course, when he cut down adverse sideslip by coordinating he also cut down on his roll rate, due to the negative dihedral effect. He picked $N'_{\delta_{RP}}$ for light forces when he did coordinate on larger maneuvers. For $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.02$, on one evaluation he picked "a little heavier rudder" to keep sideslip where he wanted with an airplane that "didn't need an awful lot of coordination," and for which he "was reasonably good at coordinating." On the repeat evaluation, there was another aircraft which was used as the evaluation task reference. It would appear that the pilot's attention was less occupied by perfection in coordination and that, having picked a higher $L'_{\delta_{AS}}$, he didn't worry about overcontrol in coordination, which would cut down roll rate. For the proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ case, there was very little sideslip excited in aileron maneuvers, therefore requiring little coordination. So coordination was not a necessity. Hence, the pilot picked heavier rudder forces or low $N'_{\delta_{RP}}$ and, therefore he wouldn't overcontrol if he did coordinate. He couldn't use rudders in the normal manner to augment roll rate.

Configuration 5ND received its best pilot ratings for values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ which resulted in the lowest amount of sideslip excited by an aileron input keeping in mind the constant small proverse N'_p. Deterioration of pilot opinion was swift with increasing $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. As evidenced by the pilot comments, a prominent reason for this was the negative dihedral effect with its attendant unnatural phasing between roll and yaw in the Dutch roll. Also, the reversed effect of sideslip on roll rate resulted in the pilot's inability to augment roll control with rudder. There was a significant effect of sideslip on roll rate even with the low to moderate value of L'_β $(|\phi/\beta|_d \approx 2.14)$.

For the larger adverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$, the above mentioned problems associated with reversed effects are clearly evident from the pilot's comments. First of all, the relatively low initial sideslip (though adverse) followed by a substantial amount, necessitated a complicated rudder input time history which was very difficult to accomplish. But, the pilot needed to coordinate particularly on larger maneuvers simply to confine sideslip build-up. However, coordinating tended to cut down on roll rate (negative dihedral effect with reduced adverse sideslip). For small corrections in bank angle, whether to try to maintain a particular bank angle or during the bank angle tracking task, the pilot normally would not coordinate. However, lack of coordination meant some adverse sideslip which, in turn, augmented roll rate resulting in overcontrol or mild PIO tendencies for the small corrections, much like proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ would cause with positive dihedral effect. When he would allow sufficient sideslip buildup to excite a noticeable Dutch roll, the strange out-of-phase feeling of heading versus bank angle motion was a degrading factor. This same problem impaired his ability to control heading. It furthermore degraded his ability to alleviate the effects of random disturbance inputs resulting in a turbulence rating of D. All this would reflect strongly on the air-to-ground task in turbulence where the pilot normally would use rudder to help put the nose on a target. Finally, the pilot remarked that when using normal coordination, the effects of aileron and rudder control inputs on roll rate were working against each other.

For the small amount of adverse aileron yaw ($N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.02$), there were two evaluations, one rated a 3 and the other a 2, but for the PR= 2 the task included a reference aircraft. Interestingly, the pilot comments for the two evaluations differ but are in harmony with the ratings. For the evaluation with the other aircraft, he had generally favorable superlatives for such tasks as bank angle and heading control. The only significant complaint was the turbulence response (TR of C) which showed up more noticeably in roll than sideslip ($|\phi/\beta|_d \approx 2.14$). Coordination requirements were small and the pilot reported that coordination was easy and natural to perform. On the other evaluation, he was somewhat more critical of the same test point. He still commented favorably about bank angle and heading control. However, he seemed more aware of sideslip per se (watching sideslip needle instead of another airplane), and that appears to be the primary reason for the rating difference. Also, he reported that the primary effect of turbulence was on sideslip (as opposed to primary effect on roll in other evaluation) resulting in the TR of D.

For the proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ case, the pilot reported very little sideslip with aileron inputs resulting in very little coordination required. In the ground attack task, he didn't use rudder to move the nose onto a target, thereby bypassing the unnatural effects of negative dihedral. From the pilot comments, it was noted that the rating of 3 was due principally to the inability to augment roll with rudder despite the $|\phi/\beta|_d$ of 2.15 and to the fact that over-coordination tended to cut down roll rate.

4.3.4.1 Comparison of the Medium Dutch Roll Frequency, Negative Effective Dihedral Configuration (5ND) With MIL-F-8785B(ASG) Roll-Sideslip Coupling Requirements

Configuration 5ND was intended to supplement a scanty amount of existing data on aircraft with negative effective dihedral. It was chosen with essentially the same characteristics as Configuration 5 discussed in Section 4.2.2.1 except for 5ND having a slightly higher $|\phi/\beta|_d$ (2.14 vs. 1.61) and, of course, the required numerical sense of L'_β and L'_r to give the negative dihedral effect.

This configuration did not meet the requirements of MIL-F-8785B(ASG) paragraphs 3.3.6.2 and 3.3.6.3. These paragraphs respectively require:

(1) that right bank angle shall accompany an increase in right sideslip and vice versa,

(2) right aileron-control deflection and force shall accompany right sideslips and vice versa.

However, the configuration did meet Level 1 requirements of MIL-F-8785B (ASG) for Dutch roll frequency and damping (both damping ratio ζ_d and total damping $\zeta_d\omega_d$) for Class IV airplanes in Flight Phase Category A. However, the evaluation comments for the test points in which the Dutch roll was significantly excited during task performance indicate that additional damping in Dutch roll would have been beneficial. The pilot reported that "the airplane had a funny out-of-phase feeling between sideslip and roll in the Dutch roll" which made heading a bit difficult to control and added to problems with turbulence. Hence the $\measuredangle\phi/\beta$ in the Dutch roll is bothersome to the pilot as contrasted with an equivalent situation with Configuration 5. Clearly one way to limit the Dutch roll motion is to require increased damping (in this case in the form of ζ_d) for aircraft with negative dihedral. The amount of this increase would require further study.

The only accommodation present in MIL-F-8785B(ASG) specifically for negative effective dihedral is in p_{osc}/p_{AV} vs. ψ_β requirement. This is to account for the change in ψ_β for which closed-loop bank angle control difficulties would occur and results in a 180° shift in the ψ_β scale of the p_{osc}/p_{AV} versus ψ_β requirement. The three data points for Configuration 5ND are compared to the p_{osc}/p_{AV} versus ψ_β requirement on Figure 37. The medium $|\phi/\beta|_d$ of 2.14 and the relatively small values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ for which this configuration was tested resulted in a relatively small spread of zeros of $\phi(s)/\delta_{AS}(s)$ transfer function (Figure 35) about the Dutch roll pole and consequently small magnitudes of p_{osc}/p_{AV} . In fact, the Level 1 boundary included all these points and this suggests that p_{osc}/p_{AV} as a parameter was not the problem indicator with this configuration. The pilot comments confirm this.

The sideslip excursion parameters ($\Delta\beta_{MAX}/k$) for Levels 1 and 2 are plotted against the MIL-F-8785B(ASG) requirements on Figures 28 and 29,

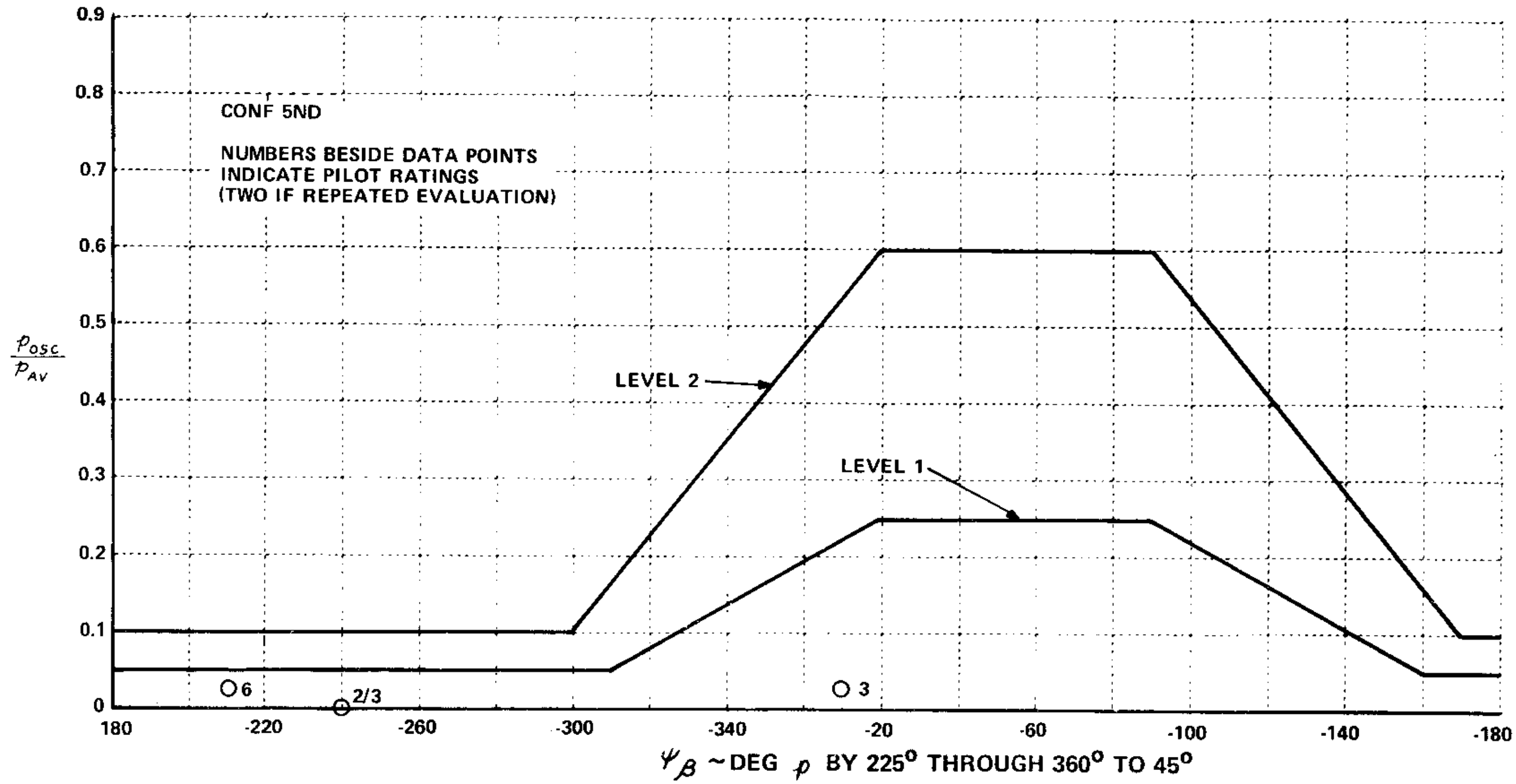
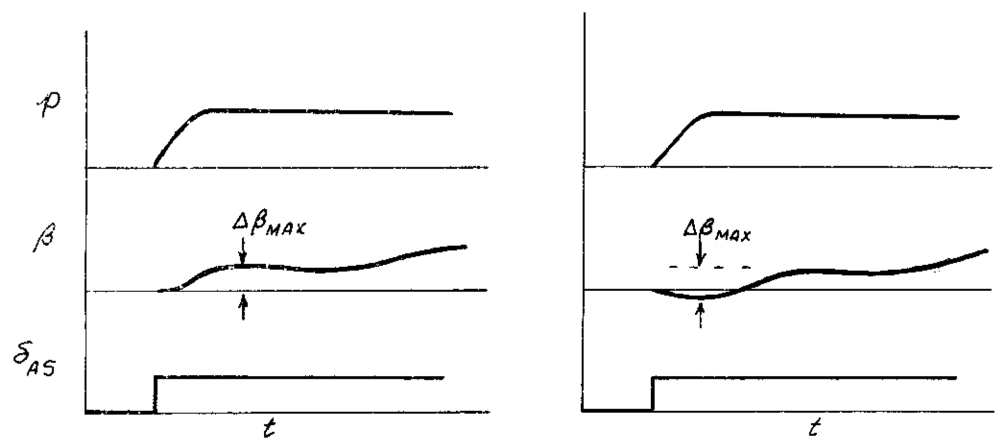


Figure 37 Medium Dutch Roll Frequency, Medium $|\phi/\beta|_d$, Negative Effective Dihedral Configuration Compared to p_{osc}/p_{AV} Requirements of MIL-F-8785B(ASG)

repeated in this section on pages 89 and 90 for the convenience of the reader. These parameters do provide some stratification with pilot ratings but not as much as might have been expected. As seen from the Level 1 plot (Figure 28), the boundary includes a Level 2 rating while it excludes by a wide margin a Level 1 point. There is not much difference between the $\Delta\beta_{MAX}/t$ values for the three test points, at least as $\Delta\beta_{MAX}$ is defined by MIL-F-8785B(ASG). The distinction is that for the Level 2 point ($N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.06), $\Delta\beta_{MAX}$ (or maximum change in β in a specific time period) is the actual magnitude of the unidirectional sideslip buildup from trim (adverse sense) as shown in sketch 1 below.

