Handling Quality Criterion for Heading Control

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A heading control criterion based on the aileron-rudder sequencing required to achieve coordinated turns is presented. Quantification of the aileron-rudder shaping is obtained by consideration of the ideal crossfeed which completely eliminates sideslip induced by aileron inputs. The shaping and gain parameters based on this ideal crossfeed are defined and correlated with pilot opinion ratings. Excellent correlation is obtained with data from simulation of STOL, fighter aircraft, and space shuttle vehicles.

Nomenclature

g	= acceleration due to gravity
L	= aerodynamic roll moment divided by roll moment of inertia
L_λ	$= \partial L/\partial\lambda$ where $\lambda = \delta_w$, ϕ, or β
L'_λ	$= [L_\lambda + (I_{xz}/I_x)N_\lambda]/[1-(I_{xz}^2/I_xI_z)]$
N	= aerodynamic yawing moment divided by yaw moment of inertia
N_λ	$= \partial N/\partial\lambda$ where $\lambda = \delta_w$, δ_r, β, r, or p
N'_λ	$= [N_\lambda + (I_{xz}/I_z)L_\lambda]/[1-(I_{xz}^2/I_xI_z)]$
N_δ^λ	= numerator of λ/δ transfer function
p	= roll rate
r	= yaw rate
s	= Laplace operator
U_0	= steady-state velocity
Y_{CF}	= aileron-to-rudder crossfeed function
Y_{δ_a}	$= \partial Y/\partial\delta_a$
β	= sideslip angle
$\Delta_{\beta_{max}}$	= maximum sideslip excursion at the c.g. occuring within two seconds or one-half period of the dutch roll, whichever is greater, for a step aileron control command[2]
Δ	= characteristic determinant-denominator for transfer functions
δ_r	= rudder pedal deflection at the cockpit
$\delta_{r(3)}$	= rudder pedal deflection 3 seconds after a unit step lateral wheel input
δ_w	= lateral wheel (or stick) deflection at the cockpit
ζ_d	= dutch roll damping
μ	= crossfeed shaping parameter
ϕ	= bank angle
$\lvert\phi/\beta\rvert_d$	= roll/sideslip ratio in the dutch roll mode
ϕ_{osc}/ϕ_{ave}	= 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[2]
ψ_β	= phase angle expressed as a lag for a cosine representation of the dutch roll oscillation in sideslip[2]
ω_d	= dutch roll frequency

Introduction

THE ability to make precise changes in aircraft heading is a key factor in pilot evaluation of lateral-directional handling qualities. Assuming other good qualities (e.g., adequate roll response, yaw frequency/damping, etc., per Ref. 2), deficiencies in heading control, which can nevertheless exist, are directly traceable to excitation of the dutch roll mode due to roll-yaw crosscoupling effects. It is commonly accepted piloting technique to reduce these excursions by appropriate use of the aileron and rudder, usually referred to as "coordinating the turn." The problem is that existing criteria (see, for instance, Refs. 1-4) for heading control are based on aileron-only parameters, and the effects of rudder control are only indirectly apparent as they may have influenced individual pilot ratings. The fact that these criteria are not satisfactory is shown in Ref. 5, where several configurations which violated boundaries based on aileron-only parameters were given good to excellent pilot ratings. The approach taken here is that for an otherwise acceptable airplane the aileron-rudder shaping necessary to coordinate the turn is a dominant factor in pilot evaluation of heading control.

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‡References 1-4 discuss other measures previously considered.

Approach

A comprehensive review of pilot commentary made during the heading control experiments reported in Refs. 5 and 6 indicated that the rudder characteristics necessary to coordinate turns played a dominant role in the evaluations. While the use of "coordinated" aileron and rudder is accepted as common piloting technique, a quantitative measure of what exactly is acceptable or desirable is not known. The purpose of this study was to provide a quantitative measure of coordinating activity and to correlate this with pilot opinion ratings from available data. We utilized the idealized aileron-to-rudder crossfeed necessary to obtain perfectly coordinated turns as a measure‡ of heading control acceptability because it is indicative of: 1) The complexity of the rudder activity necessary to achieve perfectly coordinated turns; 2) The heading excursions that occur when the pilot does not use rudder.

Analysis and Basic Concept

In general, coordinated flight implies min. yaw coupling due to roll entries and exits which can be quantified in many ways, e.g.: 1) zero sideslip angle ($\beta=0$); 2) zero lateral acceleration at the c.g.; 3) turn rate consistent with bank angle and speed ($r = g\phi/U_0$); and 4) zero lateral acceleration at the cockpit (ball in the middle).

Conditions 1-3 are equivalent when the side force due to aileron, Y_{δ_a}, is very small, which is usually the case. The fourth turn coordination criterion is complicated by pilot location effects which, however, appear to be mainly associated with ride qualities and not with heading control itself.[5] Based on these considerations it appears that sideslip angle is an appropriate indicator of turn coordination. Accordingly, the following formulation undertakes to identify the parameters that govern the aileron-rudder shaping required to maintain coordinated flight as defined by zero sideslip angle ($\beta=0$).

With an aileron-rudder crossfeed, Y_{CF}, the rudder, by definition, is given by

$$\delta_r \equiv Y_{CF}\delta_w \tag{1}$$

For the assumed ideal (zero sideslip) coordination

$$\beta=\left(\frac{N^{\beta}_{\delta_w}}{\Delta}+Y_{CF}\frac{N^{\beta}_{\delta_r}}{\Delta}\right)\delta_w\equiv 0$$

whereby the ideal crossfeed is

$$Y_{CF}\equiv\frac{\delta_r}{\delta_w}=-\frac{N^{\beta}_{\delta_w}}{N^{\beta}_{\delta_r}} \qquad (2)$$

The Ref. 7 approximations to these numerators yield

$$Y_{CF}=\frac{N'_{\delta_w}[(s+A_w(g/U_0)][(s+(1/T_{\beta_w})]}{Y^*_{\delta_r}[s+A_r(g/U_0)][s+(1/T_{\beta_r})][s-(N'_{\delta_r}/Y^*_{\delta_r})} \qquad (3)$$

where

$$A_i=\frac{L'_r-(L'_{\delta_i}/N'_{\delta_i})N'_r}{L'_p-(L'_{\delta_i}/N'_{\delta_i})[N'_p-(g/U_0)]} \qquad i=w \text{ or } r$$

$$\frac{1}{T_{\beta_i}}=-L'_p+(L'_{\delta_i}/N'_{\delta_i})[N'_p-(g/U_0)]$$

For the frequency range of interest, i.e., excluding both low and high frequencies $[A_i(g/U_0)<<s<<N'_{\delta_a}/Y^*_{\delta_r}]$

$$Y_{CF}\doteq-\frac{N'_{\delta_w}[s+(1/T_{\beta_w})]}{N'_{\delta_r}(s+(1/T_{\beta_r})]} \qquad (4)$$

