Loop Separation Parameter: A New Metric for Landing Flying Qualities

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Loop Separation Parameter is a metric used to evaluate the longitudinal flying qualities of aircraft in the landing flight phase. It combines simple pilot models with classical root locus and frequency response methods to predict Cooper-Harper pilot ratings for aircraft in the landing phase. Loop Separation Parameter was originally developed using fighter-type aircraft flight test data; in this paper the concept is extended and shown to be a good tool for predicting pilot ratings for large bomber, transport, and highly augmented Space Shuttle configurations. Loop Separation Parameter anticipates the tendency for and predicts the frequency of pilot-induced oscillations. The effects of control system time delay and altitude lag time constant are discussed. It is recommended that Loop Separation Parameter be included in the Flying Qualities Handbook.

Nomenclature

G_c	= control system transfer function (control/command)
G_P	= pilot transfer function (command/error)
G_γ	= aircraft flight-path angle pertubation transfer function (deg/deg control)
G_θ	= aircraft pitch attitude perturbation transfer function (deg/deg control)
K_P	= pilot model DC gain
OLTF	= open-loop transfer function
s	= La Place operator $\sigma + j\omega$
T_L	= pilot lead time constant, s
T_{θ_2}	= pitch rate transfer function numerator time constant, heave
δ_e	= pitch control perturbation deflection (deg control)
γ	= flight-path angle referenced to the horizontal
θ	= pitch attitude
ζ	= damping ratio
ϕ_P	= Bode open-loop phase angle at crossover frequency (deg)
τ	= pilot delay time constant, s
ω_c	= crossover frequency, r/s
ω_{SP}	= short-period mode natural frequency
ω_γ	= observed flight-path angle control "pumping" frequency, r/s
$\hat{\omega}_\gamma$	= flight-path angle control loop model resonant frequency, r/s
ω_θ	= observed pitch attitude control "pumping" frequency, r/s
$\hat{\omega}_\theta$	= pitch attitude control loop model resonant frequency, r/s
ω'_θ	= pitch attitude control loop model PIO frequency prediction, r/s
$[p]$, $[z]$	= shorthand transfer function first-order term
$[\zeta,\omega_n]$	= shorthand transfer function second-order term

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I. Introduction

It has been well documented that overcontrol, pilot-induced oscillations (PIO), and degradations in pilot opinion rating may occur for some aircraft as the pilot makes the transition from the apparently benign flying qualities of the approach segment to the landing flare.[1] Although MIL-F-8785C, "Military Specification, Flying Qualities of Piloted Airplanes,"[2] provides criteria for the Terminal Flight Phase, it does not distinguish between the approach task and the flare to touchdown and thus has predicted overly optimistic landing flying qualities for many new configurations under development and testing.[3]

Loop Separation Parameter (LSP) was developed specifically to address this problem as it relates the longitudinal flying qualities of the Category C Terminal Flight Phase.[4] This parameter applies simple pilot models to predict pilot rating, PIO tendency and frequency of oscillation, and the ease of transition between the approach and landing flare segments.[5]

LSP was derived using fighter-type aircraft flight test data, specifically the Landing Approach of High Order Systems (LAHOS) study.[6] In this research study, the LSP criterion has been updated and applied to a set of landing flight test data not only for fighters but also for transport and Space Shuttle aircraft configurations. The new results are based on comparisons to pilot ratings from in-flight investigations of flight control systems flown by Calspan during September 1983[7] and 1985.[8] The host aircraft for these tests was the Total In-Flight Simulator (TIFS).

In Sec. II, the principles underlying LSP are reviewed and the calculation methods and prediction criterion are presented. Section III presents results of the application of LSP to two sets of flight test data independent of the development data base. The LSP criterion is shown to yield effective predictions of the landing flying qualities for a variety of aircraft types. The effects of control system time delay and altitude lag on LSP are discussed. In the final section of this paper, recommendations are made concerning the future use and application of LSP.

II. Loop Separation Parameter Method

Control Loop Separation

Pilot comments in the flight test study of Ref. 8 indicated a definite shift in strategy from emphasis on pitch attitude control during the approach to emphasis on flight-path angle control during the landing flare. Figure 1 illustrates the concept, and in this paper it is hypothesized that the emphasis shift occurs because the pilot (when using front-side control techniques) uses the horizon as a pitch control cue during approach but uses visual altitude rate cues during flare to control touchdown point and sink rate.

DiDomenico[5] observed a shift in "stick pumping" frequencies using pilot stick force amplitude spectra from the LAHOS study. As shown in Fig. 2, those control frequencies for approach (last 20 s) and those control frequencies for flare (final 6 s) tend to gather into different dominant "clumps" for the same configuration. In some cases, dominant peaks could be observed (see Fig. 3).