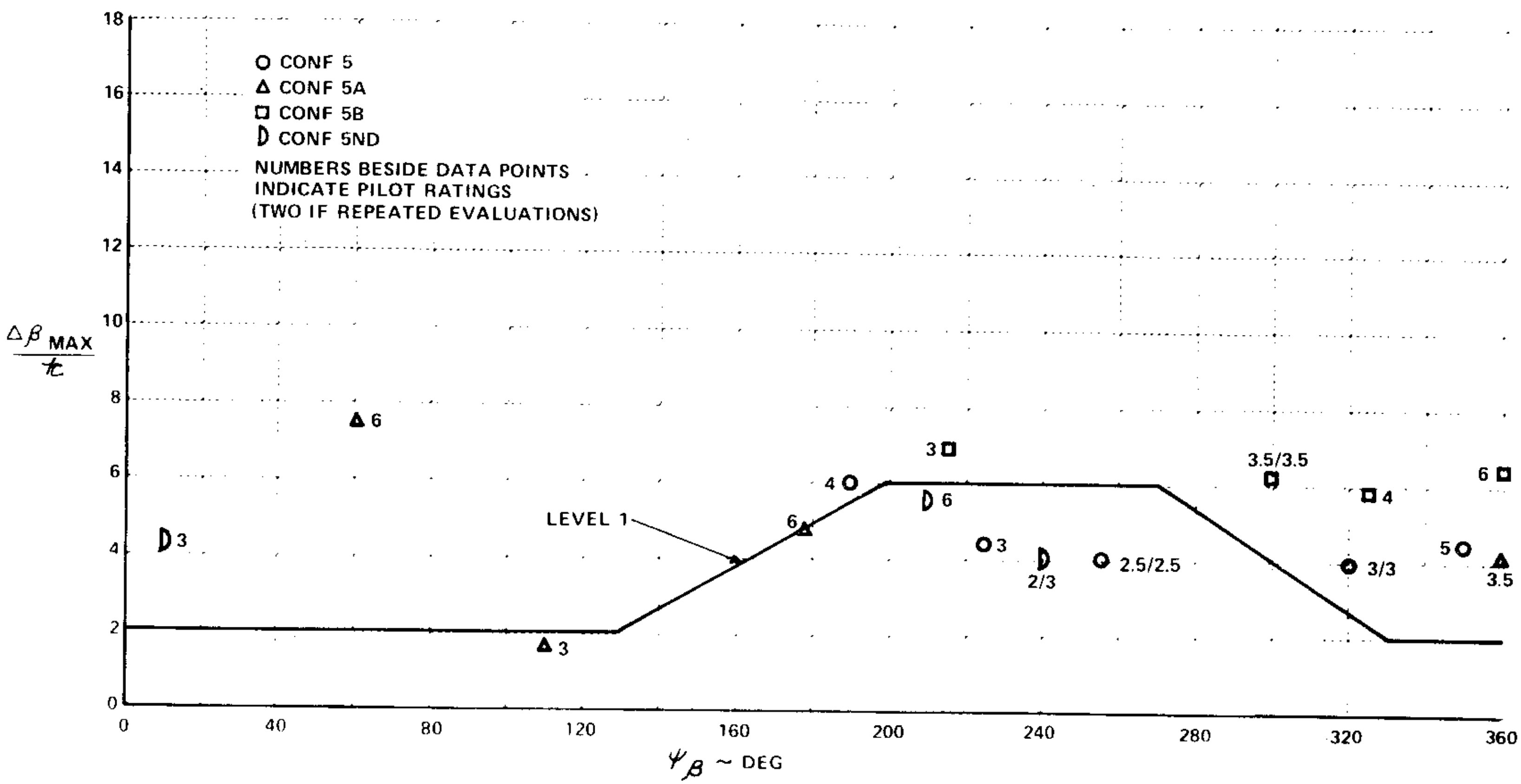


Sketch 1
Adverse Sideslip

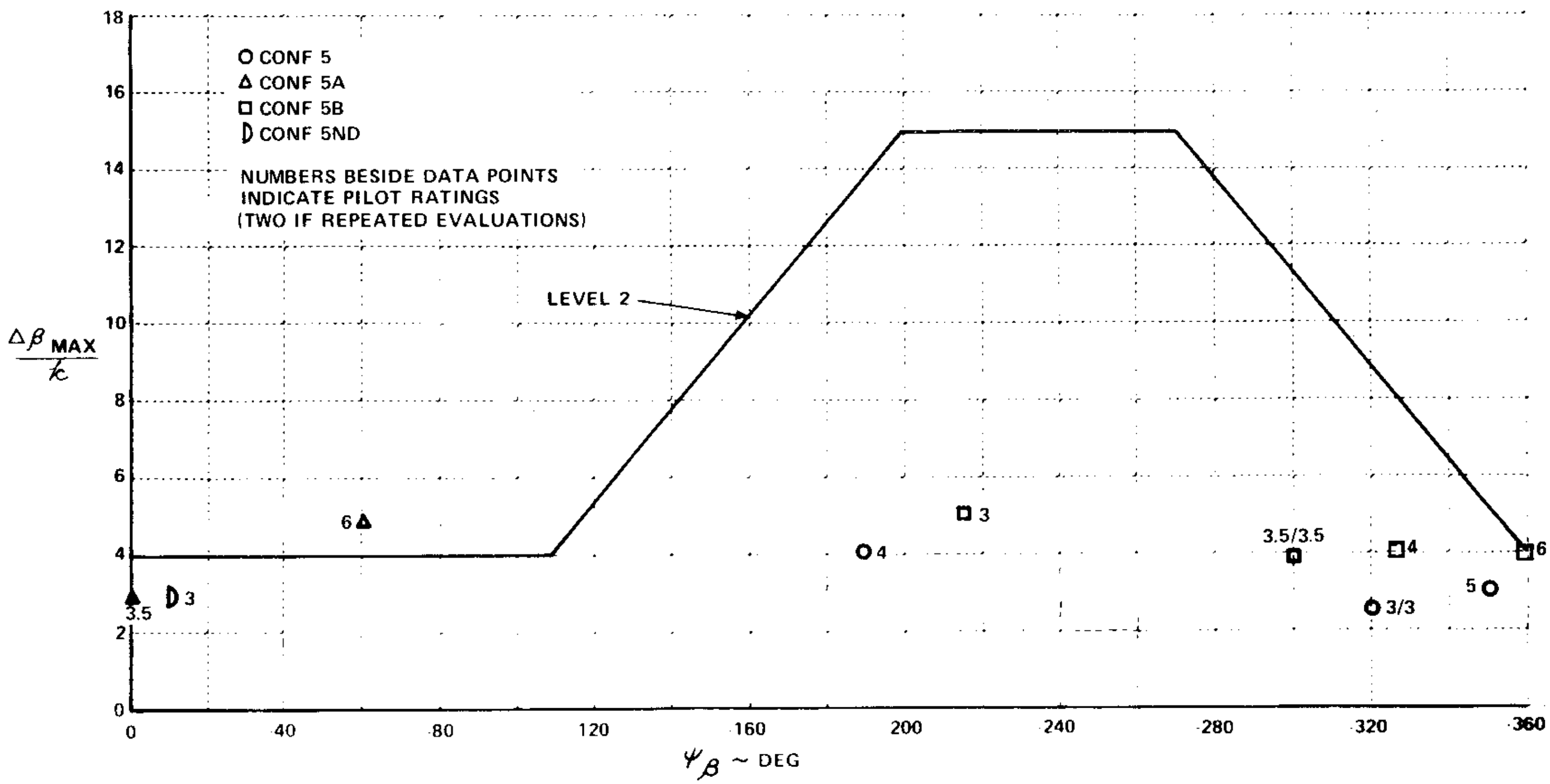
Sketch 2
Proverse to Adverse Sideslip

For the $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = + 0.05 points, $\Delta\beta_{MAX}$ was the maximum β change from proverse to adverse as shown in sketch 2. In the latter case, the actual excursion from trim was therefore of much smaller magnitude. Since, from the comments, one of the primary problems with this configuration stemmed from the reversed effects of sideslip on roll, the difference in ratings despite the values of $\Delta\beta_{MAX}/t$ becomes more understandable. This suggests that for airplanes with negative effective dihedral, the requirement ought to be based on a $\Delta\beta/t$ parameter where t is defined as presently but $\Delta\beta$ is maximum excursion of β from trim in some specified period of time, instead of the maximum change in that period.

The pilot comments for the Level 2 point ($N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.06) indicate that his ability to control heading and to use his controls to damp out Dutch roll oscillation, however they may be excited, is strongly impeded by the unnatural motions of the Dutch roll. The almost equivalent magnitude of proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ (+.0.05) evidently was no problem to the pilot (rating of 3) because in combination with adverse sideslip contributed by the spiral mode it produced a sideslip time history of the shape shown in sketch 2 where



REPEAT
Figure 28 Medium Dutch Roll Frequency, Medium $|\phi/\beta|_d$ Configurations Compared to Level 1 $\Delta\beta_{MAX}/t$ Requirements of MIL-F-8785B(ASG)



REPEAT
Figure 29 Medium Dutch Roll Frequency, Medium $|\phi/\beta|_d$ Evaluation Points That Do Not Meet Level 1 $\Delta\beta_{MAX}/k$ Requirements Compared to Level 2 $\Delta\beta_{MAX}/k$ Requirements of MIL-F-8785B(ASG)

the sideslip never became appreciable in the time period that the pilot waits after an aileron input. As a result, the pilot reported that very little coordination was required. Furthermore, the Dutch roll when excited was of low amplitude (since it is a function of the sideslip disturbance). Although $\psi/_\beta$ put the test point in an area of difficult coordination, it didn't bother the pilot. The point is somewhat inconclusive in terms of suggestions to better define the Level 1 boundary.

The Level 2 plot of Figure 29 includes all Configuration 5ND points as expected. The PR of 6 point is, as explained earlier, likely downrated for reasons other than $\Delta\beta_{MAX}/k$ causing the point to be so far below the Level 2 boundary.

4.4 CONFIGURATIONS WITH HIGH DUTCH ROLL FREQUENCY

Four configurations were evaluated at a Dutch roll frequency of approximately 4.5 radians per second. Configurations 6 and 7 both had the medium value of roll-to-sideslip ratio ($|\phi/\beta|_d \approx$ 1.6) of this experiment, but differed by their values of the Dutch roll damping ratio, ζ_d (0.10 and 0.23 respectively). Configurations 12 and 13 both had the high value of roll to sideslip ratio ($|\phi/\beta|_d \approx 5.0$) but differed by their values of $\zeta_d = 0.095$ and $\zeta_d = 0.24$ respectively. The results for each configuration are discussed separately. Finally, the results for all the high Dutch roll frequency configurations are compared to certain MIL-F-8785B(ASG) lateral-directional requirements.

4.4.1 Results for High Dutch Roll Frequency, Medium $|\phi/\beta|_d$ Configurations

The $\phi(s)/\delta_{AS}(s)$ transfer function zero locations with respect to the Dutch roll poles for Configurations 6 and 7 are shown on Figure 38. The experimental results are shown on Figure 39. A detailed definition of these configurations is given in Appendix IV where the pilot comment data and transient responses are also presented.

4.4.1.1 Configuration 6 - Lower Dutch Roll Damping Ratio

The lateral-directional modal characteristics for Configuration 6 were as follows:

$$\omega_d \approx 4.5 \text{ rad/sec} \qquad \tau_R \approx 0.42 \text{ sec}$$
$$\zeta_d \approx 0.10 \qquad \tau_s \approx 35 \text{ sec}$$
$$|\phi/\beta|_d \approx 1.68$$

The pilot ratings for this configuration show that the best rating occurred with $N'_{\delta_{AS}}/L'_{\delta_{AS}} = 0$. This value of the aileron yaw parameter was, however, evaluated twice receiving pilot ratings of 4.5 and 2.5. Accompanying the two ratings are apparent differences in the pilot's assessment of the airplane's response to random disturbance inputs and differences in the pilot selection of both aileron and rudder control sensitivities, $L'_{\delta_{AS}}$ and $N'_{\delta_{RP}}$ respectively. With the rating of 2.5, the pilot assigned a turbulence effect rating of D and with the rating of 4.5, the pilot assigned a turbulence effect rating of E. This difference in turbulence effect rating, as can be seen on Figure 12, indicates a substantial difference in pilot effort from "more effort required" to "best efforts required" which was reflected in the overall pilot rating.

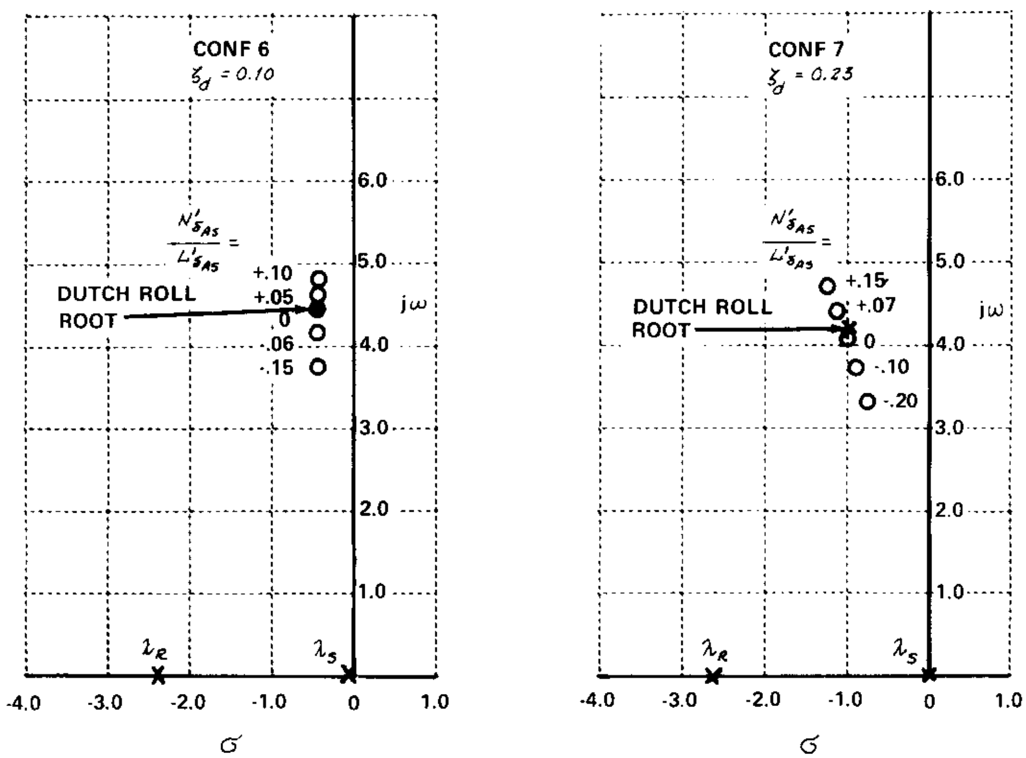


Figure 38 $\phi(s)/\delta_{AS}(s)$ Pole-Zero Locations for High ω_d, Medium $|\phi/\beta|_d$ Configurations

The pilot selected value of aileron control sensitivity was 380 deg per sec^2-in. for the 2.5 pilot rating, and the pilot reported that perhaps he had selected too sensitive a value since in a constant banked turn the airplane would oscillate a little in roll. However, he reported his bank angle tracking task performance as good; and reported the roll control as a good feature of the airplane. For the 4.5 pilot rating the pilot-selected value of aileron control sensitivity was 430 deg/(sec^2-in.) and the pilot reported his bank angle tracking task performance as only fair. He also listed poor bank angle controllability as an objectionable feature. Hence, the higher value of aileron control sensitivity for the PR = 4.5 case probably aggravated the pilot's bank angle control problems and therefore contributed to the poor pilot rating. With both of the above cases, heading control was reported as good. The dif-

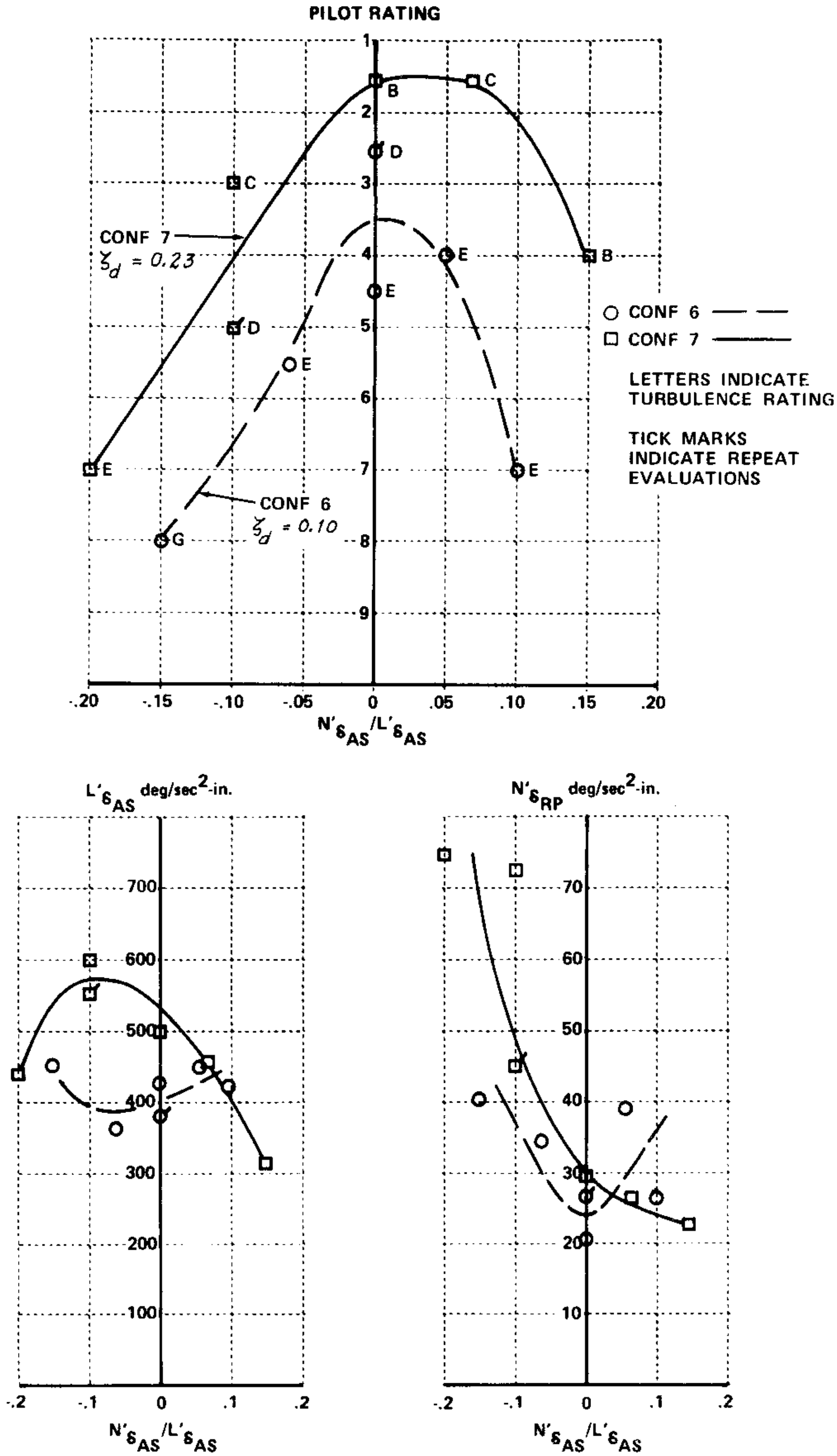


Figure 39 Pilot Ratings and Pilot Selected Control Sensitivities for High ω_d , Medium $|\phi/\beta|_d$ Configurations

ference in the selected values of rudder control sensitivity probably did not contribute to the difference in pilot ratings. In both the above cases, the pilot reported that coordination really wasn't a factor. Therefore, his selected values of rudder sensitivity had little meaning since he didn't use the rudder.

With adverse aileron yaw ($N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.06) the pilot objected to the lightly damped Dutch roll oscillation, primarily in sideslip, that was excited any time the airplane was maneuvered abruptly. His heading control suffered as a result. It would take some time for the airplane to settle on a heading. He found he could not coordinate well enough to prevent exciting the Dutch roll. The major objection, however, was the airplane's response to disturbance inputs. Random disturbance inputs produced large and persistent excursions in the directional response which deteriorated an otherwise reasonable performance. Pilot comments for the most adverse aileron yaw case were lost because of a recorder malfunction.

The evaluations with proverse aileron yaw presented the pilot with a difficult coordination problem and in the most proverse case he reported very poor bank angle control, and poor heading control. The coordination difficulty resulted from the high frequency Dutch roll and the requirement to cross-control with the rudder. The pilot stated that he "didn't stand a chance of coordinating" so he didn't use the rudder. Because of the high frequency Dutch roll he couldn't keep up with the oscillations and found that rudder used in coordination attempts only served to further excite the Dutch roll and severely reduce his precision of heading control. Again, the airplane's response to random disturbance inputs was objectionable to the pilot, being classified as severe and causing a continuous directional oscillation in the most proverse aileron yaw case.