To provide a meaningful reference for the control crosscoupling term, N'_{δ_w}, in Eq. (4), it is expressed as the ratio of yawing to rolling acceleration, $N'_{\delta_w}/L'_{\delta_w}$. Also, since the rudder sensitivity can be separately optimized and does not usually represent a basic airframe limitation, it is appropriate to remove it from consideration. Accordingly, the resulting modified crossfeed, Y'_{CF}, is given as

$$Y'_{CF}\equiv Y_{CF}\frac{N'_{\delta_r}}{L'_{\delta_w}}=-\frac{N'_{\delta_r}}{L'_{\delta_w}}\frac{N^{\beta}_{\delta_w}}{N^{\beta}_{\delta_r}}\doteq-\frac{N'_{\delta_w}[s+(1/T_{\beta_w})]}{L'_{\delta_w}[s+(1/T_{\beta_r})]} \qquad (5)$$

Equation (5) indicates that the aileron-to-rudder shaping required to maintain coordinated flight ($\beta=0$) is directly related to the separation between the aileron (wheel or stick) and rudder (pedal) sideslip zeros. Using the above approximations for $1/T_{\beta_w}$ and $1/T_{\beta_r}$, the separation between these zeros is a function of the control crosscoupling and the roll rate coupling as follows.

$$\frac{1}{T_{\beta_w}}-\frac{1}{T_{\beta_r}}\doteq\left(\frac{L'_{\delta_w}}{N'_{\delta_w}}-\frac{L'_{\delta_r}}{N'_{\delta_r}}\right)\left(N'_p-\frac{g}{U_0}\right)^{\S} \qquad (6)$$

Control Crosscoupling Terms — Roll Coupling Term

Equation (6) merely serves to confirm that the pilot's rudder coordination requirements are directly related to the crosscoupling derivatives.

As a basis for direct correlation with pilot opinion, a "rudder shaping parameter," μ, is defined in "theoretical" form as

$$\mu=(T_{\beta_r}/T_{\beta_w})-1 \qquad (7)$$

The frequency response characteristics of Y'_{CF}, Eq. (5), as a function of the sign of μ are shown in Fig. 1 in terms of literal expressions for the Bode asymptotes. These asymptotes indicate that the *magnitude* of the coordinating rudder is a function of $N'_{\delta_w}/L'_{\delta_w}$ at all frequencies and that the shaping of the rudder response is determined by μ. These parameters are summarized in terms of their analytical and pilot-centered functions in Table 1.

§As noted earlier, all derivatives are in the stability axis system.

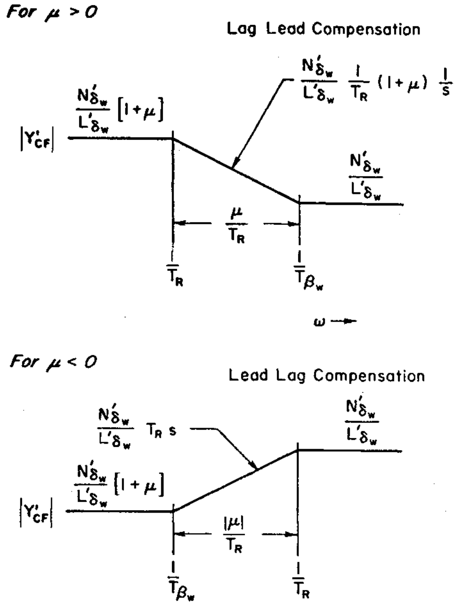

Fig. 1 Asymptotes of aileron-rudder crossfeed.

Practical Considerations

The parameters $N'_{\delta_w}/L'_{\delta_w}$ and μ are a natural choice for correlation of heading control pilot rating data since they completely define the aileron-to-rudder crossfeed necessary for turn coordination. Such ideal crossfeed is difficult to isolate with simple flight test procedures, but is nevertheless considered a viable correlation concept because of modern usage[2] which permits simulation and analysis methods to demonstrate specification compliance. Computation of μ is straightforward as long as the β numerators in Eq. (2) are well behaved, i.e., are well represented by the approximation of Eq. (5). When they are not, a more general time response definition of μ is used which derives from the Eq. (5) form as follows.

Assuming a unity high frequency gain for the Eq. (5) form, and the ideal definition of μ [Eq. (7)], the rudder time history required to coordinate a unit step wheel or stick input is

$$\delta_r(t)=1+\mu(1-e^{-t/T_{\beta_r}}) \qquad (8)$$

Note that $\delta_r(t)$ refers to the rudder *pedal* motion (thereby including effects of rudder gearing and accounting for the SAS). Solving Eq. (8) for the rudder shaping parameter, μ

$$\mu=\frac{\delta_r(t)-1}{1-e^{-t/T_{\beta_r}}} \qquad (9)$$

Table 1 Parameters defining the aileron-rudder crossfeed

Parameter	Analytical function	Pilot-centered function
μ	defines shape of Y'_{CF}	determines complexity of rudder activity necessary for ideally-coordinated turns. Also defines phasing of heading response when rudder is not used
$N'_{\delta_w}/L'_{\delta_w}$	defines magnitude of Y'_{CF}	determines magnitude of rudder required and/or high-frequency yawing induced by aileron inputs.

When the β numerators are of the Eq. (5) form, the value of μ computed from time histories is independent of (large values of) the final time chosen and equivalent to that obtained from the Bode asymptotes of the first-order model in Fig. 1. However, for cases where the β numerators are not well approximated by the first-order model, the value of μ depends on the value of t used, which is properly set by the lower limit on the frequency range of interest for piloted heading control. The simulation experiments of Ref. 11 indicated that a minimum heading crossover of about 1/3 rad/sec was necessary for desirable handling qualities. Therefore a corresponding time of 3 sec was selected as being most pertinent to a pilot-centered characterization of crossfeed properties. Recognizing further [Eq. (3)] that $T_{\beta_r} \doteq -1/L'_p$ is approximately equal to the roll mode time constant, T_R, and that the latter must generally be less than 1.0 to 1.4 sec. for acceptable roll control[2] sets the following limits on the exponential in Eq. (9).

$$T_R \leq 1.0^{\P} \qquad e^{-3/T_R} \leq 0.049$$

$$\leq 1.4^{**} \qquad \leq 0.117$$

Accordingly, Eq. (9) reduces within a maximum error of 5-10%, depending on airplane class, to

$$\mu \doteq \delta_r(3) - 1 \tag{10}$$

This simple relationship was used to compute μ for the pilot rating correlations later shown.