DiDomenico discovered empirically that this shift in pilot emphasis could be described quantitatively using uncoupled longitudinal control equations that treat the flight-path angle and pitch attitude control loops independently. This unconventional modeling approach only makes sense if the hypothesis on the shift of pilot emphasis is substantially correct, thus allowing (or perhaps requiring) separate pilot models for the approach loop (pitch command and pitch feedback) and for the flight-path angle loop (flight-path command and flight-path feedback). These loops are shown together in Fig. 4 and isolated in Fig. 5. These separated models allow independent adjustment of the pilot model parameters, which in this study are those of the crossover lead-delay pilot model:

$$G_P(j\omega) = K_P(T_L j\omega + 1)\exp(-0.2j\omega) \tag{1}$$

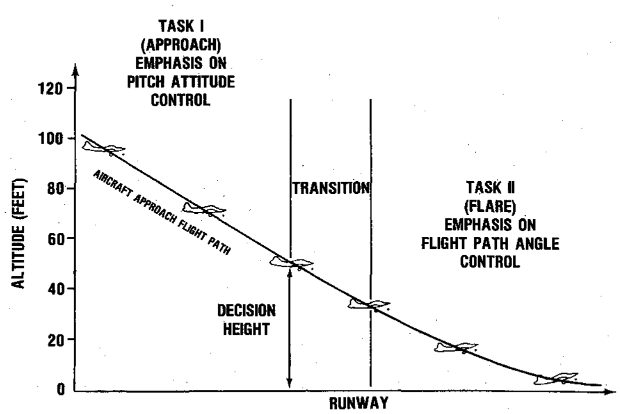


Fig. 1 Landing tasks (front-side piloting technique).

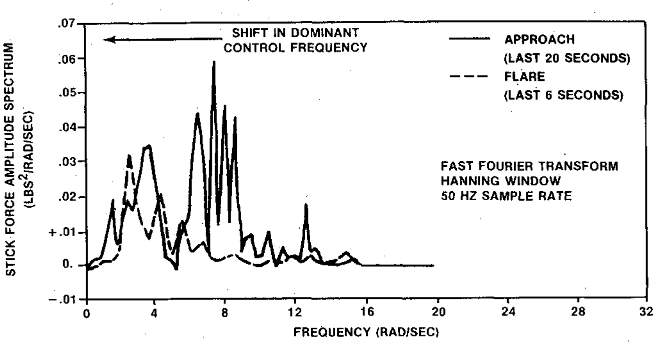


Fig. 2 LAHOS configuration 3-C landing stick force amplitude spectrum.

If a first-order Pade's approximation is used for the lumped pure time delay of 0.2 s, this pilot model becomes

$$G_P(j\omega) = K_P(T_L j\omega + 1)(j\omega - 10)/(j\omega + 10) \tag{2}$$

The landing loop frequencies selected from stick input amplitude spectra for the LAHOS data base are given by columns 2 and 3 of Table 1, and the correlation of the difference between the higher and the lower pumping frequencies (column 4) with average pilot rating (column 5) is shown in Fig. 6. The problem is to reproduce this control frequency separation data with simple models and then to select a priori pilot model parameters used in Eq. (1) to predict the flying qualities of unknown configurations.

Pilot Model Parameter Selection

For the pilot models to be a useful prediction tool, some parameters must be chosen a priori. The lead-time constants were initially selected to force a match between the closed-loop model resonant frequencies with the observed "pumping" frequencies in the LAHOS flight tests. To uniquely specify the model, pilot gains were selected which provided a stable damping ratio. Table 2 depicts this procedure as applied to nine LAHOS configurations. Except for two outliers, pilot lead times for the pitch loop were observed to closely group about an average value of 0.55 s, which was selected as the a priori value for T_{L_θ}, the lead time for the pitch attitude loop pilot model. For the flight-path loop, the model crossover frequen-

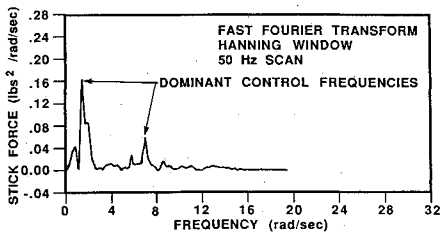


Fig. 3 LAHOS configuration 6-2 landing stick force amplitude spectrum (last 20 s).

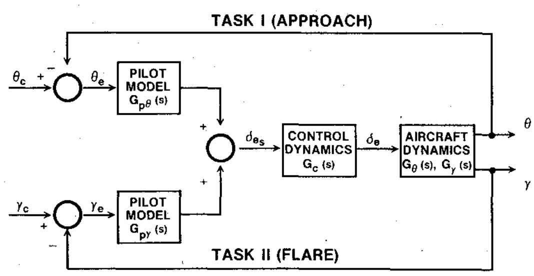


Fig. 4 Parallel control model.