The consistent objection to this configuration at all points tested was the airplane's response to random disturbance inputs causing the airplane to react primarily directionally with a lightly damped oscillation of the nose. The larger the aileron yaw became in either direction, the more objectionable the random disturbance responses became as was reflected by the pilot comments. Although the turbulence response of the open-loop airplane is independent of aileron yaw, the pilot rated the closed-loop pilot-airplane combination which is affected by aileron yaw.

For all values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ tested, the pilot selected quite large values of aileron control sensitivity, $L'_{\delta_{AS}}$, basing his choice on the ability to have light forces and good roll capability without a tendency to overcontrol in bank angle. The selected values of $L'_{\delta_{AS}}$ were relatively insensitive to variations in $N'_{\delta_{AS}}/L'_{\delta_{AS}}$, however, the pilot's selection of large values of $L'_{\delta_{AS}}$ may have contributed to his bank angle control problems. The selection of rudder control sensitivity, $N'_{\delta_{RP}}$, has little meaning except for the adverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ cases where the pilot selected rudder forces compatible with the coordination requirements. For the zero and proverse aileron yaw cases, the pilot stated that he didn't use the rudder and, therefore, he attached little meaning to his selection.

4.4.1.2 Configuration 7 - Higher Dutch Roll Damping Ratio

The lateral-directional modal characteristics for Configuration 7 were as follows:

$$\omega_d \approx 4.30 \text{ rad/sec} \qquad \tau_R \approx 0.38 \text{ sec}$$
$$\zeta_d \approx 0.23 \qquad \tau_S \approx 136 \text{ sec}$$
$$|\phi/\beta|_d \approx 1.78$$

This configuration was found to be quite satisfactory at $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = 0.0 and at $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = + 0.07 receiving a pilot rating of 1.5 in both cases. The pilot objected somewhat to the response to random inputs for the evaluation with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = + 0.07, but listed no objectionable features for the zero aileron yaw case. Good features of the airplane included negligible sideslip generation and therefore no need for rudder coordination, precise bank angle control and smooth roll control.

Figure 39 shows that for this configuration the pilot was more tolerant of proverse yaw due to aileron inputs than he was for adverse. For $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = + 0.07, the pilot noticed the proverse yawing moment generated with aileron inputs but stated that it didn't make much difference. He also noted that the airplane was quite stiff directionally and that the Dutch roll was very well damped. Reference to the time histories, Appendix IV, shows that proverse sideslip indeed developed with aileron inputs, but, because of the high Dutch roll frequency, the proverse sideslip was limited in magnitude. Also the time to damp for this configuration was quite short. For an aileron step input the sideslip, after going proverse, was back to zero in less than two seconds and thereafter remained adverse and quite similar to the sideslip response of the $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = 0 case. It can also be noted from the time histories for both the $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = + 0.07 and $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = 0.0 cases that the yaw rate was non-oscillatory and that there was no tendency for the airplane to begin turning in the direction opposite to the aileron input. This supports the pilot's comments about good heading control. The results for this configuration indicate, therefore, that moderate proverse aileron yaw is acceptable for an airplane with the characteristics of Configuration 7 - that is a well damped, high frequency Dutch roll with a relatively low value of $|\phi/\beta|_d$.

In the most adverse aileron yaw case ($N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.20) a large amount of sideslip was generated to an aileron input and a persistent oscillation would develop both in roll and sideslip. Because of the high frequency Dutch roll the pilot was unable to phase his rudder inputs and found he could not dampen the oscillations with the rudder. As a result, heading control was degraded. Attempts to coordinate with the rudder required large rudder inputs and heavy rudder forces, even with the relatively high rudder control sensitivity that was selected. In the presence of random disturbances the airplane exhibited high frequency oscillations in both bank angle and sideslip.

With less adverse aileron yaw, $N'_{\delta_{AS}}/L'_{\delta_{AS}}$, the handling qualities were considerably improved over those of the most adverse aileron yaw case. The configuration was evaluated twice at this value of aileron yaw and received pilot ratings of 3 and 5. In both cases the pilot objected to the sideslip generated with an aileron input, but with the pilot rating of 5 he objected to the amount of rudder and the high rudder forces required for coordination. His selection of rudder control sensitivity, $N'_{\delta_{RP}}$ = 45.0 deg/sec^2 in., for the PR = 5 case was quite low compared to the PR = 3 case where he selected rudder control sensitivity at $N'_{\delta_{RP}}$ = 72.0 deg/sec^2 in. The airplane still required rudder coordination for the PR = 3 case, but the pilot found it to be in the proper direction and easy to accomplish. The rms values of the pilot's rudder pedal force inputs were computed and it was found that 16.4 lb rms was used when the PR = 5 but only 7.4 lb rms was used for the PR = 3 case. The rms error in the bank angle tracking task was 7.2 degrees for PR = 5 and 6.2 degrees for PR = 3. Hence, there is evidence that the pilot had to work much harder with the rudder in the PR = 5 case to achieve approximately the same performance that he achieved in the PR = 3 case. This factor may account, at least partially, for the difference in pilot ratings.

The evaluation of the most proverse value of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ for this configuration presented the pilot with a difficult coordination problem requiring rudder inputs initially in the direction opposite a turn and then into the turn. The high Dutch roll frequency of this configuration compounded the difficulties of the coordination requirement forcing the pilot to attempt rudder inputs in one direction and then very quickly in the opposite direction. Still, the pilot reported that heading control was not really difficult because of the high directional stiffness and good damping of the Dutch roll.

The pilot's selection of aileron and rudder control sensitivities shows definite trends with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ except for the rudder sensitivity selections at $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.10 which was discussed above.

The aileron control sensitivity, $L'_{\delta_{AS}}$, was chosen generally for light maneuvering forces in roll. In the most adverse aileron yaw case ($N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.20), the pilot chose less sensitive aileron control in order to limit the excitation of sideslip with aileron inputs. In the more proverse aileron yaw cases, the aileron control sensitivity was selected at relatively low values to prevent overcontrol of bank angle. In these cases the proverse sideslip generated with aileron inputs augmented roll rates and control of sideslip was difficult because it required awkward, crossed control rudder inputs. The selection of rudder control sensitivities reflects either the need for rudder coordination of aileron inputs or the pilot's ability to coordinate. With the adverse aileron yaw cases the pilot chose light rudder forces in order to more easily control the adverse sideslip generated with aileron control inputs. For the cases with proverse aileron yaw, the pilot chose heavier rudder pedal forces to prevent overcontrol and the aggravation of roll acceleration resulting from the roll rate coupling with proverse sideslip. During maneuvering the pilot would inadvertently revert to normal coordination techniques (rudder into the turn) which would increase the already proverse sideslip generated with aileron inputs. The heavier rudder pedal forces helped alleviate this difficulty.

4.4.2 Results for High Dutch Roll Frequency, High $|\phi/\beta|_d$ Configurations

The $\phi(s)/\delta_{AS}(s)$ transfer function zero locations with respect to the Dutch roll poles for Configurations 12 and 13 are shown on Figure 40. The experimental results are shown on Figure 41. A detailed definition of these configurations is given in Appendix IV where the pilot comment data and transient responses are also presented.

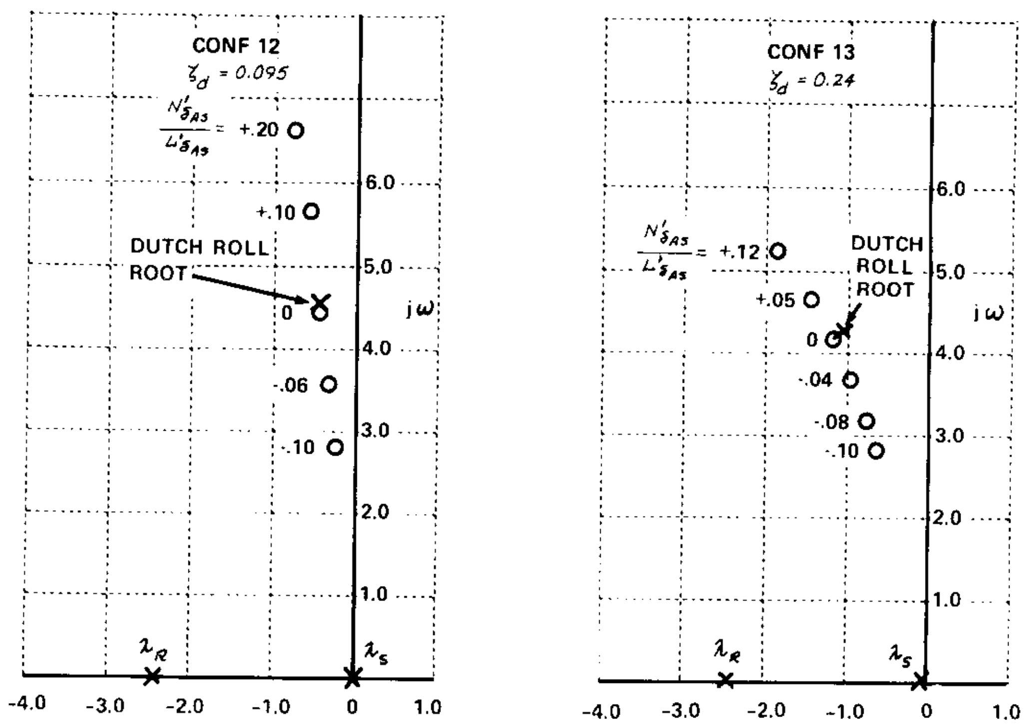


Figure 40 $\phi(s)/\delta_{AS}(s)$ Pole-Zero Locations for High ω_d, High $|\phi/\beta|_d$ Configurations

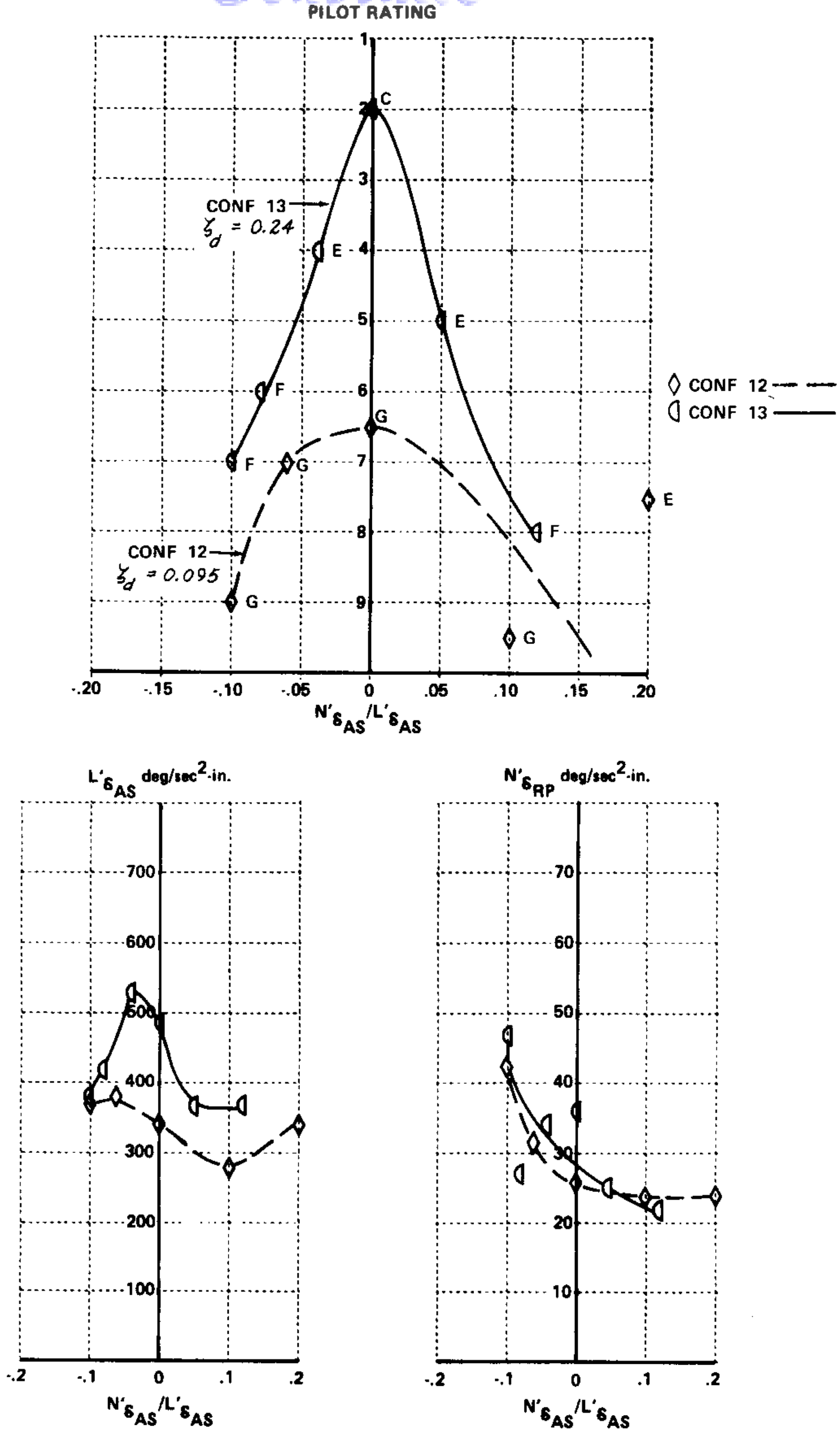


Figure 41 Pilot Ratings and Pilot Selected Control Sensitivities for High ω_d, High $|\phi/\beta|_d$ Configurations

4.4.2.1 Configuration 12 - Lower Dutch Roll Damping Ratio

The lateral-directional modal characteristics for Configuration 12 were as follows:

$$\omega_d \approx 4.5 \text{ rad/sec} \qquad \tau_R \approx 0.41 \text{ sec}$$
$$\zeta_d \approx 0.095 \qquad \tau_S \approx \infty \text{ sec}$$
$$|\phi/\beta|_d \approx 5.6$$

This configuration was never rated as satisfactory. The best pilot rating of 6.5 was obtained with $N'_{\delta_{AS}}/L'_{\delta_{AS}} = 0$. In smooth air with aileron yaw at zero, the sideslip disturbances were small, no coordination was required and roll performance was good. There was a tendency for the pilot to overcontrol bank angle and for the airplane to oscillate about the desired bank angle. Heading control, however, was not a problem since the oscillations were fairly symmetrical. The encounter of any natural turbulence deteriorated the bank angle controllability, and the introduction of random disturbance inputs caused a major degradation of the handling qualities. With random disturbance inputs the pilot reported "quite high" side accelerations. The response to random disturbances was the pilot's major objection to the configuration. He also stated that a reasonable job could be accomplished with the airplane in smooth air.

With increases of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ in the adverse direction, the handling qualities deteriorated quite rapidly from an already unsatisfactory condition. The pilot listed no good features for the airplane. His objections to the airplane included:

(1) Extreme side accelerations to an aileron input.

(2) Imprecise bank angle control and a "rachety" type roll control which affected the heading control.

(3) Excitation of the lightly damped, high frequency Dutch roll when trying to maneuver.

(4) The large deterioration in his performance when the airplane was subjected to the effects of random disturbance inputs.

In the most adverse aileron yaw case, $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.10$, the pilot found that the bank angle tracking task was nearly impossible because of high frequency roll oscillations that appeared nearly divergent during the closed-loop tracking.

With proverse yaw due to aileron inputs, bank angle controllability with any degree of precision was very difficult. The pilot found that he induced bank angle oscillations when trying to precisely control bank angle. The harder he worked at precise control the worse the PIO would become. Hence, performance during the bank angle tracking task was quite poor. Attempts at rudder coordination were not successful in that they seemed to further deteriorate the performance of the airplane. Rudder coordination required rudder out of the turn which is unnatural for the pilot. Also, the high frequency of the Dutch roll prevented the pilot from damping the roll oscillations through rudder coordination because he simply could not phase his rudder inputs with the relatively fast oscillations.

At all values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ tested for this configuration, the airplane's response to either natural turbulence or the random disturbance inputs was very objectionable and showed little variation with aileron yaw. This can be principally attributed to the low Dutch roll damping and high roll to sideslip ratio; a combination of parameters known to be highly susceptible to turbulence upsets (Reference 3).

The pilot's selection of aileron control sensitivity, $L'_{\delta_{AS}}$, generally decreased as aileron yaw became more proverse except in the most proverse aileron yaw case ($N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.20$) where aileron control sensitivity was chosen at a value almost as large as that chosen in the most adverse aileron yaw case. In the most proverse aileron yaw case the relatively high value of $L'_{\delta_{AS}}$ may have contributed to the bank angle PIO problem. The pilot stated that he selected what he considered rather low aileron control sensitivity in order to reduce the bank angle oscillation tendencies and to reduce the side accelerations that accompanied aileron inputs.