However, before this simple formula can be applied it is necessary to avoid the high frequency responses which occur due to pairs of roots which frequently occur with complex SAS installations having associated higher order β numerators. For example, a simple washed out yaw rate feedback and a first-order lagged aileron rudder crossfeed results in seventh-order β numerators. High frequency pairs can also occur in the β numerators of unaugmented airplanes. Most of the zeros of these polynomials occur at very high frequency, having negligible effect on the dynamics near the pilot's crossover frequency. Therefore, the standard procedure utilized to compute the values of μ was to eliminate all roots of the β numerators above values of 6 rad/sec in pairs, i.e., keeping their order relative to each other the same (e.g., a third over fourth would be reduced to a second over third order, etc.). Roots above 6 rad/sec which do not occur in pairs are left unmodified.

The following example illustrates a typical computation of μ and the effect of removing the high frequency roots from Eq. (2). The aileron-rudder crossfeed for one of the Ref. 6 configurations used in the pilot rating correlations is given as

$$\frac{\delta_r}{\delta_w} = \frac{.19(s-.102)(s-.922)(s+605.2)}{(s-.057)(s+5.6)(s+109.9)} \tag{11}$$

As discussed above, all roots above 6 rad/sec are removed in pairs and the high-frequency gain is set to unity, resulting in the following equation

$$\frac{\delta_r}{\delta_w} = \frac{(s+.102)(s-.922)}{(s-.057)(s+5.6} \tag{12}$$

The rudder time responses to a unit wheel input for Eqs. (11) and (12) are plotted in Fig. 2. Equation (12) is plotted with a non-unity high frequency gain (1.046) to allow direct comparisons of shape with Eq. (11). Removal of the high frequency roots is seen to replace the initial rapid rudder reversal with a unity initial condition. These responses are essentially equivalent to the pilot who sees the necessity to use immediate rudder with aileron inputs (which must be removed 1/2 sec later). The value of μ corresponding to this response is $\delta_r(3) - 1 = -1.17$

¶For small, light, or highly maneuverable airplanes.

**For medium to heavy weight, low to medium maneuverability airplanes.

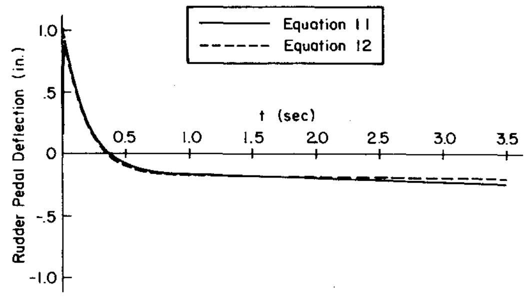

Fig. 2 Effect of removing high-frequency roots from β numerators.

Further Physical Interpretation

Figure 3 presents typical coordinating ($\beta = 0$) rudder time histories for step aileron inputs on a grid of μ vs. $N'_{\delta_w}/L'_{\delta_w}$. Moving vertically on this grid changes the shape (μ) of the crossfeed, Y_{CF}, keeping the initial value (high frequency gain) constant. Moving horizontally produces a change in the crossfeed gain ($N'_{\delta_w}/L'_{\delta_w}$) at all frequencies without changing the shape. Note that this is consistent with Table 1 and Fig. 1, where it is shown that μ dictates the required aileron-to-rudder shaping and N'_{δ_w} defines the magnitude of the gain for all times (and frequencies). The basic shapes of the time histories in Fig. 3 are indicative of the fundamental assumption that the rudder time history can be fit by the Eq. (5) form. The basic implication of this form is that the rudder response is essentially monotonic in the frequency range of interest.

For augmented airplanes the effective values of $N'_{\delta_w}/L'_{\delta_w}$ (which represent the high frequency yawing and rolling accelerations) are taken as the high frequency gain of the simplified β/δ_w and ϕ/δ_w transfer functions, e.g., all roots above 6.0 rad/sec are taken as equivalent gains. In effect this defines N'_{δ_w} and L'_{δ_w} as the yawing and rolling accelerations due to a wheel (or stick) input at frequencies above 6.0 rad/sec. A physical interpretation relating the crosscoupling derivatives N'_{δ_w} and N'_p with the rudder shaping parameter, μ, is given in Table 2.

Known values of $N'_{\delta_w}/L'_{\delta_w}$ and μ define a unique aileron-to-rudder coordination time history as discussed above, so it is possible to establish how (or if) pilot rating of heading control is dominated by such coordination requirements by plotting applicable pilot rating data on a grid of μ vs $N'_{\delta_w}/L'_{\delta_w}$.

Table 2 Physical interpretation of μ

Value of rudder shaping parameter	Roll yaw crosscoupling characteristics
$\mu > 0$	N'_{δ_w} and N'_p are additive, indicating that the crosscoupling effects increase with time after an aileron input.
$\mu = 0$	$N'_p = g/U_0$, indicating that all roll-yaw crosscoupling is due to N'_{δ_w}. The aileron-rudder crossfeed is therefore a pure gain.
$-1 < \mu < 0$	N'_{δ_w} and N'_p are opposing. Initial crosscoupling induced by N'_{δ_w} is reduced by N'_p as the roll rate builds up. Exact cancellation takes place when $\mu = -1$, resulting in a zero rudder requirement for steady rolling.
$\mu << -1$	low-frequency and high-frequency crosscoupling effects are of opposite sign, indicating a need for complex rudder reversals for coordination. If rudder is not used, the nose will appear to oscillate during turn entry and exit.