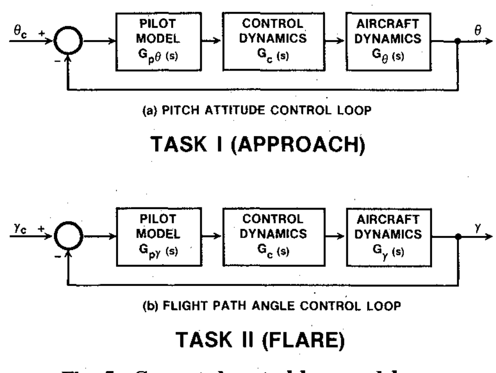


Fig. 5 Separated control loop models.

cies group closely about an average of 2.18 r/s, indicating that the lead time should be based upon achieving a desired crossover frequency. Therefore, T_{L_γ} was based on an empirical technique. This technique is described in the next section along with the formal method for calculating an estimated loop separation parameter using two simple pilot models.

Calculation Method

Applying the described techniques to select a priori pilot model parameters, the method for calculating the Loop Separation Parameter is summarized in the following four steps.

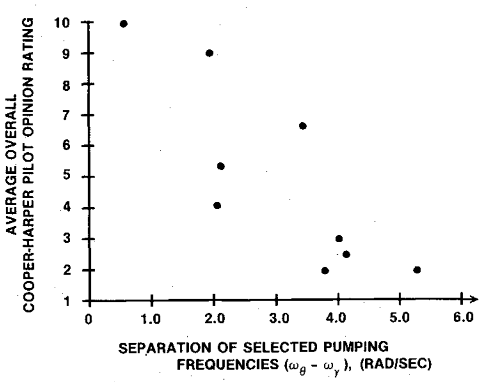


Fig. 6 Correlation of average pilot ratings and observed control frequency separation for nine LAHOS configurations.

1) Obtain open-loop $\theta/\delta e(s)$ and $\gamma/\delta e(s)$ transfer functions.
2) Close the pitch attitude loop as shown in Fig. 5a with

$$G_{P_\theta} = K_{P_\theta}(0.55s + 1)(s - 10)/(s + 10) \tag{3}$$

Raise the pilot gain K_{P_θ} to obtain a damping ratio of 0.15 for the dominant closed-loop roots. If more than one pair of closed-loop roots can be considered dominant, obtain the desired damping ratio for the first pair of roots that migrates into the right half-plane. The resonant frequency of the closed pitch attitude loop (the pilot model prediction of a "stick pumping" frequency) is $\hat{\omega}_\theta$, the damped frequency of this dominant root pair.

3) Close the flight-path angle control loop with a delay-only pilot model (pilot lead T_{L_γ} initially equal to zero):

$$G_{P_\gamma} = K_{P_\gamma}(T_{L_\gamma}s + 1)(s - 10)/(s + 10) \tag{4}$$

For systems with a dominant short-period pair, calculate the open-loop Bode phase angle ϕ_P (deg) of the system at a frequency ω_c equal to

$$\omega_c = 0.8\omega_{SP} \tag{5}$$

The rationale for not using a crossover frequency that exceeds the dominant short-period frequency is explained in Ref. 9. Determine the flight-path pilot lead to obtain a −140-deg phase angle shift at this crossover frequency (for minimum

Table 1 Dominant control frequency selections for nine LAHOS configurations

Cooper-Harper pilot opinion ratings for overall landing task				
(1) LAHOS configuration	(2) Selected ω_θ, rad/s	(3) Selected ω_γ, rad/s	(4) $\omega_\theta - \omega_\gamma$, rad/s	(5) Average flying qualities rating
1-1	5.0	2.9	2.1	4
2-C	6.7	6.7	4.1	2.5
2-1	6.6	2.8	3.8	2
2-7	5.5	2.0	3.5	6.5
3-C	6.7	2.7	4.0	3
3-1	5.0	2.9	2.1	5.3
4-10	5.0	3.0	2.0	9
6-1	2.7	2.1	0.6	10
6-2	7.0	1.8	5.2	2