Values of rudder control sensitivity, $N'_{\delta_{RP}}$, were selected at large values for adverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ and decreased as $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ was made more positive. The pilot based his selection on rudder coordination requirements, choosing lighter rudder forces in the more adverse aileron yaw cases. In the proverse aileron yaw cases the pilot stated that he didn't use the rudder and therefore accepted a lower value of rudder sensitivity.

4.4.2.2 Configuration 13 - Higher Dutch Roll Damping Ratio

The lateral-directional modal characteristics for Configuration 13 were as follows:

$$\omega_d \approx 4.34 \text{ rad/sec} \qquad \tau_R \approx 0.40 \text{ sec}$$
$$\zeta_d \approx 0.24 \qquad \tau_s \approx 40 \text{ sec}$$
$$|\phi/\beta|_d \approx 5.3$$

This configuration was found to be quite satisfactory for $N'_{\delta_{AS}}/L'_{\delta_{AS}} = 0$ where the zero of the $\phi(s)/\delta_{AS}(s)$ transfer function was very close to the Dutch roll pole. The pilot reported that the airplane had smooth roll control, very little need for rudder coordination and apparently a well damped Dutch roll. The small amount of rudder coordination required was in a direction that was natural for the pilot to perform. Bank angle control was reported as good and the airplane could be flown aggressively without encountering any significant bank angle oscillations. Hence, there were no difficulties encountered during the bank angle tracking task. Response to random disturbance inputs were reported as certainly noticeable, but not a degrading factor.

As shown on Figure 41, the pilot rating for Configuration 13 degraded rapidly as $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ was increased in either the adverse or proverse direction. For small adverse aileron yaw ($N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.04) the most objectionable feature of the airplane was the response to random disturbance inputs. The pilot still reported good bank angle controllability and easy to achieve coordination of the adverse aileron yaw, but the airplane was rated as unsatisfactory because of the response to disturbance inputs. Further increases in $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ in the adverse direction led to poor bank angle control and a tendency to oscillate about a desired bank angle. The pilot had little difficulty, however, with heading control. There was a marked tendency to overcontrol bank angle. The airplane was oscillatory in sideslip and bank angle during a closed-loop tracking task. Response to turbulence or to disturbance inputs was quite objectionable in that large, rapid roll disturbances and quite large side accelerations were produced.

As aileron yaw was increased in the proverse direction from the $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = 0.0 case, bank angle controllability became more difficult. There were tendencies to overshoot the desired bank angle and for the airplane to oscillate about the desired bank angle. The bank angle oscillations were more associated with the closed-loop pilot-airplane combination than with the open-loop airplane. As a result, the pilot's bank angle tracking task performance was degraded. An increase in proverse aileron yaw to $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = + 0.12 further degraded bank angle controllability to the point that the airplane was even difficult to fly straight and level. Attaining a given heading was also quite difficult because of the bank angle control. Attempts to track in bank angle resulted in continuous pilot-induced oscillations. The pilot stated that as he approached the desired bank angle he had to ease up on the controls, (lower his gain) and let the airplane seek a nominal bank angle. With proverse aileron yaw, response to random disturbance inputs was quite pronounced in roll excursions and side accelerations causing task performance to deteriorate more severely as aileron yaw was increased in the proverse directions.

The pilot selected the aileron control sensitivity so that he could maneuver the airplane rapidly with small force inputs. His selection was generally a compromise such that he could limit bank angle oscillations and not overcontrol in making small bank angle corrections while retaining light forces for large magnitude maneuvering. With $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = 0 , he selected the aileron control sensitivity based on his personal preference for light forces since no oscillatory tendencies in roll rate or bank angle were noticed. Rudder control sensitivities were selected, in the case of adverse aileron yaw, to allow the pilot to coordinate with light rudder forces. With proverse aileron yaw the pilot found that coordination either was not necessary or that he was unable to coordinate because of the high Dutch roll frequency and having to use rudder opposite to the turn direction. In these cases he accepted lower rudder control sensitivity, or simply accepted the starting value given to him.

4.4.3 Comparison of the High Dutch Roll Frequency Configurations With MIL-F-8785B(ASG) Lateral-Directional Requirements

In this section, the high Dutch roll frequency configurations ($\omega_d \approx$ 4.5 rad/sec) of this investigation are compared to the following MIL-F-8785B(ASG) requirements:

- (a) Dutch Roll Frequency and Damping Requirements (Reference 1, Paragraph 3.3.1.1).
- (b) Lateral-Directional Dynamic Response Requirements including:
  - (1) Roll rate requirements for small inputs (Reference 1, paragraph 3.3.2.2.1)
  - (2) Sideslip requirements for small inputs (Reference 1, paragraph 3.3.2.4.1)

4.4.3.1 Dutch Roll Frequency and Damping Ratio

MIL-F-8785B(ASG) requirements on minimum Dutch roll frequency have already been discussed in paragraph 4.2.3.1. There is no direct requirement limiting the maximum Dutch roll frequency, however, Reference 3 points out that a degradation in performance and, therefore, in pilot ratings may occur with high ω_d airplanes in the presence of atmospheric turbulence. Hence, an indirect specification limiting maximum ω_d has been made through the requirement for additional damping, $\Delta\zeta_d\,\omega_d$, as a function of the parameter $\omega_d{}^2|\phi/\beta|_d$ when $\omega_d{}^2\,|\phi/\beta|_d > 20$ (rad/deg)^2. For a given ω_d and $|\phi/\beta|_d$ this increment in Dutch roll damping serves to improve controllability in the presence of atmospheric disturbances.

From MIL-F-8785B(ASG), the minimum Dutch roll damping ratio (ζ_d) for Class IV airplanes in Flight Phase Category A is 0.19 for Level 1, and 0.02 for Levels 2 and 3. With the additional damping required when $\omega_d{}^2|\phi/\beta|_d$ is greater than 20 (rad/sec)^2 included, the minimum ζ_d corresponding to various levels of handling qualities for the four configurations under discussion were determined as shown below:

$$\zeta_{d_{req'd}} = \zeta_d + \frac{\Delta \zeta_d \omega_d}{\omega_d}$$

where ζ_d is 0.19 for Level 1 and 0.02 for Levels 2 and 3 and $\Delta \zeta_d \omega_d = C\,(\omega_d^2\,|\phi/\beta|_d - 20)$. From Reference 1, the constant C has the following specified values:

C = .014 for Level 1
.009 for Level 2
.005 for Level 3

Using the above expressions, the required Dutch roll damping ratio for the high ω_d configurations is

Configuration	ζ_d for Level 1	ζ_d for Level 2	ζ_d for Level 3
6	0.23	0.048	0.036
7	0.23	0.047	0.035
12	0.48	0.21	0.123
13	0.48	0.19	0.112

From this tabulation, it is apparent that with the actual ζ_d the above configurations possessed, the following handling qualities Levels would apply:

Configuration	Level
6	2
7	1
12	3
13	2

Referring to the faired pilot rating curves on Figures 39 and 41, it is seen that in terms of the best pilot ratings that were assigned to any of the four high frequency configurations, the experimental results generally conform with the MIL-F-8785B(ASG) Level criteria listed above. Configuration 7 (Figure 39) with ζ_d = 0.23 and medium $|\phi/\beta|_d$ was rated Level 1 (PR ≤ 3.5) for the range of aileron yaw parameter of $-0.08 \leq N'_{\delta_{AS}}/L'_{\delta_{AS}} \leq +0.12$. On the other hand, Configuration 6 with ζ_d = 0.10 and also medium $|\phi/\beta|_d$ was rated marginally Level 1 (PR = 3.5) with $N'_{\delta_{AS}}/L'_{\delta_{AS}} = 0$ and worse than Level 1 at all other points tested. Figure 41 indicates Level 1 handling qualities for Configuration 13 with $\zeta_d \approx 0.24$ and a high $|\phi/\beta|_d$ for only a very narrow range of the aileron yaw parameter $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. Actually, only one test point ($N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = 0.0) was rated as satisfactory, PR < 3.5. In contrast, Configuration 12 with ζ_d = 0.095 and also a high $|\phi/\beta|_d$ was never rated better than Level 3, PR ≥ 6.5. Thus, the evaluation results correlate quite well with the appropriate MIL-F-8785B(ASG) requirements on Dutch roll damping including the additional increment $\Delta\zeta_d\omega_d$ when $\omega_d^2\,|\phi/\beta|_d > 20$. Furthermore, the data for Configurations 6 and 7 with medium $|\phi/\beta|_d$ tend to confirm the basic Level 1 Dutch roll damping requirement ($\zeta_d \geq 0.19$) of MIL-F-8785B(ASG). The data for Configurations 12 and 13 with a high $|\phi/\beta|_d$, however, neither confirm nor refute directly this requirement. But the results for all four configurations support the imposition of additional damping ($\Delta\zeta_d\omega_d$) as a function of the parameter $\omega_d^2\,|\phi/\beta|_d$.

4.4.3.2 Lateral-Directional Dynamic Response Requirements

Figure 42 shows a comparison of the high Dutch roll frequency configurations for the various values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ tested, with the p_{osc}/p_{AV} versus ψ_β requirement of MIL-F-8785B(ASG), Reference 1. Except for those points indicated as having been derived from computer generated data, the parameters p_{osc}/p_{AV} and ψ_β were measured from actual flight data. For these configurations, p_{osc}/p_{AV} is not an effective discriminator of the airplane handling qualities, largely because only one of the configurations met Level 1 Dutch roll damping requirements when the additional damping as a function of $\omega_d^2\,|\phi/\beta|_d$ was considered.

The medium $|\phi/\beta|_d$ configurations (6 and 7) met Level 1 p_{osc}/p_{AV} requirements at all values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ tested. For these configurations the pilot had some complaints about bank angle control, especially at the larger values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$, but generally reported good roll control. Major objections, other than response to disturbance inputs, centered around control of sideslip, that is, the difficulty of rudder coordination.

For the high $|\phi/\beta|_d$ configurations (12 and 13) some dominant objections on the part of the pilot were poor bank angle controllability, roll rate oscillations with adverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ and pilot-induced bank angle oscillations with proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. In the two most proverse aileron yaw cases, Configuration 12 was Level 3 in terms of p_{osc}/p_{AV} versus ψ_β and commensurately received Level 3 pilot ratings. In the zero and adverse aileron yaw cases, p_{osc}/p_{AV} was not a good discriminator of handling qualities, again, largely because the airplane's response to disturbance inputs caused the degradation in pilot rating, but the pilot did have strong objections to the roll characteristics in these cases. Configuration 13 failed to meet Level 1 p_{osc}/p_{AV} requirements only in the proverse aileron yaw cases where one point was on the Level 1 border and the most proverse point was clearly Level 2. Both these points received pilot ratings greater than PR = 3.5.

It is significant, and defensive of the p_{osc}/p_{AV} boundary locations, that none of the points which fell outside the Level 1 boundary received satisfactory pilot ratings. Further, points which fell outside the Level 2 boundary received pilot ratings greater than 6.5. Hence, the p_{osc}/p_{AV} requirement did not erroneously reject any of the test points.

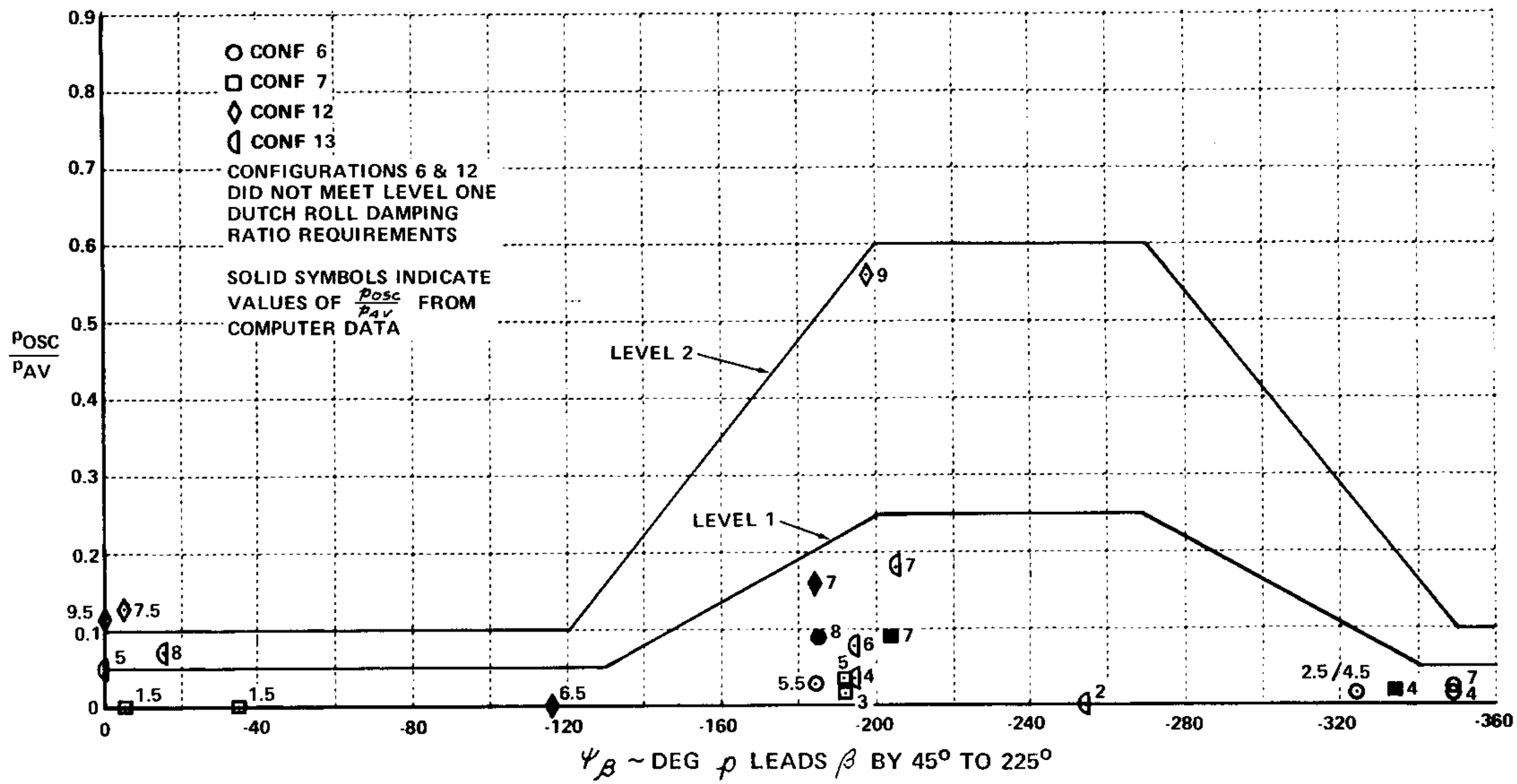


Figure 42 High Dutch Roll Frequency Configurations Compared to p_{osc}/p_{AV} Requirements of MIL-F-8785B(ASG)

The test points for the high Dutch roll frequency configurations are compared to the Level 1 $\Delta\beta_{MAX}/k$ versus ψ_β requirement on Figure 43. Those points which failed to meet Level 1 $\Delta\beta_{MAX}/k$ requirements are compared to the Level 2 $\Delta\beta_{MAX}/k$ versus ψ_β requirement on Figure 44. As in the case for p_{osc}/p_{AV}, none of the points which fell outside the Level 1 boundary received satisfactory pilot ratings. Neither the Level 1 nor the Level 2 boundaries erroneously rejected any of the test points. Configuration 7, the only high frequency configuration which met Level 1 Dutch roll damping requirements, received only one PR > 3.5 that fell within the Level 1 $\Delta\beta_{MAX}/k$ boundary. This same point was, however, evaluated twice receiving pilot ratings of 3 and 5.

As was pointed out, none of the requirements to which the data for the high ω_d configurations was compared relegated any test point to Level 2 when the point received a Level 1 pilot rating, or to Level 3 when the point received a Level 2 or better pilot rating. Many of the pilot ratings within a given Level 1 boundary represented less than Level 1 flying qualities because of some reason other than the requirement to which the data were compared. The major pilot objections to the high ω_d configurations were low Dutch roll damping or the airplane response to random disturbance inputs. For the data to refute the requirement boundaries it would be necessary for points receiving satisfactory pilot ratings to be above or outside the Level 1 boundaries. Level 2 boundaries would likewise be refuted by test points falling outside the Level 2 area which received pilot ratings in the range $3.5 < PR \leq 6.5$. Hence, the data for the high ω_d configurations of this investigation supply no evidence that the roll sideslip coupling requirement boundaries are inadequate. The data do serve to verify the imposition of additional Dutch roll damping as a function of $\omega_d^2 |\phi/\beta|_d$.