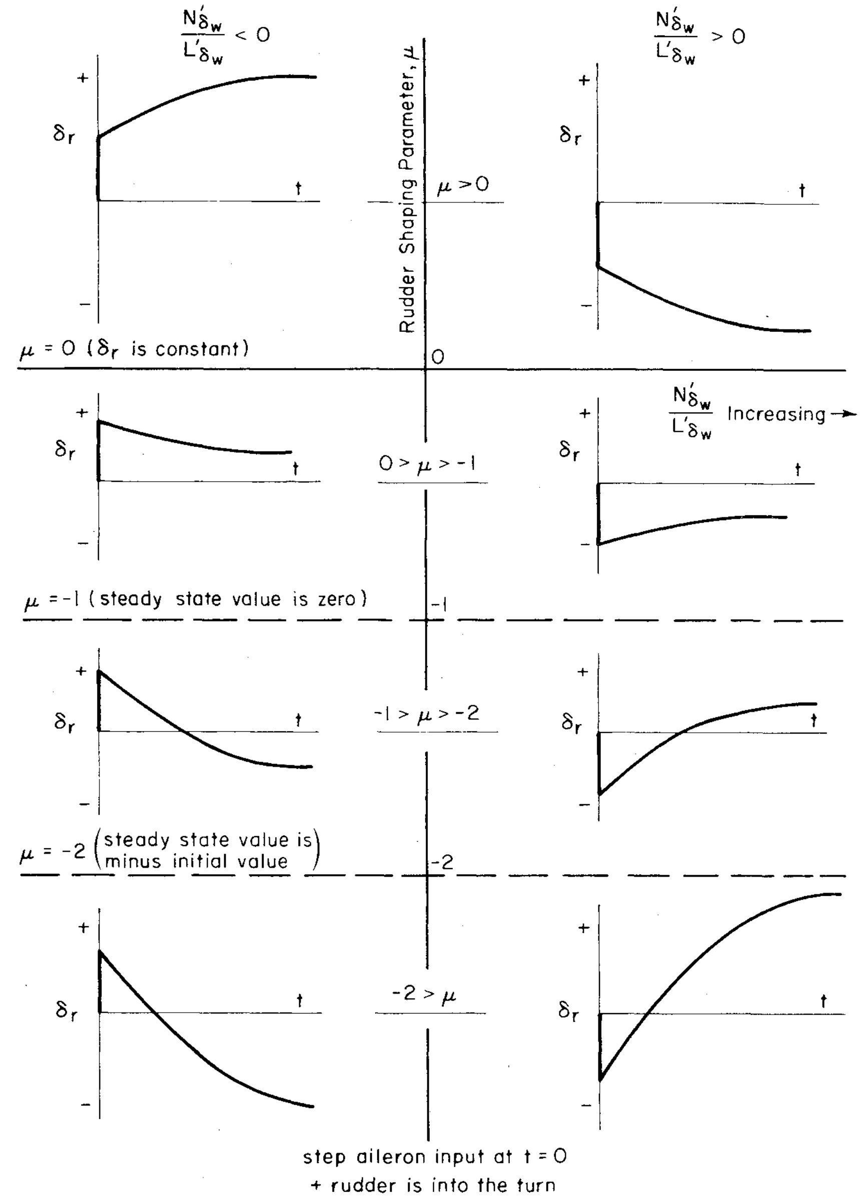

Fig. 3 Typical rudder time histories for zero sideslip.

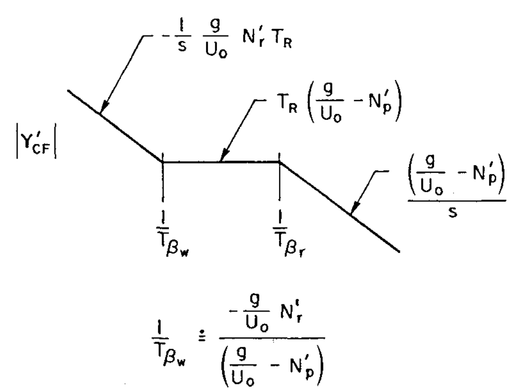

Fig. 4 Required crossfeed for $N'_{\delta_w} = 0$.

$N'_{\delta_w}/L'_{\delta_w}$ Near Zero

Before so doing, it is important to recognize, however, that available rating data and pilot commentary[5,11,12] indicates that *control* crosscoupling effects are not a factor when $|N'_{\delta_w}/L'_{\delta_w}| < 0.03$. This may occur when the basic control crosscoupling is small or with augmentation systems which result in ideal crossfeeds, Y_{CF}, having denominators of higher order dynamics than numerators (e.g., the augmented N'_{δ_w} is zero). For $N'_{\delta_w}/L'_{\delta_w}$ identically zero, the required aileron-rudder crossfeed takes the Bode asymptote form shown in Fig. 4. The rudder *magnitude* required to coordinate mid-frequency and high-frequency aileron (wheel) inputs is seen to be dependent on the roll crosscoupling, $g/U_0 - N'_p$, whereas low-frequency rudder requirements are dependent on N'_r. The required rudder shaping has the characteristics of a rate system (ramp δ_r to step δ_w input) at low and high frequency. Accordingly, aileron-rudder *shaping* per se is not the essence of the problem, which reduces, instead, to concern with the general magnitude of the required rudder crossfeed.

From Fig. 4 it is seen that $g/U_0 - N'_p$ provides a good measure of such magnitude; and, in fact, correlation of pilot rating data (for $|N'_{\delta_w}/L'_{\delta_w}| < 0.03$ with $g/U_0 - N'_p$ is quite good. However, difficulties associated with estimating an effective $g/U_0 - N'_p$ for augmented airframes presents practical problems which make this parameter somewhat unattractive. Also, for configurations with $1/T_{\beta_w}$ close to $1/T_{\beta_r}$, the effects due to N'_r (see Fig. 4) can be important. A more general approach is to compute a time history based on a unit step aileron input into Y_{CF}. Utilizing the same response considerations as in the computation of μ, δ_r((3) is suggested as the correlating parameter when $|N'_{\delta_w}/L'_{\delta_w}| < 0.03$ or when the denominator of Y_{CF} is of higher order than the numerator.

Table 3 Ground rules for application of rating data to heading control criteria

1) $T_R < 1.25$
2) $\omega_d > 0.4$
3) $\zeta_d > 0.08$ and $\zeta_d \omega_d > 0.15$
4) $|\phi/\beta|_d < 1.5$ when turbulence is a factor and $|N'_{\delta_w}/L'_{\delta_w}| > 0.03$
5) meets Fig. 6 boundaries when $|N'_{\delta_w}/L'_{\delta_w}| \leq 0.03$
6) meets Level 2 ϕ_{osc}/ϕ_{ave} in Ref. 2
7) pilot comments do not indicate:
   a) significant roll control problems
   b) control power or sensitivity problems
   c) nonlinear control system problems such as friction, breakout, etc.
   d) excessive gust response

Table 4 Summary of current data

Type of aircraft simulated	Description of simulator	Ref.	Total number of data points	Number of points meeting ground rules
Executive jet and military Class II	variable stability T33	13	84	16
STOL	variable stability helicopter	6	109	30
General aviation (light aircraft)	variable stability navion	14	26	6
Jet fighter-carrier approach	variable stability navion	12	36	22
Space shuttle vehicle	6 DOF moving base with Redifon display (NASA Ames FSAA)	5	52	52
STOL	3 DOF moving base (NASA Ames S-16)	1	8	7

Experimental Data Correlations

On the basis of the foregoing, pilot ratings should correlate: for $|N'_{\delta_w}/L'_{\delta_w}| > 0.03$, with μ and $N'_{\delta_w}/L'_{\delta}$; and for $|N'_{\delta_w}/L'_{\delta_w}| < 0.03$, with $\delta_r(3)$. However, before proceeding with such correlations, it is necessary to segregate pilot rating data properly reflecting heading control problems. In this regard it is important to recognize that heading control is basically an outer loop[11] and cannot be satisfactory if the inner (bank angle) loop is unsatisfactory. The ground rules listed in Table 3 reflect basic requirements for good inner-loop characteristics and for other (except heading control) good handling properties. If these requirements are satisfied, the remaining problems are assumed to be associated directly with heading control.