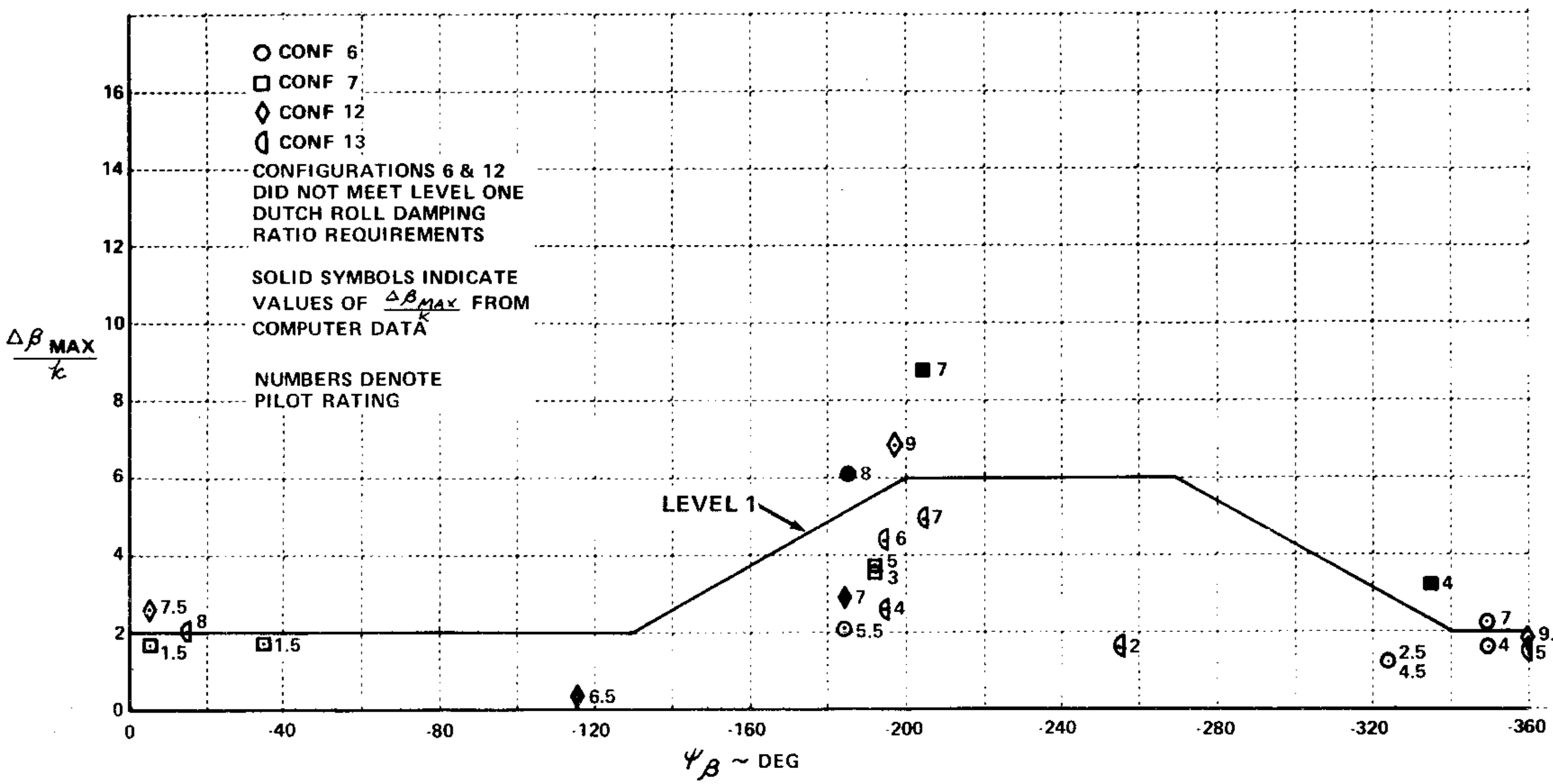


Figure 43 High Dutch Roll Frequency Configurations Compared to Level 1 $\Delta\beta_{MAX}/k$ Requirements of MIL-F-8785B(ASG)

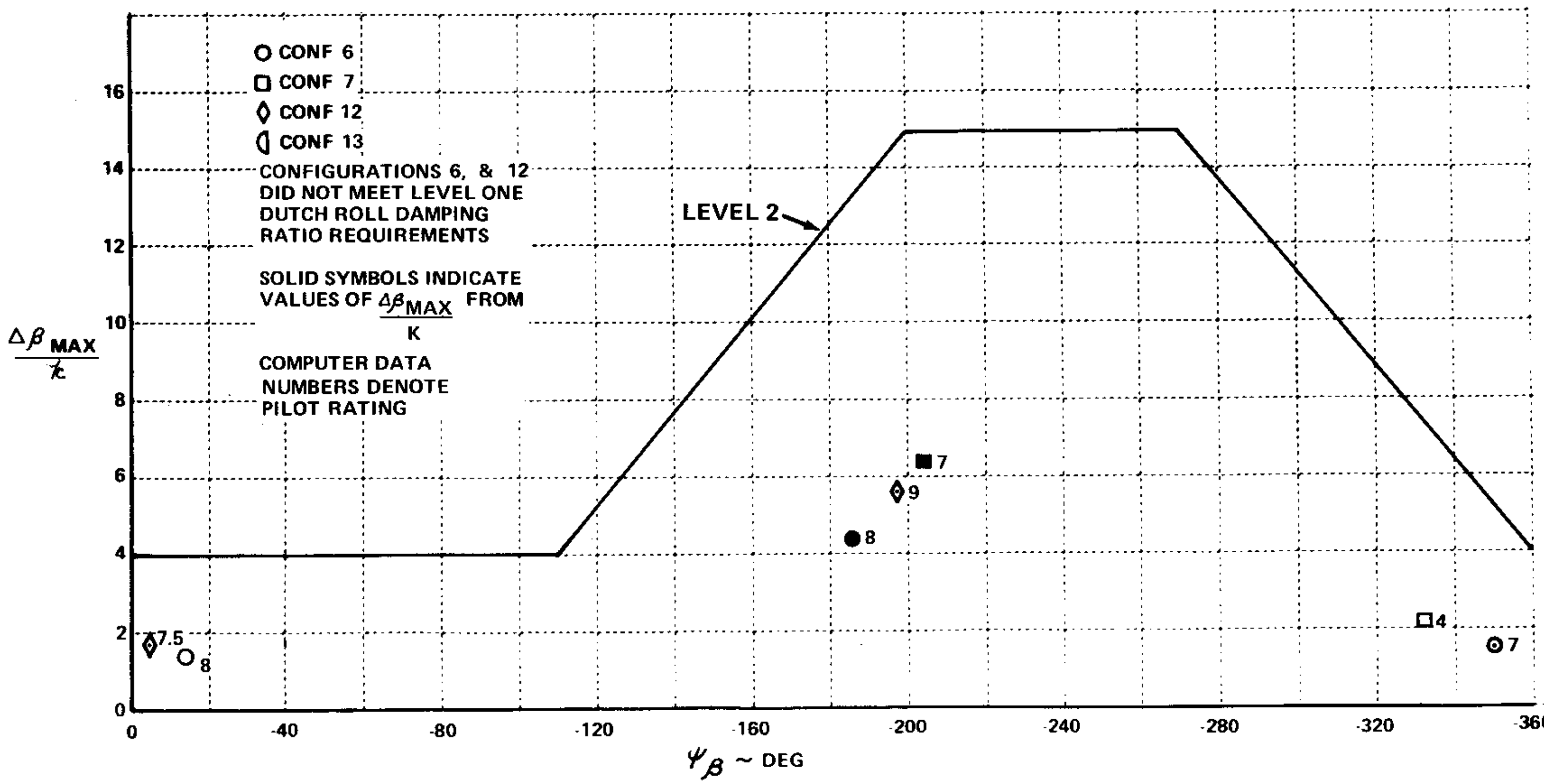


Figure 44 High Dutch Roll Frequency Configurations That Do Not Meet Level 1 $\Delta\beta_{MAX}/k$ Requirements Compared to Level 2 $\Delta\beta_{MAX}/k$ Requirements of MIL-F-8785B(ASG)

SECTION V

SUMMARY OF RESULTS

5.1 GENERAL

The experimental results of this investigation have been discussed in detail in Section IV of this report. In this section the results are summarized and discussed briefly. Figures 45 through 48 present data in the MIL-F-8785B(ASG) requirements planes for roll-sideslip coupling. The pilot ratings shown on these figures were taken from the faired pilot rating curves of Section IV. The data points plotted on Figures 45 through 48 have been selected so that comparison can be made with a single requirement of MIL-F-8785B(ASG) in so far as possible. For example, a given point must have met Level 1 Dutch roll frequency, Dutch roll damping and ρ_{osc}/ρ_{AV} versus ψ_β requirements in order to appear on the summary plot of $\Delta\beta_{MAX}/k$ versus ψ_β requirements. In this way the pilot ratings shown on the plot of $\Delta\beta_{MAX}/k$ versus ψ_β should reflect the effects of sideslip excursions and should not be degraded by some other factor. Regardless of this procedure, however, it was found that pilot rating was sometimes degraded for other reasons and these points are discussed. This same procedure has been followed for the other requirements planes summary plots as is indicated by the titles and notes shown thereon.

Figure 49 presents a comparison of the data with one of the roll-sideslip requirements planes of MIL-F-83300. Finally, Figures 50 and 51 show a partial mapping of the areas of Level 1 and Level 2 flying qualities in the s plane in terms of the $\phi(s)/\delta_{AS}(s)$ transfer function. On these plots pilot rating boundaries of 3.5 and 6.5 are shown where there were sufficient data to establish a boundary.

5.2 DUTCH ROLL FREQUENCY AND DAMPING

Three nominal values of Dutch roll frequency were evaluated: 1.0 rad/sec, 2.5 rad/sec and 4.5 rad/sec. MIL-F-8785B(ASG) requires a minimum Dutch roll frequency of 1.0 rad/sec for Level 1 Class IV airplanes. Four configurations in this investigation, Configurations 2, 3, 8 and 9, had a Dutch roll frequency near 1.0 radian per second. None of the four configurations received a pilot rating of PR = 3.5 or better at any value of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ tested. The most common objections, by the evaluation pilot, to all of the evaluations with low Dutch roll frequency were sideslip excursions and the difficulty of control of sideslip. It was also determined, Figure 18, that none of the configurations with $\omega_d \approx 1.0$ rad/sec met the Level 1 $\Delta\beta_{MAX}/k$ versus ψ_β requirements of MIL-F-8785B(ASG). Further, the slow directional response of the $\omega_d = 1.0$ configurations made it difficult for the pilot to arrive at and maintain a given heading.

The pilot did not indicate that he had much difficulty with roll or bank angle control. The response of the $\omega_d \approx 1.0$ rad/sec configurations to random disturbance inputs was generally mild.

Two values of Dutch roll damping, $\zeta_d \omega_d \approx 0.27$ and $\zeta_d \omega_d \approx 0.50$, were evaluated at the low Dutch roll frequency of $\omega_d \approx 1.0$ rad/sec. MIL-F-8785B(ASG) requires that $\zeta_d \omega_d \geq 0.35$ for Class IV airplanes in Flight Phase Category A. When the zero of the $\phi(s)/\delta_{AS}(s)$ transfer function was nearly on the Dutch roll pole, there was no significant difference in pilot rating between the two $\zeta_d \omega_d$ values. However, as the $\phi(s)/\delta_{AS}(s)$ transfer function zero was moved away from the Dutch roll pole, the pilot ratings for the lower $\zeta_d \omega_d$ cases degraded more rapidly with increases in $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ than did the pilot ratings for the higher damping cases. The requirement $\zeta_d \omega_d \geq 0.35$ is adequate provided that there is compliance with other provisions such as roll-sideslip coupling requirements of MIL-F-8785B(ASG).

Eight configurations were evaluated at the medium Dutch roll frequency of this experiment, $\omega_d \approx 2.5$ rad/sec, and a Dutch roll damping ratio of $\zeta_d \approx 0.25$. Both these values meet the Level 1 requirements of MIL-F-8785B(ASG). There were no objectionable features of these configurations which were directly attributable to the Dutch roll frequency or damping characteristics. In fact, the pilot often commented that the Dutch roll was well damped and that the configurations had good directional stiffness.

The highest Dutch roll frequency evaluated was $\omega_d \approx 4.5$ rad/sec. Of the four configurations evaluated at $\omega_d \approx 4.5$ rad/sec, Configurations 6 and 12 had a Dutch roll damping ratio of $\zeta_d \approx 0.10$ and for Configurations 7 and 13, $\zeta_d \approx 0.25$. At the medium value of $|\phi/\beta|_d$ evaluated, $|\phi/\beta|_d \approx 1.7$, Configuration 7 was twice rated PR = 1.5, the best in the entire investigation. However, the other $\omega_d \approx 4.5$ configurations, 6, 12, 13, with low Dutch roll damping, Configurations 6 and 12, or high $|\phi/\beta|_d$, Configurations 12 and 13, were very susceptible to the effects of random disturbance inputs. A common objection by the pilot to all these configurations was the response to random disturbance inputs or natural turbulence, if it was encountered. MIL-F-8785B(ASG) does not directly address a requirement to limit the effects of atmospheric turbulence but it does require an additional increment of Dutch roll damping when $\omega_d^2 |\phi/\beta|_d > 20$ in order to improve flying qualities in the presence of atmospheric turbulence. Configurations 6, 12 and 13 would all have required an additional increment of Dutch roll damping in order to meet Level 1 requirements when the effects of $\omega_d^2 |\phi/\beta|_d$ were considered. Configuration 12 met only Level 3 ζ_d requirements when the required damping specified through $\Delta \zeta_d \omega_d = C[\omega_d^2 |\phi/\beta|_d - 20]$ was computed. In fact, the $\omega_d = 4.5$ rad/sec configurations were found to meet Levels of flying qualities, based on the required additional increment of Dutch roll damping, as listed below:

Configuration	Level
6	2
7	1
12	3
13	2

Configuration 7 received Level 1 pilot ratings, PR $\leq$ 3.5, through a wide range of the aileron yaw parameter $N'_{\delta_{AS}} / L'_{\delta_{AS}}$. Configuration 12 generally received Level 3 pilot ratings, PR > 6.5, being rated once PR = 6.5. Configurations 6 and 13 were generally rated PR > 3.5, each being once rated at PR $\leq$ 3.5. This correlation of pilot rating with the Levels derived from the requirement based on $\omega_d^2 |\phi/\beta|_d$ and listed above, supports the specification of additional damping as a function of the parameter $\omega_d^2 |\phi/\beta|_d$. Further investigation of this requirement is warranted, however.

5.3 LATERAL-DIRECTIONAL DYNAMIC RESPONSE REQUIREMENTS

Figures 45 through 48 summarize the data obtained in this investigation in the MIL-F-8785B(ASG) requirements planes for sideslip excursions and roll rate oscillations for small inputs. Those configurations which did not meet Level 1 Dutch roll damping requirements are not shown on the summary plots since the pilot rating was degraded for reasons other than sideslip excursions and roll rate oscillations per se. The high Dutch roll frequency configurations, for example, received poor pilot ratings largely as a result of their response to random disturbance inputs. This can be seen by referring to the turbulence effect ratings shown on the pilot rating plots in Section 4.4. The low Dutch roll frequency configurations with the low value of Dutch roll damping showed no effects of the low damping near the best tested value of $N'_{\delta_{AS}} / L'_{\delta_{AS}}$. But, the pilot rating degraded as a result of low Dutch roll damping as $N'_{\delta_{AS}} / L'_{\delta_{AS}}$ was increased in either direction from the value receiving the best pilot rating. Hence, the pilot ratings for these configurations may reflect degradation for reasons other than roll-sideslip coupling.

Figure 45 compares the data of this experiment to the Level 1 $\Delta\beta_{MAX}/k$ versus ψ_β requirements plane for those data points which met the Level 1 p_{osc}/p_{AV} versus ψ_β requirements. The pilot ratings shown are from the faired P.R. curves of Section IV. Since these data points also met all other requirements of MIL-F-8785B(ASG) the pilot rating assigned should reflect the effects of sideslip excursions.

Reference to Figure 45 shows that six points rated as satisfactory without improvement, PR $\leq$ 3.5, fall above the Level 1 $\Delta\beta_{MAX}/k$ versus ψ_β boundary indicating that these points, though Level 1 according to pilot rating, would be rejected from the Level 1 area by the sideslip excursion criteria. It should be noted that all but one of these points are members of the family of Configuration 5.

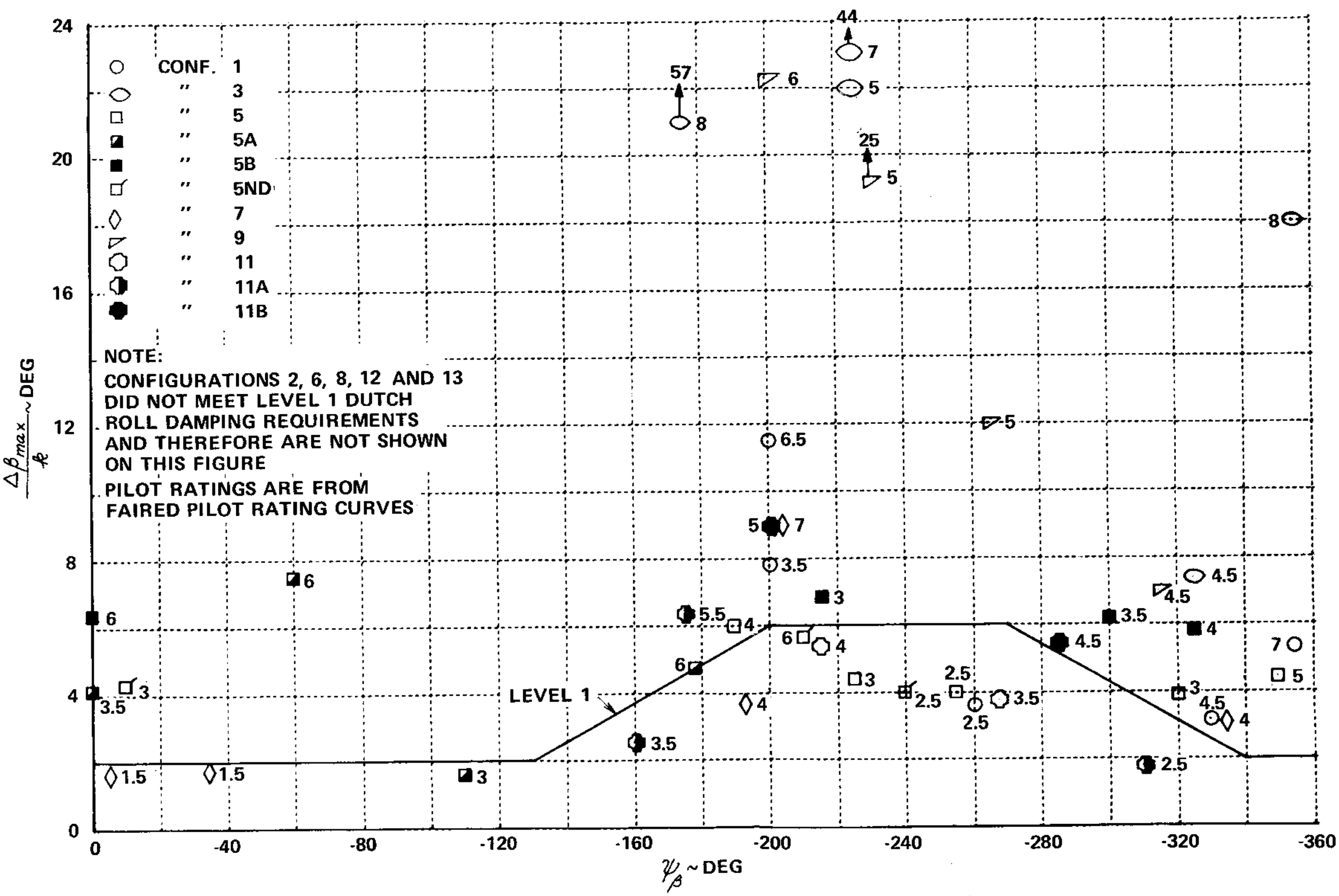


Figure 45 $\Delta\beta_{MAX}/k$ Versus ψ_β For Evaluation Points Which Meet Level 1 $\varphi_{osc}/\varphi_{AV}$ Criteria

There are also four points falling within the Level 1 $\Delta\beta_{MAX}/k$ versus ψ_β boundary which received pilot ratings greater than 3.5. One of these points fell on the boundary receiving PR = 6.0.

Each of these anomalous points has been discussed in detail in Section IV of this report, however, a review of their salient features is considered in order here. Beginning with those points which were rated PR ≤ 3.5 and fell above the Level 1 $\Delta\beta_{MAX}/k$ boundary, the following tabulation furnishes the necessary identification for the convenience of the reader.

Conf.	P.R.	$\frac{N'_{\delta_{AS}}}{L'_{\delta_{AS}}}$	$\frac{\Delta\beta_{MAX}}{k}$ *	ψ_β
1	3.5	-0.06	7.8	-200
5	3.0	+0.05	3.9	-320
5A	3.5	+0.04	4.1	0
5B	3.0	-0.02	6.9	-215
5B	3.5	+0.01	6.2	-300
5ND	3.0	+0.05	4.3	-010

Configuration 1 with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = -0.06 was considered "marginally satisfactory and slightly on the satisfactory side" by the evaluation pilot, but not to the point of requiring moderate pilot compensation. The pilot liked the maneuverability and reported the bank angle control as good. The only objectionable feature reported was the large sideslip generated with aileron inputs, requiring a lot of rudder for coordination. Coordination, however, required rudder in the direction of the turn and the pilot found this to be natural. Because of the very low value of $|\phi/\beta|_d$, the sideslip generated had little effect on the roll or bank angle controllability. Hence the pilot was willing to accept the rudder coordination task even though he stated that it required a "conscientious effort to coordinate."

Configuration 5 with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = +0.05 was evaluated twice and in both cases received a PR = 3 and a TR = B. The pilot noted that for an aileron input, the airplane exhibited a small amount of proverse yaw followed by adverse yaw, but the Dutch roll frequency was high enough that the sideslip centered itself before the pilot could compensate with rudder. He found rudder coordination quite difficult and became satisfied to keep his feet off the rudder pedals and just accept the sideslip excursions. The

* The parameter k was determined using Level 1 criteria.

roll capability and maneuverability were reported as quite good. In this case, the pilot also considered the airplane as marginally satisfactory. It is of interest to note here that a 0.1 sec difference in the measurement of t_{n_β} for the determination of ψ_β, could have changed the value of ψ_β from -320° to -305° which would have put this point on the Level 1 $\Delta\beta_{MAX}/k$ boundary. This may be within the expected degree of accuracy that can be obtained by measurement from in-flight recorded data.

For Configuration 5A with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = +0.04, the airplane had good roll performance and quite good bank angle controllability. The only objection the pilot stated was the substantial proverse sideslip generated with an aileron input. However, the sideslip seemed to have little effect on the roll control and the airplane was stiff enough directionally so that the sideslip was of short duration. As a result, the airplane was assessed as marginally satisfactory.

Configuration 5B with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = - 0.02 was reported to have quite good bank angle controllability, good heading control and good roll performance. The pilot stated that he could "really fly the airplane aggressively". His only objection was the "fair amount of adverse sideslip generated" for an aileron input. He found coordination somewhat difficult with a tendency to overcontrol with the rudder but found these deficiencies only mildly unpleasant requiring minimal pilot compensation.

Configuration 5B with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = +0.01 was also considered to have good roll control, fair to good heading controllability, but difficult to coordinate with a changing requirement for rudder as the airplane rolled. However, the sideslip didn't strongly affect the roll performance or bank angle controllability. So again, the airplane was assessed as marginally satisfactory.

With the negative effective dihedral case, Configuration 5ND with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = +0.05, the pilot had no major objections to the airplane but stated that he did dislike the inability to augment the roll rate with rudder. Although, in terms of $\Delta\beta_{MAX}/k$, this configuration was definitely Level 2, the pilot noted that very little coordination was required. The coordination required was in the normal, into-the-turn, direction. As discussed in Section 4.3.4.2 the character of the sideslip, proverse then adverse and continuing adverse, presented the pilot with little difficulty since he saw the sideslip as generally adverse and easy to coordinate.

In all of the cases above, except the negative effective dihedral case, the pilot was well aware of the substantial amounts of sideslip generated with an aileron input and in each case commented on the sideslip as an objectionable feature of the airplane. However, since the sideslip did not adversely affect the rolling performance or bank angle controllability and since he found the configurations quite maneuverable in spite of the sideslip, the pilot was willing to accept these evaluation configurations as marginally satisfactory assigning pilot ratings of 3.0 to 3.5. Except for the negative effective dihedral case, these configurations had a roll to sideslip ratio of $|\phi/\beta|_d \leq 1.60$. Hence, it appears that as long as $|\phi/\beta|_d$ is small enough such that sideslip has little coupling with the roll response the pilot is willing to accept more sideslip than is allowed by the MIL-F-8785B(ASG) $\Delta \beta_{MAX}/k$ criterion provided rudder coordination is relatively simple or can be neglected. Configuration 5ND also had medium $|\phi/\beta|_d$, $|\phi/\beta|_d = 2.14$. Again the pilot found little coupling of sideslip with roll response and accepted more total sideslip excursion than would be expected from the above cited criterion.

Considering those data points which fell within the Level 1 boundary but received PR > 3.5, the following tabulation furnishes the necessary identification for the convenience of the reader.

Conf.	P.R.	$\frac{N'_{\delta_{AS}}}{L'_{\delta_{AS}}}$	$\frac{\Delta \beta_{MAX}}{k}$ *	ψ_β
5A	6	-.08	4.7	-178°
5ND	6	-.06	5.7	-210°
7	4	-0.10	3.6	-193°
11	4	-0.03	5.5	-215°

Configuration 5A with $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.08$ presented the pilot with what he considered to be a difficult coordination task even though the sideslip response to an aileron input was adverse requiring coordination in the normal or natural direction. The pilot categorized the sideslip response as "very objectionable" requiring considerable pilot compensation. It is difficult to assess from the data why this point was so much more objectionable than neighboring points receiving better pilot ratings. It should be recognized that a small shift in ψ_β could place this point well into the Level 2 area of the $\Delta\beta_{MAX}/k$ requirements plane, but a recheck of the flight data showed no cause for changing ψ_β.

Configuration 5ND with $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.06$ was very objectionable to the pilot; not because of the magnitude of the adverse sideslip per se, but because of the general "out of phase feeling" of the airplane. Because of the negative effective dihedral, attempts to coordinate with the rudder reduced the attainable roll rate. The pilot felt that his aileron and rudder controls were working against each other and he had difficulty phasing his rudder inputs to his aileron inputs.

Configuration 7 with $N'_{\delta_{AS}}/L'_{\delta_{AS}} = -0.10$ was originally rated PR = 3 and repeat rated a PR = 5 resulting in a pilot rating of 4 from the faired curve of Figure 46. The primary difference in the two evaluations was the pilot's selection of rudder control sensitivity. The pilot also found the response to random disturbance inputs more objectionable during the repeat evaluation and had more objection to the amount of sideslip because he had to work harder with the lower rudder control sensitivity. Hence there is doubt as to whether this data point actually defies the $\Delta\beta_{MAX}/k$ versus ψ_β Level 1 boundary since the repeat pilot rating of 5 may be attributable to deficiencies other than sideslip excursions.

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* The parameter k was determined using Level 1 criteria.

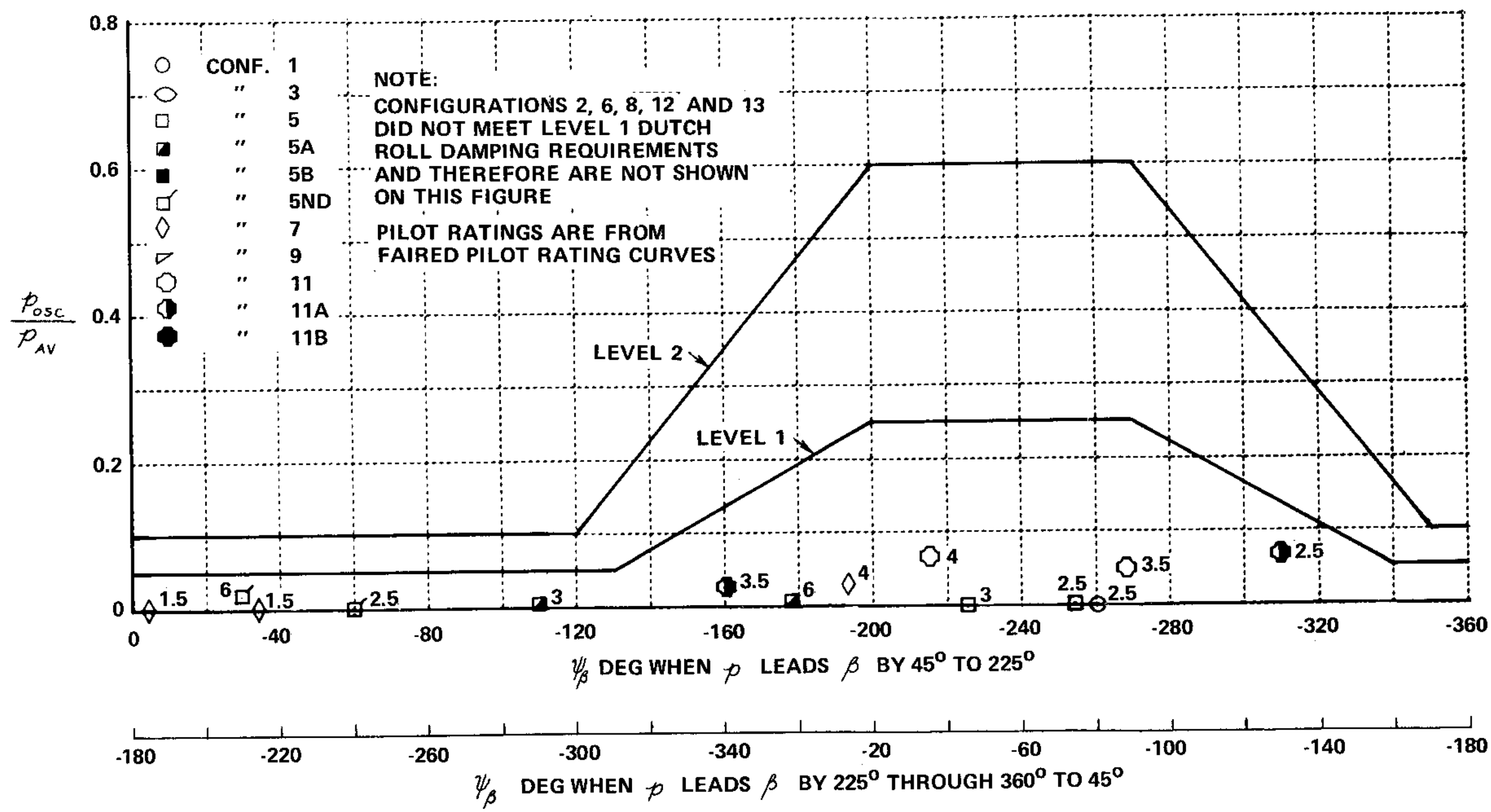

Figure 46 p_{osc}/p_{AV} Versus ψ_β For Evaluation Points Which Meet Level 1 $\Delta\beta_{MAX}/k$ Criteria

Configuration 11 with $N'_{\delta AS}/L'_{\delta AS}$ = -0.03 appeared to have a combination of minor objections which required a moderate amount of pilot compensation. The small amount of sideslip generated with an aileron input caused small roll rate oscillations. Coordination of the sideslip helped, but also led to some oscillation in bank angle. The pilot could not precisely control sideslip which contributed to bank angle control problems. The response to random disturbance inputs was found objectionable to the point that the pilot assigned a TR = D. Although the configuration met Level 1 requirements, including p_{osc}/p_{AV} and $\Delta\beta_{MAX}/k$, the pilot found the overall configuration requiring more than minimal pilot compensation.

All of the configurations which received PR > 3.5 but were Level 1 in the $\Delta\beta_{MAX}/k$ versus ψ_β requirements plane, with the exception of Configuration 5A with $N'_{\delta AS}/L'_{\delta AS}$ = -0.08, were, in all probability, assigned PR > 3.5 for reasons other than sideslip excursions or roll rate oscillations per se. However, these configurations also met all other Level 1 MIL-F-8785B(ASG) requirements. But, as a result of the pilot comments briefly summarized above, there is no evidence that these configurations lend themselves to conclusions suggesting specification revision. Configuration 5A with $N'_{\delta AS}/L'_{\delta AS}$ = -0.08 is a very marginal point that should probably be considered Level 2.

Although the data are sparse, the pilot ratings and comments for the configuration with negative effective dihedral provide evidence that the present sideslip excursion specification is inadequate to predict the flying qualities for configurations with negative effective dihedral. The negative effective dihedral configuration did not, however, satisfy the requirements of MIL-F-8785B(ASG) which specify that right bank angle shall accompany an increase in right sideslip and vice versa and that right aileron control deflection and forces shall accompany right sideslips and vice versa. Further study of this phenomenon certainly appears warranted.

Figure 46 shows the locations in the p_{osc}/p_{AV} versus ψ_β requirements plane for those data points which met the Level 1 $\Delta\beta_{MAX}/k$ requirement. All of these points were well within the Level 1 area of the p_{osc}/p_{AV} requirements plane. For the configurations evaluated, even the $|\phi/\beta|_d \approx$ 6.0 cases, roll rate oscillations were minimal or even zero when sideslip excursions approached or exceeded the allowed limits.

Figure 47 compares the data of this investigation to the Level 2 $\Delta\beta_{MAX}/k$ versus ψ_β requirements plane of MIL-F-8785B(ASG) for those data points which fail to meet Level 1 $\Delta\beta_{MAX}/k$ versus ψ_β requirements but do meet Level 2 p_{osc}/p_{AV} versus ψ_β requirements. In this case there were five points for which PR < 6.5 which fall outside the boundary. Four data points which fall inside the boundary received a pilot rating of PR > 6.5, all four of which were rated PR=7.