The requirements on ζ_d, ω_d, and T_R are based on the current MIL-F-8785B limits for Level 1 flying qualities. The Level 2 boundary on ϕ_{osc}/ϕ_{ave} is used because the Level 1 boundary appeared too restrictive, i.e., many data points with good pilot ratings were found to plot outside the Level 1 ϕ_{osc}/ϕ_{ave} boundary. This result is also found in Ref. 13 and a less conservative boundary is proposed there. The restriction on $|\phi/\beta|_d$ for $|N'_{\delta_w}/L'_{\delta_w}|$ greater than 0.03 is based on results obtained from the in-flight simulation data of Refs. 13 and 14. The Ref. 13 data plotted in Fig. 5 show that pilot ratings are very sensitive to increasing values of $|N'_{\delta_w}/L'_{\delta_w}|$ when $|\phi/\beta|_d > 1.5$. The pilot commentary corresponding to selected points in Fig. 5 are given below to help explain the data.

Configuration 7A2. "Difficulty in coordination in terms of maintaining heading under turbulent conditions."

Configuration 9A1. "Problems in non-turbulent conditions magnified in turbulence. Pilot must cope with rudders and some aileron to keep aircraft in control."

Configuration 4A2. "Rapid deterioration of handling qualities in turbulence."

This commentary is consistent with the results obtained in Ref. 12 where it is shown that increasing dihedral (large $|\phi/\beta|_d$) is primarily a problem when turbulence is a factor.

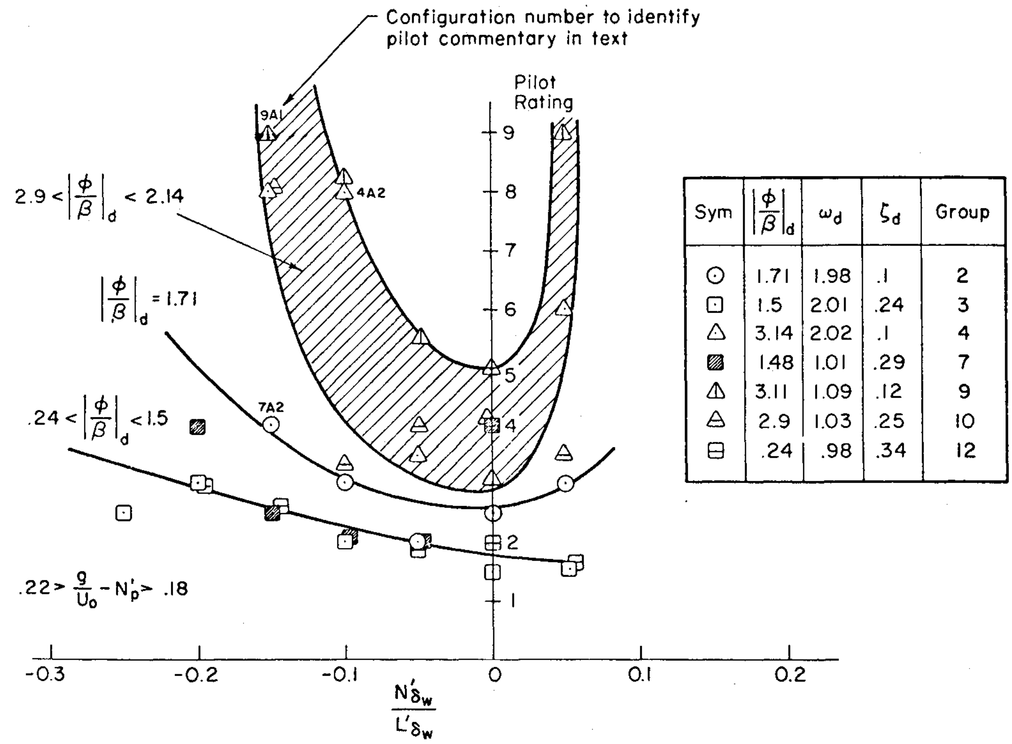

Fig. 5 Effect of $|\phi/\beta|_d$ and $N'_{\delta_w}/L'_{\delta_w}$ on pilot ratings in turbulence (Ref. 13 data).

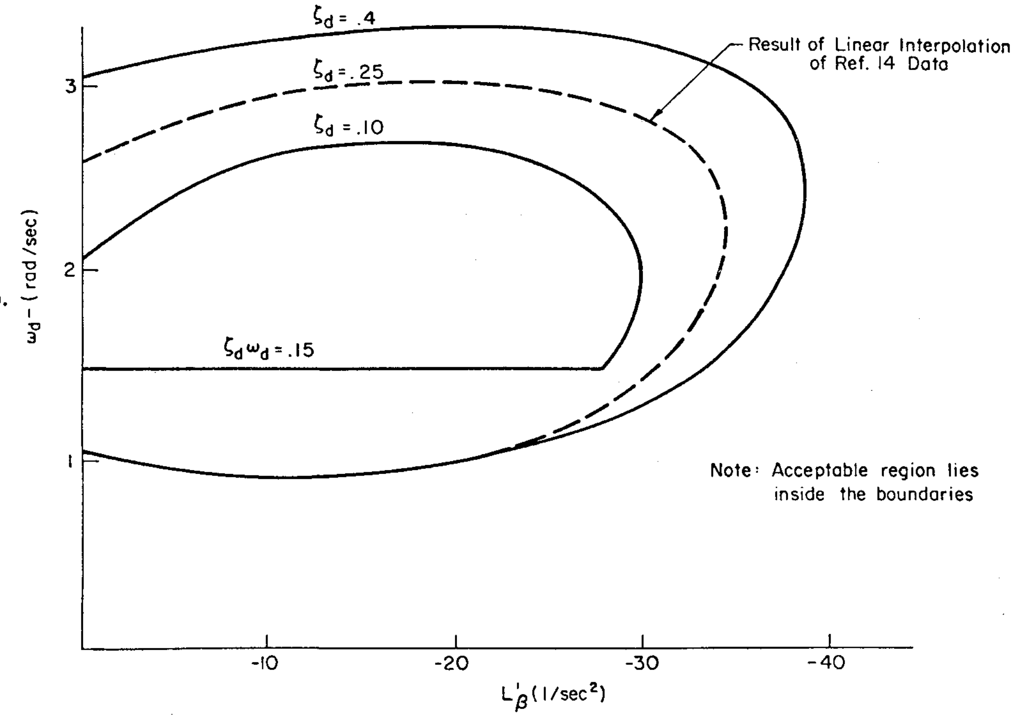

Fig. 6 Pilot rating boundaries for acceptable roll control in turbulence with $N'_{\delta_w}/L'_{\delta_w} < 0.03$ (from Ref. 12).

Such effects can be interpreted in terms of basic piloting technique as follows. The problem of flying a constant heading in turbulence primarily consists of keeping the average bank angle at zero. Because of the inherent neutral stability of an aircraft in roll ($L_\phi = 0$), the pilot is required to continually use aileron to pick up a low wing to keep the aircraft from turning. If the aircraft has large aileron-yaw crosscoupling (large $N'_{\delta_w}/L'_{\delta_w}$), each aileron input will induce a large sideslip which further magnifies the effect of turbulence. This sort of rolling and sideslipping is extremely disconcerting and may, in some cases, border on loss of control. Rather than accept this, the pilot must use coordinated rudder with aileron when regulating against rolling gusts. The increased workload imposed dy this requirement gives rise to the rapid deterioration in rating with increasing aileron-yaw crosscoupling. On the other hand, aircraft with low $|\phi/\beta|_d$ exhibit a snaking tendency in turbulence, requiring very little aileron input to keep wings level. Because of the inherent directional stability (N_β), the lateral oscillations tend to average out with little effect on the lateral flight path angle. The data presented in Fig. 5 quantitatively define the value of $|\phi/\beta|_d$ where heading control is contaminated by roll control problems (in turbulence) as about 1.5. This is the basis for Ground Rule No. 4 (Table 3).

It is clear from the above discussion and Fig. 5 that when aileron crosscoupling is small, the effect of dihedral is less critical. This is accounted for by using the variable stability Navion data from Ref. 12 where the dihedral (L'_β) was varied over a wide range with low or zero $|N'_{\delta_w}/L'_{\delta_w}|$. The 3-½ pilot rating boundaries from these experiments are given in Fig. 6 and form the basis for Ground Rule No. 5.[††] Comparison of these boundaries with other low $|N'_{\delta_w}/L'_{\delta_w}|$ data[13,14] is favorable. They were used to allow inclusion of certain of the $|\phi/\beta|_d > 1.5$ data for $|N'_{\delta_w}/L'_{\delta_w}| < 0.03$ and thereby to permit an expanded base for the pertinent correlations. It should be noted that attempts to isolate these $|/\beta|_d$ characteristics using ϕ_{osc}/ϕ_{ave} were not successful. It is felt that the reason for this is that ϕ_{osc}/ϕ_{ave} is an aileron-only parameter, whereas the roll control problems under discussion are related to rudder coordination requirements.

[††]The boundary for $\zeta_d = 0.4$ is based on only a few data points and was faired by the authors.

A summary of the data sources considered is given in Table 4. Each of the data points found to be applicable to heading control (i.e., met the ground rules) is plotted and faired on a logarithmic grid of $N'_{\delta_w}/L'_{\delta_w}$ vs μ in Fig. 7. When $N'_{\delta_w}/L'_{\delta_w}$ is near zero (≤ 0.03) the pilot rating data are plotted versus $\delta_r(3)$ in Fig. 8. Due to a lack of data for large adverse N'_p it was necessary to extrapolate the data fairing in Fig. 8 to obtain a Level 2 requirement for $\delta_r(3)$. This boundary should be adjusted as more data become available. Only in-flight and moving-base simulator data were considered. With the exception of one or two points the data from all the sources in Table 4 coalesce quite nicely. The criterion in Fig. 7 is conservative in that the few points that do not fit are rated better than the other data in the same region.

The data plotted in Figs. 7 and 8 are replotted on the current MIL-F-8785B sideslip criterion in Fig. 9 to compare the rudder coordination boundaries with boundaries set by aileron-only considerations. Many very good pilot ratings are seen in Fig. 9 to fall outside even the 6-½ boundary. The pilot commentary from three of the Ref. 5 configurations having ratings of 4.5 and better but falling outside the 6-½ (Level 2) boundary are given in Table 5. These comments reflect the pilot's ability to improve the aircraft heading characteristics

Table 5 Pilot commentary

Pilot 4 B

"Required considerable rudder for directional control."
"Can do better with rudders."
"Has a tendency to snap around with aileron."

Pilot 5A

"Has to be coordinated." "Is simple to coordinate."
"Bad without rudder." "Rudder makes it flyable. Give it a 7 without rudder and a 4.5 with rudder."

Pilot 5B

"Good heading control configuration; easy to lead aileron with rudder."
"Give it a pilot rating of 5.5 without rudder and a 3.5 with the rudder."