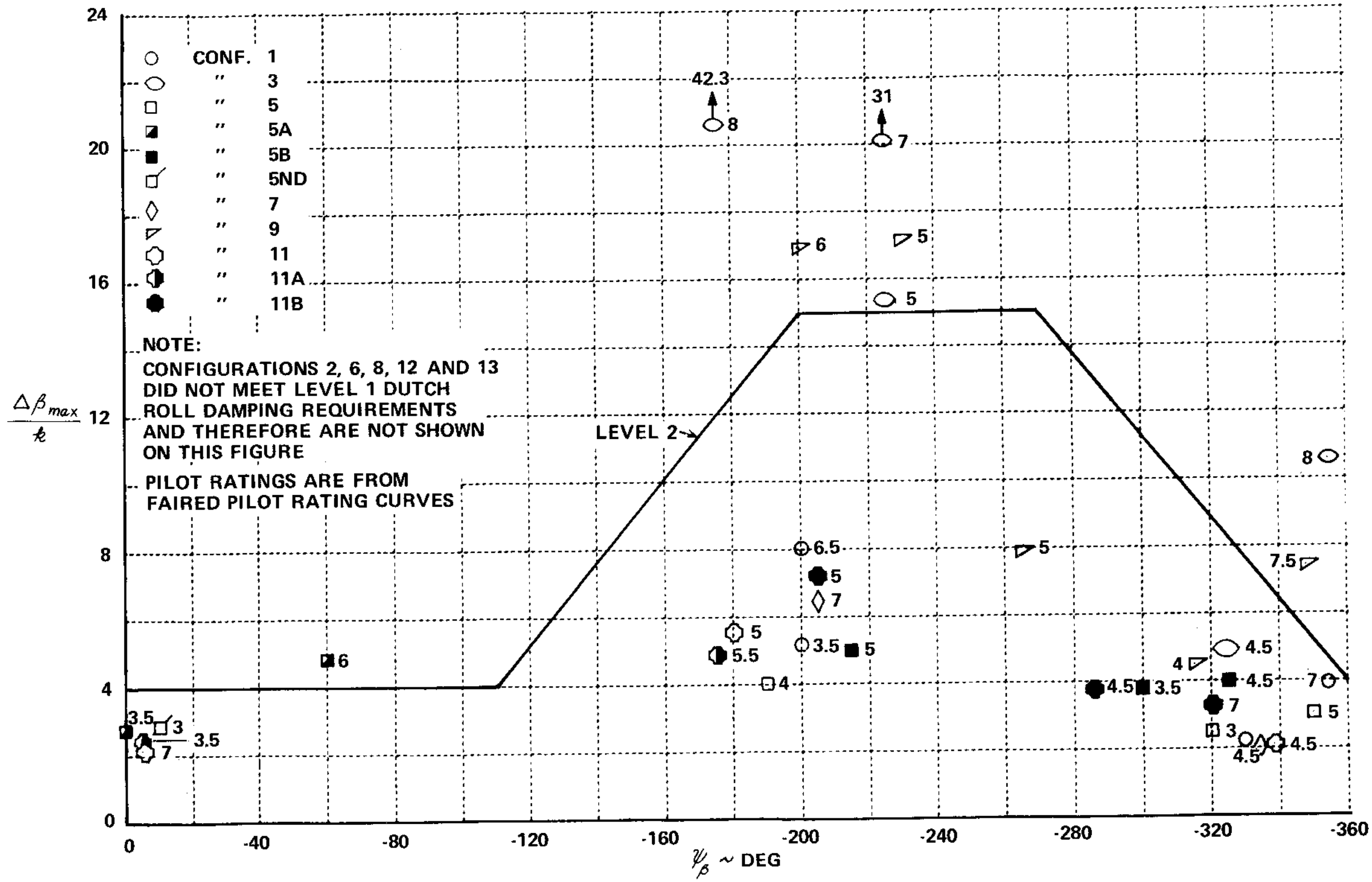

Figure 47 Level 2 $\Delta\beta_{MAX}/k$ Versus ψ_β For Evaluation Points Which Fail to Meet Level 1 $\Delta\beta_{MAX}/k$ Criteria and Which Do Meet Level 2 ρ_{osc}/ρ_{AV} Criteria

For the points rated PR < 6.5 and falling outside the boundary, a review of the pilot comments indicates that the pilot's problems with coordination and bank angle controllability were simply not as severe as would be predicted by the Level 2 $\Delta\beta_{MAX}/k$ boundary. These points will not be discussed in detail in this summary as were similar points on Figure 45.

The points which fell within the Level 2 boundary and were rated PR > 6.5, however, may deserve more scrutiny. The Configuration 7 point received a turbulence effect rating of TR = E. Though the pilot objected to the sideslip and the coordination difficulties at the high Dutch roll frequency, the response to random disturbances further degraded the overall pilot rating. The Configuration 1 point is very close to the boundary so PR = 7 is really acceptable as far as fitting the requirements plane is concerned. Furthermore, the pilot objected mainly to coordination difficulties and bank angle oscillations and not sideslip per se. He discussed at some length whether to rate the airplane a 6, 6.5 or 7.

For the Configuration 11B point, the pilot objected mainly to poor bank angle controllability, especially during the bank angle tracking task even though the configuration met Level 2 $\varphi_{osc}/\varphi_{AV}$ requirements as well as Level 2 $\Delta\beta_{MAX}/k$ requirements. There was a tendency during the tracking task for the pilot to induce bank angle oscillations. Perhaps being Level 2 on two counts degrades the pilot rating to Level 3. The Configuration 11 point fits the description given above for the Configuration 11B point with the pilot encountering the same difficulties.

Therefore, the PR $\geq$ 6.5 for two of the above cases is either due to a cause other than sideslip excursion, e.g., response to random disturbance, or a very marginal configuration relative to the Level 2 boundary. The other two points represent cases of the configurations being Level 2 in more than one respect. This situation has not been studied and may indicate that a greater than Level 2 pilot rating is warranted. Also, all four of the test points under discussion were rated only one half pilot rating higher than Level 2 which is within the degree of pilot rating variability normally expected.

In consideration of all the anomalous points on Figure 47, and based primarily on the five points rated PR < 6.5 and failing Level 2, it appears that the Level 2 $\Delta\beta_{MAX}/k$ versus ψ_β requirement of MIL-F-8785B(ASG) is too conservative. It should be noted, Figures 17 and 27, that the five points falling outside the Level 2 $\Delta\beta_{MAX}/k$ boundary and rated PR < 6.5 were all within the Level 1 $\varphi_{osc}/\varphi_{AV}$ versus ψ_β boundary.

Figure 48 shows the location in the $\varphi_{osc}/\varphi_{AV}$ versus ψ_β requirements plane of MIL-F-8785B(ASG) for data points which met Level 2 $\Delta\beta_{MAX}/k$ versus ψ_β requirements but not Level 1. Five of the points which met Level 2 $\Delta\beta_{MAX}/k$ versus ψ_β did not meet Level 1 $\varphi_{osc}/\varphi_{AV}$ versus ψ_β requirements. Two of these points, Configurations 11 and 11B with PR = 7, have been discussed above. The other three points which were Level 2 in both $\varphi_{osc}/\varphi_{AV}$ and $\Delta\beta_{MAX}/k$ were Configuration 11 with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ = -0.06

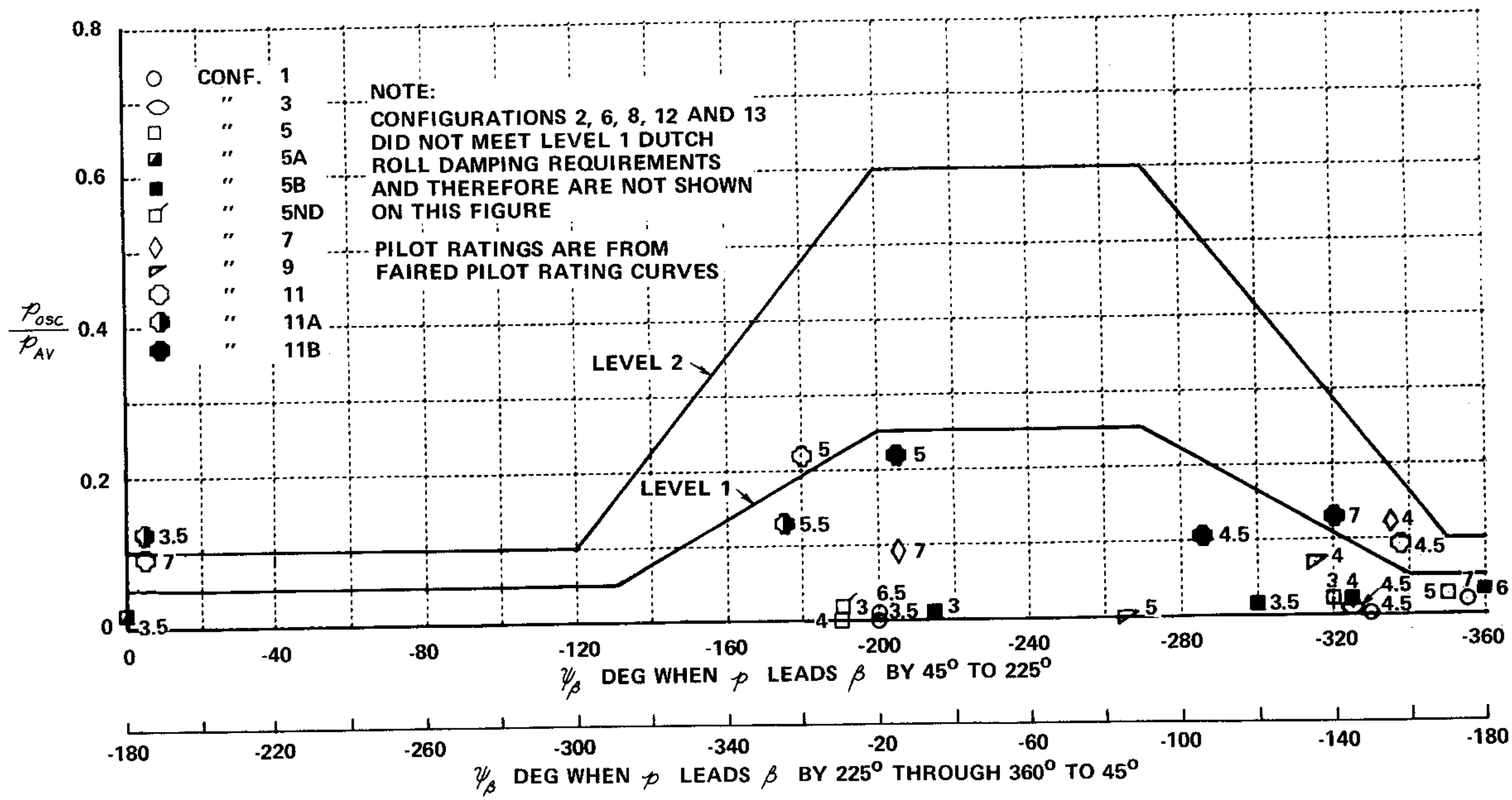

Figure 48 p_{osc}/p_{AV} Versus ψ_β For Evaluation Points Which Meet Level 2 $\Delta\beta_{MAX}/k$ Criteria But Fail to Meet Level 1 $\Delta\beta_{MAX}/k$ Criteria and +0.03, with pilot ratings of 5 and 4.5 respectively and Configuration 11A with $N'_{\delta_{AS}}/L'_{\delta_{AS}} = +0.03$. Even though the two Configuration 11 points were Level 2 in ρ_{osc}/ρ_{AV} the pilot had little difficulty with roll rate oscillations or bank angle control. His problems were primarily concerned with sideslip and rudder coordination. So, although these two evaluation configurations were technically Level 2 for two reasons, the pilot objected only to the sideslip difficulties and expressed in both cases that the roll response and heading control were good.

The Configuration 11A data point at ψ_β = -5 degrees and PR = 3.5 was Level 2 in both the $\Delta\beta_{MAX}/k$ and ρ_{osc}/ρ_{AV} requirements planes. The pilot's major objections were a tendency to overcontrol bank angle and the proverse sideslip which he found difficult to coordinate. However, he found the rolling maneuverability quite good and stated that the sideslip was not excessive and sideslip oscillations damped quite rapidly. Hence this point rather defies the requirements boundaries with the marginal pilot rating of PR = 3.5, but also lends some further credence to the apparent conservative nature of the $\Delta\beta_{MAX}/k$ criteria.

As may have been noted in the above discussions, evaluation configurations which satisfied Level 1 $\Delta\beta_{MAX}/k$ versus ψ_β requirements were generally well below the Level 1 ρ_{osc}/ρ_{AV} versus ψ_β boundary. Likewise evaluation configurations which satisfied Level 2 $\Delta\beta_{MAX}/k$ versus ψ_β requirements were well below the Level 2 ρ_{osc}/ρ_{AV} versus ψ_β boundary and were frequently even Level 1 in the ρ_{osc}/ρ_{AV} requirements plane. From the pilot comments it is evident, for the configurations evaluated in this investigation, that the pilot was usually more concerned with sideslip excursions than he was with roll rate oscillations. Hence, for values of $|\phi/\beta|_d \leq 6$, it appears the sideslip excursion requirements are such that, if complied with, roll rate oscillations will not be a problem to the pilot, It is likely therefore, that if a particular configuration fails to meet Level 1 ρ_{osc}/ρ_{AV} requirements, it will also generally fail to meet Level 1 $\Delta\beta_{MAX}/k$ requirements. The inverse however, is not true. To adequately evaluate the ρ_{osc}/ρ_{AV} versus ψ_β requirements plane, values of $|\phi/\beta|_d$ greater than those evaluated in this program would have to be investigated. Hence, the results of this program do not attest to the proper location of the ρ_{osc}/ρ_{AV} Levels 1 and 2 boundaries.

Figure 49 compares those data points of this investigation which met Level 1 ρ_{osc}/ρ_{AV} requirements of MIL-F-8785B(ASG), and also, therefore the Level 1 ϕ_{osc}/ϕ_{AV} versus ψ_β requirements of MIL-F-83300, with the $|\Delta\beta/\phi_1| \times |\phi/\beta|_d$ versus ψ_β requirements of MIL-F-83300. This requirement was not very discriminanting for the data of this experiment and therefore was not presented, in detail, in Section VI "Discussion of Results". All of the moderate and low $|\phi/\beta|_d$ configurations were within the Level 1 area of the $|\Delta\beta/\phi_1| \times |\phi/\beta|_d$ requirements plane regardless of pilot rating with the exception of one point for Configuration 7 which was rated PR = 7. Five points for the high $|\phi/\beta|_d$ configurations were above the boundary all of which received a pilot rating of PR > 3.5. The data is not shown in the $|\Delta\beta/\phi_1|$ versus ψ_β requirement plane of MIL-F-83300 since all of it was well within the Level 1 area. Therefore, at least for the data of this investigation, the

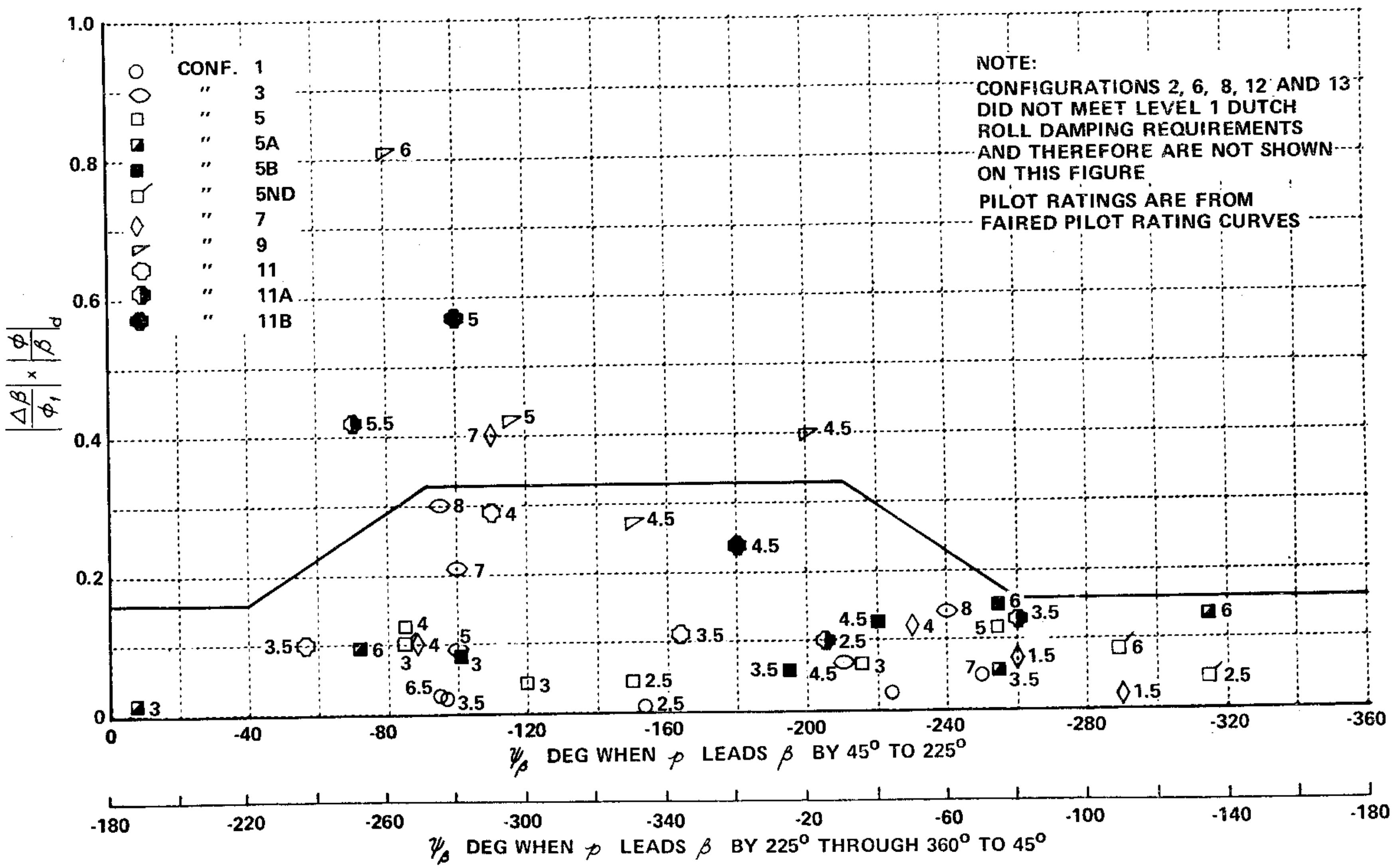

Figure 49 $|\Delta\beta/\phi_1| \times |\phi/\beta|_d$ Versus ψ_β For Evaluation Points Which Meet Level 1 p_{osc}/p_{AV} (or ϕ_{osc}/ϕ_{AV}) Criteria roll-sideslip coupling requirements of MIL-F-83300 are not applicable to high speed Class IV airplanes in Flight Phase Category A.