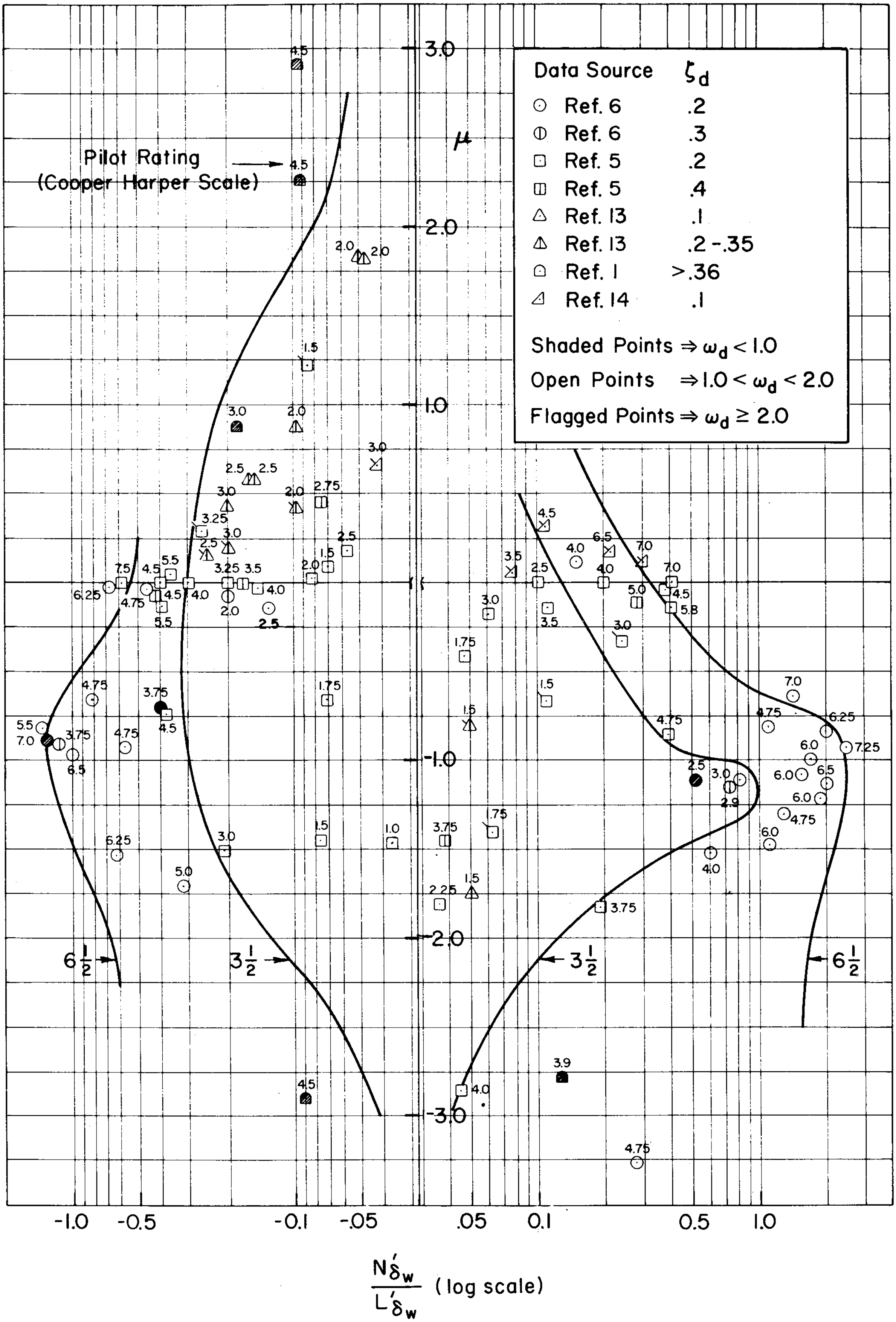

Fig. 7 Pilot rating correlation with crossfeed parameters.

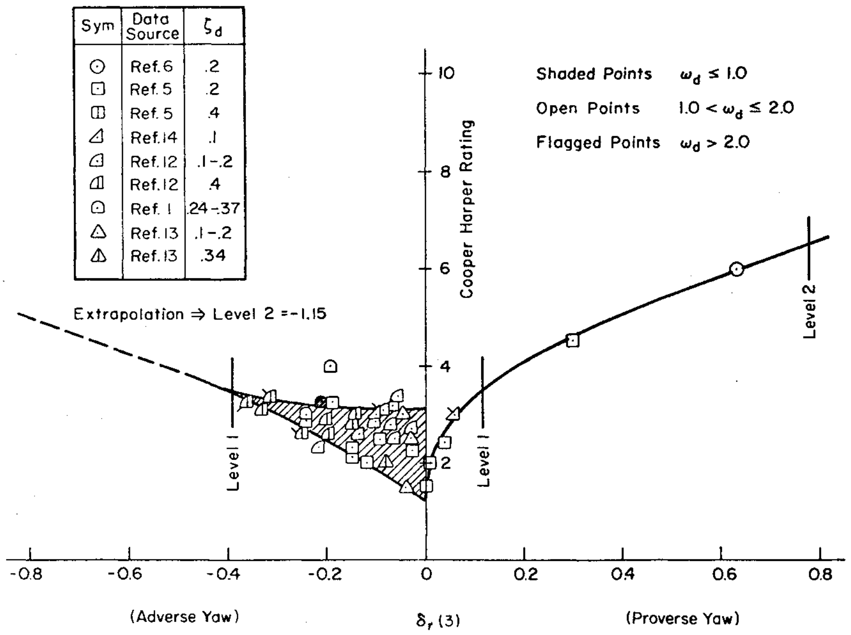

Fig. 8 Pilot rating correlations when $|N'_{\delta_w}/L'_{\delta_w}| < 0.03$.

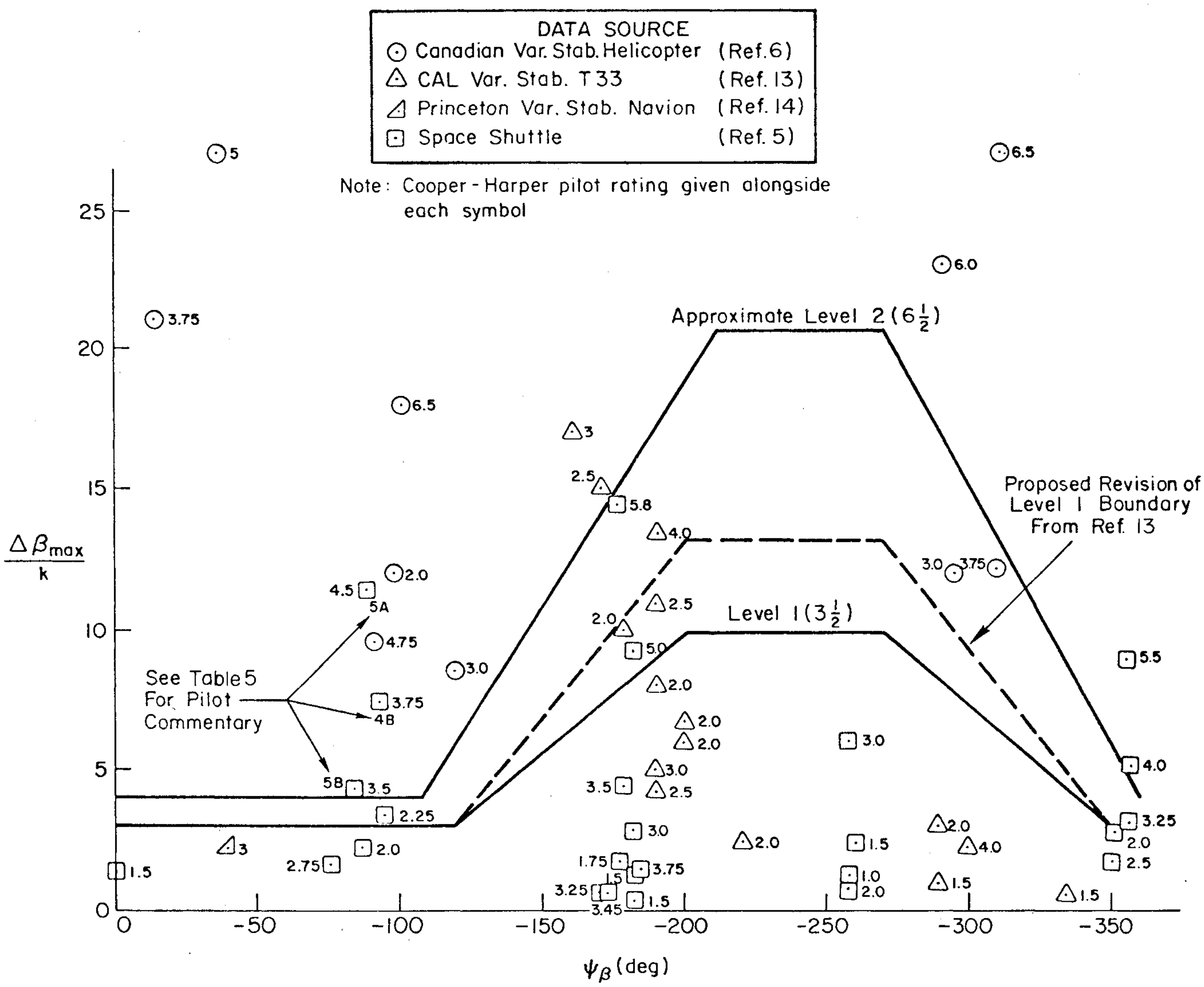

Fig. 9 Correlation data on $\Delta\beta_{max}/k$ vs ϕ_β plot.

with proper rudder usage. The poor correlation with the current specification (Fig. 9) is therefore attributable to the fact that rudder control is not accounted for therein.

Physical Interpretation

The iso-opinion lines in Fig. 7 indicate that some values of the rudder shaping parameter, μ, are more desirable than others in that they are less sensitive to an increase in aileron yaw. The following observations help to explain this trend in terms of pilot-centered considerations: 1) Moderately high proverse (positive) N'_{δ_w} is acceptable in the region where $\mu \doteq -1$. Physically, this corresponds to a sudden initial heading response in the direction of turn followed by decreasing rudder requirements. (Required steady-state rudder is zero when $\mu = -1$, see Fig. 3.) It is felt that the pilots are accepting the initial proverse yaw as a heading lead and are not attempting to use cross control rudder. 2) The allowable values of proverse N'_{δ_w} decrease rapidly as μ becomes greater than -1. Physically this corresponds to an increase in the requirement for low frequency cross control rudder activity (see Fig. 3) which is highly objectionable. 3) The pilot ratings are less sensitive to the required rudder shaping when N'_{δ_w} is negative (adverse yaw). Recall that adverse yaw is consistent with conventional piloting technique.

It is significant that the pilot rating correlations are not dependent on the type of aircraft and in fact are shown to be valid for vehicles ranging from light aircraft to fighter, STOL, and space shuttle configurations. This result indicates that good heading control characteristics are dependent on a fundamental aspect of piloting technique (aileron-rudder coordination) and that such factors as aircraft size, weight, approach speed, etc., can be neglected for all practical purposes. It is felt that the invariance of ratings with aircraft configuration is related to the pilot's ability to adapt to different situations and to rate accordingly. Finally, the excellent correlation of pilot ratings with the aileron-rudder crossfeed characteristics indicates that the required rudder coordination is indeed a dominant factor in pilot evaluation of heading control.

The rudder shaping parameter is attractive as a heading control criterion because the handling quality boundaries are easily interpreted in terms of pilot-centered considerations.

Conclusions

The main conclusions are summarized as follows: 1) Pilot evaluation of heading control is highly correlatable with the aileron-rudder sequencing required to coordinate turns. 2) Very good correlation has been obtained with data from widely varying configurations.

The results to data are very encouraging. The crossfeed parameter seems to have great potential as a heading control criterion. Additional experimental data to investigate certain regions of the criterion planes in Figs. 7 and 8 are highly desirable.

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References

[1] Drake, D.E., Berg, R.A., Teper, G.L., and Shirley, W.A., "A Flight Simulator Study of STOL Transport Lateral Control Characteristics," Federal Aviation Administration, Washington, D.C., FAA-RD-70-61, Sept. 1970.

[2] "Flying Qualities of Piloted Airplanes," MIL-F-8785B(ASG), 7 Aug. 1969.

[3] Hoh, R.H. and Jex, H.R., "Effect of Sideslip on Precise Lateral Tracking," Systems Technology, Inc., Hawthorne, Calif. WP-189-3, Nov. 1969.

[4] Chalk, C.R., DiFranco, D.A., Lebacqz, J.V., and Neal, T.P., "Revisions to MIL-F-8785B (ASG) Proposed by Cornell Aeronautical Laboratory Under Contract F33615-71-C-1254," Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, AFFDL-TR-72-41, April 1973.

[5] Stapleford, R.L., Klein, R.H., and Hoh, R.H., "Handling Qualities Criteria for the Space Shuttle Orbiter During the Terminal Phase of Flight," Systems Technology, Inc., Hawthorne, Calif., TR-1002-1, Aug. 1971.

[6] Doetsch, K.H., Jr., Gould, D.G., and McGregor, D.M., "A Flight Investigation of Lateral-Directional Handling Qualities for V/STOL Aircraft in Low Speed Maneuvering Flight," Air Force Flight Dynamics Lab., Wright-Patterson Air Force Base, Ohio, AFFDL-TR-69-41, March 1970.

[7] McRuer, D., Graham, D., and Ashkenas, I., *Aircraft Dynamics and Automatic Control,* Princeton University Press, Princeton, N.J., 1972.

[8] Stapleford, R.L., McRuer, D.T., Hoh, R.H., Johnston, D.E., and Heffley, R.K., "Outsmarting MIL-F-8785B(ASG), the Military Flying Qualities Specification," Systems Technology, Inc., Hawthorne, Calif., TR-190-1, Aug. 1971.

[9] Magdaleno, R.E. and McRuer, D.T., "Experimental Validation and Analytical Elaboration for Models of the Pilot's Neuromuscular Subsystem in Tracking Tasks," NASA CR-1757, April 1971.

[10] McRuer, D., Graham, D., Krendel, E., and Reisener, W., Jr., "Human Pilot Dynamics in Compensatory Systems – Theory, Models, and Experiments with Controlled Element and Forcing Function Variations," Air Force Flight Dynamics Lab., Wright-Patterson Air Force Base, Ohio, AFFDL-TR-65-15, July 1965.

[11] Stapleford, R.L., Johnston, D.E., Teper, G.L., and Weir, D.H., "Development of Satisfactory Lateral-Directional Handling Qualities in the Landing Approach," NASA, CR-239, July 1965.

[12] Seckel, E., Franklin, J.A., and Miller, G.E., "Lateral-Directional Flying Qualities for Power Approach Influence of Dutch Roll Frequency," Rept. 797, Dept. of Aeronautical and Mechanical Sciences, Princeton University, Princeton, N.J., Sept. 1967.

[13] Hall, G.W. and Boothe, E.M., "An In-Flight Investigation of Lateral-Directional Dynamics for the Landing Approach," Air Force Flight Dynamics Lab., Wright-Patterson Air Force Base, Ohio, AFFDL-TR-70-145, Oct. 1970.

[14] Ellis, D.R., "Flying Qualities of Small General Aviation Airplanes. Part 2: The Influence of Roll Control Sensitivity, Roll Damping, Dutch-roll Excitation, and Spiral Stability," Federal Aviation Administration, Washington, D.C., FAA-RD-70-65 Part 2, April 1970.

[15] Meeker, J.I. and Hall, G.W., "In-Flight Evaluation of Lateral-Directional Handling Qualities for the Fighter Mission," Air Force Flight Dynamics Lab., Wright-Patterson Air Force Base, Ohio, AFFDL-TR-67-98, Oct. 1967.