The areas of Level 1 and Level 2 flying qualities are shown partially mapped into the s plane in terms of the $\phi(s)/\delta_{AS}(s)$ transfer function in Figures 50 and 51. Because of the design of this experiment it was only possible in most cases to show pilot iso-opinion boundaries in terms of PR = 3.5 and PR = 6.5 in a very limited area of the s plane, i.e., along a single line of zeroes of the $\phi(s)/\delta_{AS}(s)$ transfer function. For the families of Configuration 5 and 11 a wider area is shown since three values of N'_p were investigated in these cases. Comparison of the s plane plots of Figure 50 for Configurations 3, 5 and 7 shows how the Levels 1 and 2 areas of flying qualities increase with increasing Dutch roll frequency at a $|\phi/\beta|_d \approx 1.5$. The data shown have been taken from the faired pilot rating curves of Section IV.

For $\omega_d \approx 1.0$ rad/sec (Configuration 3 with $\omega_d = 1.18$ rad/sec on Figure 50) the Level 1 area is nonexistent : but it must be remembered that these configurations did not meet Level 1 sideslip excursion requirements. The Level 2 area is indeed small when compared to the $\omega_d \approx 2.5$ and $\omega_d \approx 4.5$ cases.

Comparing the plots for Configurations 7 and 6 indicates the change in s plane area for different Dutch roll damping ratios. Configuration 6 with $\zeta_d = 0.10$ was rated Level 1 only when the zero of the $\phi(s)/\delta_{AS}(s)$ transfer function was nearly on the Dutch roll pole while Configuration 7 with $\zeta_d = 0.23$ was Level 1 over a relatively wide range of $\phi(s)/\delta_{AS}(s)$ transfer function zero locations. The Level 2 area in the s plane also changed commensurately with changes in ζ_d .

Figure 51 shows the Levels 1 and 2 areas for $|\phi/\beta|_d \approx 6$ and $\omega_d \approx 2.5$. Comparison with the Configurations 5 on Figure 50 shows that the high $|\phi/\beta|_d$ expands the Level 1 s plane area considerably, however, it should be recalled that the range of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ is much smaller for the high $|\phi/\beta|_d$ cases since the distance of the $\phi(s)/\delta_{AS}(s)$ transfer function zero from the Dutch roll pole is scaled by L'_β .

From this summary of data in the s plane of the $\phi(s)/\delta_{AS}(s)$ transfer function it is seen that the s plane area of Level 1 and Level 2 flying qualities is a function of at least Dutch roll frequency, Dutch roll damping and roll to sideslip ratio in the Dutch roll. These results agree with those of Reference 2 and the rationale of Reference 3. It must be noted that the primary pilot objections to the configurations evaluated in this investigation were, however, sideslip excursions or the response to random disturbance inputs. Therefore the iso-opinion boundaries shown in the s plane plots of the $\phi(s)/\delta_{AS}(s)$ transfer function do not reflect limiting values of the parameters p_{osc}/p_{AV} or ϕ_{osc}/ϕ_{AV}.

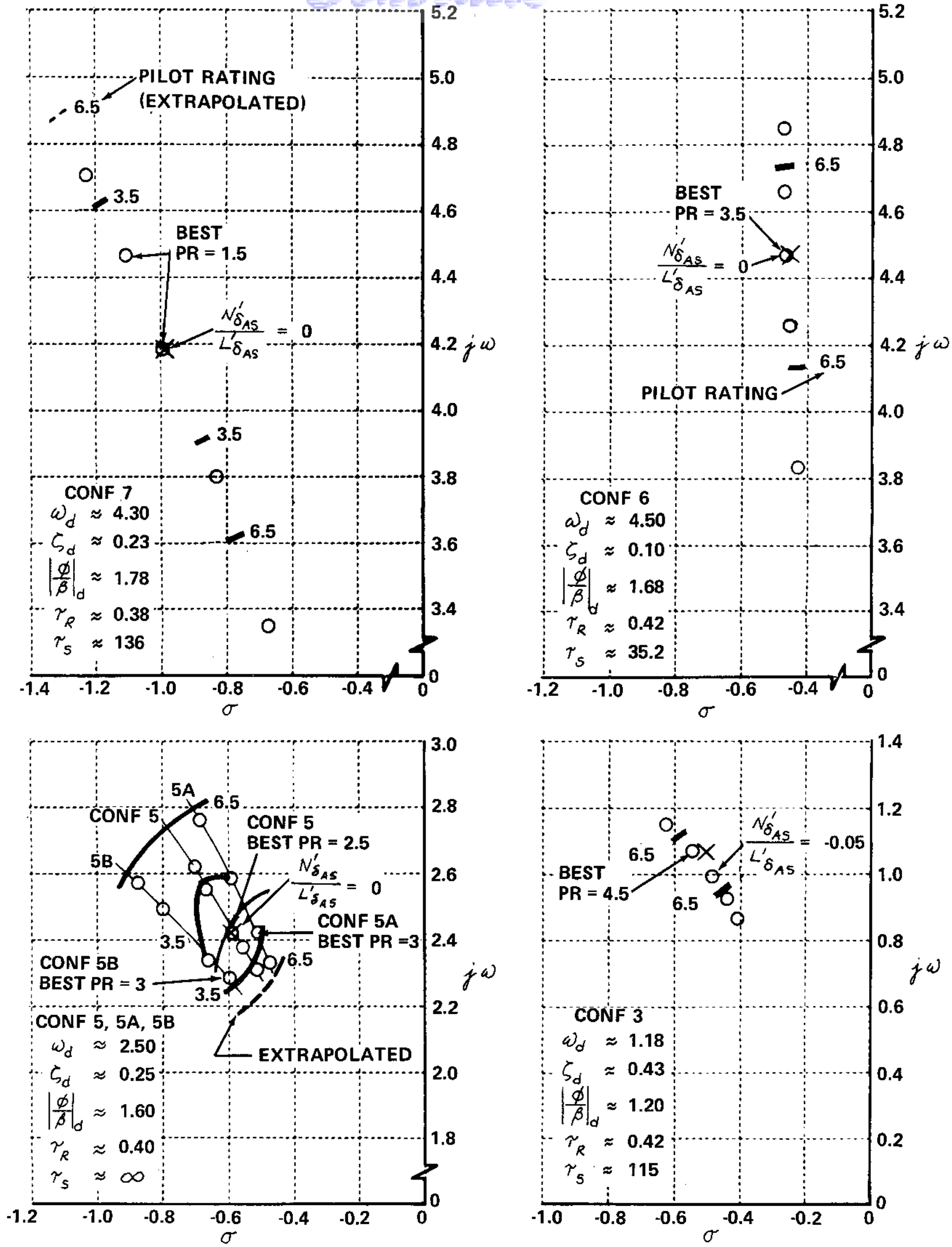

Figure 50 Pilot Rating Boundaries for $\phi(s)/\delta'_{AS}(s)$ Transfer Function Zeros for Class IV Airplanes in Flight Phase Category A With Medium $|\phi/\beta|_d$

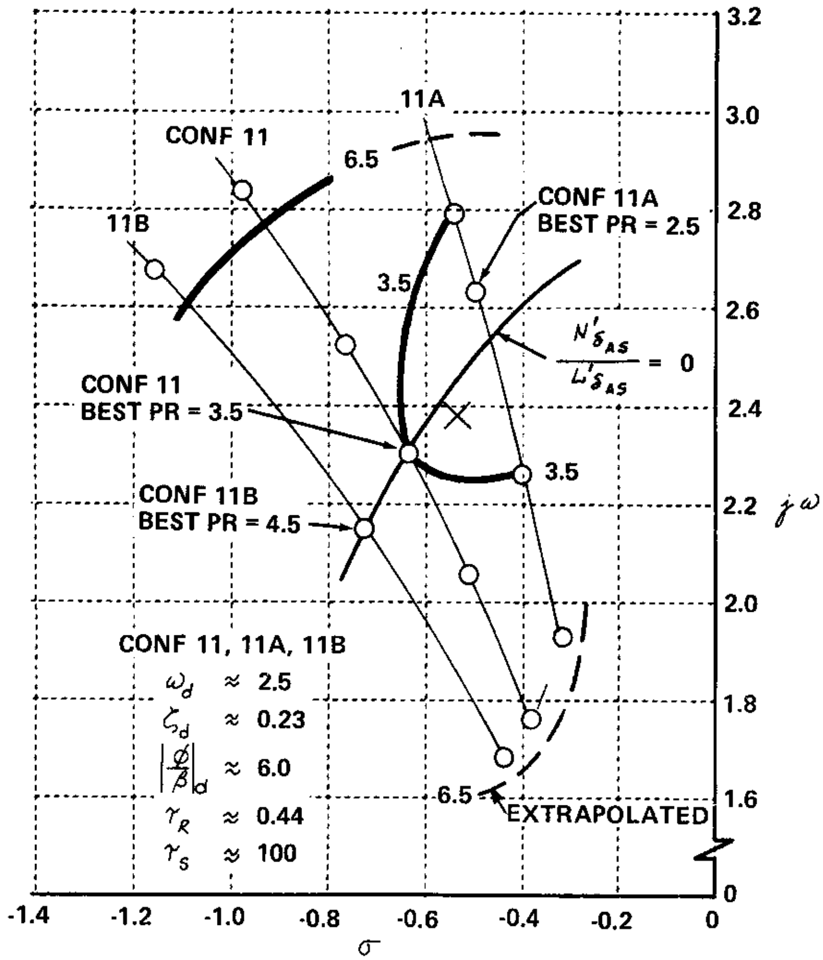

Figure 51 Pilot Rating Boundaries for $\phi(s)/\delta_{AS}(s)$ Transfer Function Zeros for Class IV Airplanes in Flight Phase Category A With High $|\phi/\beta|_d$

SECTION VI

CONCLUSIONS

An investigation to extend the data base for roll-sideslip coupling requirements specified by MIL-F-8785B(ASG) for Class IV airplanes in Flight Phase Category A was conducted in the USAF/CAL variable stability NT-33A airplane. The investigation also included an evaluation of minimum Dutch roll frequency and damping requirements and the applicability of roll-sideslip coupling requirements of MIL-F-83300 to Class IV airplanes in Flight Phase Category A. Conclusions resulting from this investigation were as follows:

1. Satisfactory flying qualities were not obtained for any of the low Dutch roll frequency ($\omega_d \approx 1.0$ rad/sec) configurations investigated in this experiment. This result was primarily due to the sideslip excursions during lateral maneuvering. Higher Dutch roll frequency is effective in reducing the sideslip excursions during lateral maneuvering.

2. Dutch roll damping ratio of $\zeta_d \approx 0.19$ is adequate provided the parameter $\omega_d^2 \, |\phi/\beta|_d$ is small.

3. The specification of additional Dutch roll damping as a function of $\omega_d^2 \, |\phi/\beta|_d$ was found to correlate with pilot ratings obtained in this investigation and therefore appears to be an effective quantitative requirement to limit response to atmospheric turbulence.

4. At moderate to low roll to sideslip ratios, $|\phi/\beta|_d < 1.6$, the results of this investigation indicate that the pilot is willing to tolerate larger sideslip excursions than are allowed by the Level 1 $\Delta\beta_{MAX}/k$ MIL-F-8785B(ASG) criteria provided rudder coordination is relatively simple or can be neglected.

5. Further study is necessary to determine the applicability of MIL-F-8785B(ASG) sideslip excursion requirements to configurations with negative effective dihedral or to determine if a separate specification is desirable for these conditions.

6. The Level 2 $\Delta\beta_{MAX}/k$ versus ψ_β requirement appears to be too conservative, especially in the range of $\psi_\beta = -200°$ to $\psi_\beta = -270°$.

7. The roll-sideslip coupling requirements of MIL-F-83300 are not applicable to high speed Class IV airplanes in Flight Phase Category A.

8. The combination of high Dutch roll frequency, $\omega_d \approx 4.5$ rad/sec, high roll to sideslip ratio, $|\phi/\beta|_d \doteq 5.0$ and low to moderate Dutch roll damping, $\zeta_d \leq 0.25$, was found to be unsatisfactory in the presence of atmospheric turbulence.

9. The combination of high Dutch roll frequency, $\omega_d \approx 4.5$ rad/sec, medium roll to sideslip ratio, $|\phi/\beta|_d \approx 1.5$, and low Dutch roll damping ratio, $\zeta_d \approx 0.10$, was found to be unsatisfactory in the presence of atmospheric turbulence.

10. For $|\phi/\beta|_d \leq 6.0$, sideslip excursions appear to be the more important roll-sideslip coupling parameter rather than roll rate oscillations. In this investigation most configurations which met $\Delta\beta_{MAX}/k$ versus ψ_β requirements easily met p_{osc}/p_{AV} versus ψ_β requirements also. The inverse, however, was not true.

11. Some configurations of this investigation which were Level 2 in more than one respect, for example in both $\Delta\beta_{MAX}/k$ and p_{osc}/p_{AV}, received Level 3 pilot ratings in this experiment. Further study is necessary to determine the effects of an airplane being Level 2 for more than one reason and Specification requirements should be established to take this factor into account.

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Lateral-directional handling qualities for Class IV airplanes in Flight Phase Category A were investigated in the USAF/CAL variable stability NT-33A airplane. The primary purpose was to extend the data base for roll-sideslip coupling requirements specified by MIL-F-8785B(ASG) for this Class of airplanes. Other purposes included evaluation of the minimum Dutch roll frequency and damping requirements of MIL-F-8785B (ASG) for Class IV airplanes in Flight Phase Category A and an investigation of the applicability of MIL-F-83300 roll-sideslip requirements to airplanes in high speed flight conditions. Maneuvering tasks representative of the fighter mission and a precision bank angle tracking task were performed for evaluations. Evaluations were conducted at three Dutch roll frequencies, three roll-to-sideslip ratios and at values of Dutch roll damping on either side of the MIL-F-8785B(ASG) boundary. Satisfactory flying qualities were not obtained for any of the low Dutch roll frequency ($\omega_d \approx$ 1.0 rad/sec) configurations investigated in this experiment. The Dutch roll damping requirements were found to be adequate, especially when the additional increment of damping as a function of Dutch roll frequency and roll-to-sideslip ratio is added. The roll-sideslip coupling requirements in terms of sideslip excursions were found to be conservative, especially at low to moderate values of roll-to-sideslip ratio. For the configurations evaluated, roll rate oscillations were quite small, even when sideslip excursions exceeded the specified limits, therefore the validity of the roll rate oscillations criteria boundaries was not sufficiently evaluated. The roll-sideslip coupling requirements of MIL-F-83300 were found to be generally not applicable to Class IV airplanes in Flight Phase Category A and high speed flight. Volume I of this report contains the body of the text; Volume II contains the appendices.

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Variable Stability NT-33A						
Lateral-Directional Study						
In-Flight Investigation						
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