Table 2 Frequency matching results for nine LAHOS configurations

System dynamics			Pitch attitude loop			Flight-path angle loop		
(1) LAHOS configuration	(2) ζ_{SP}	(3) ω_{SP}, rad/s	(4) $\hat{\omega}_\theta$, rad/s	(5) $T_{L\theta}$, s	(6) $\omega_{c\theta}$, rad/s	(7) $\hat{\omega}_\gamma$, rad/s	(8) $T_{L\gamma}$, s	(9) ω_{c_γ}, rad/s
1-1	0.74	1.0	5.0	0.71	4.0	2.9	4.0	1.6
2-C	0.57	2.3	6.7	0.25	5.2	2.6	0.4	2.0
2-1	0.57	2.3	6.6	0.33	5.2	2.8	3.0	2.2
2-7	0.57	2.3	5.5	0.71	3.9	2.0	2.0	2.1
3-C	0.25	2.2	6.7	0.50	8.8	2.7	2.0	2.5
3-1	0.25	2.2	5.0	0.87	4.0	2.9	4.0	2.5
4-10	1.06	2.0	5.0	5.0[a]	3.0	3.0	3.0	3.0
6-1	0.65	1.9	2.7	5.0[a]	2.9	2.1	2.0	1.7
6-2	0.65	1.9	7.0	0.49	4.2	1.8	2.8	2.0
Average	$\frac{1}{n}\int \sum_{L=1}^{n} x_L$			0.55	4.58		2.58	2.18
Variance	$\frac{1}{n-1}\sum_{L=1}^{n}(X_L - \bar{X})^2$			0.04	2.79		1.13	0.17

[a]Frequency match not achieved (T_{L_θ} limited to 5.0 s).

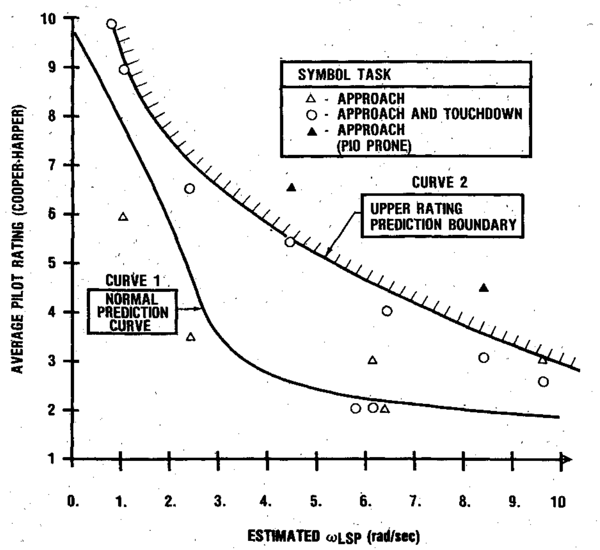


Fig. 7 Correlation of average pilot ratings and loop separation parameter for nine LAHOS configurations.

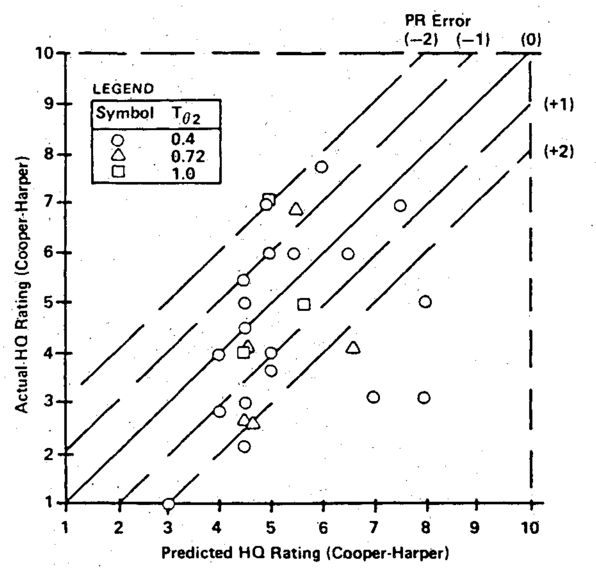


Fig. 8 Correlation of LSP-predicted and actual pilot ratings for 27 TIFS configurations (1983 study).

phase systems this achieves a 40-deg phase margin):

$$T_{L_\gamma} = \tan(-180 + 40 + \phi_p)/\omega_c; \; \{0 < T_{L_\gamma} < 5 \text{ s}\} \tag{6}$$

For systems with no dominant short-period root pair, use $T_{L_\gamma} = 3.5$ s. Include this computed pilot lead in the pilot model and raise the pilot gain K_{P_γ} to obtain roots with a damping ratio of 0.05. The damped frequency of this dominant root pair is $\hat{\omega}_\gamma$, the pilot model prediction of the flight-path "stick-pumping" frequency.

4) Loop Separation Parameter estimate is given by

$$\hat{\omega}_{\text{LSP}} = \hat{\omega}_\theta - \hat{\omega}_\gamma \tag{7}$$

III. Loop Separation Parameter Application

LAHOS Data

The method for calculating LSP was applied to the nine LAHOS development configurations. Table 3 shows the results of using the four-step process on the LAHOS data and the correlation of LSP with actual overall pilot ratings is shown by the circles in Fig. 7. Two prediction curves are drawn because some of these configurations were given separate approach-only ratings, which are shown as triangles in Fig. 7. Curve 1 predicts ratings for a benign approach and landing, and curve 2 (matching most of the more critical "overall" ratings) predicts ratings for a disturbed, high-workload offset landing task or one with pilot-induced oscillations. Curve 2 can be used as a worst-case prediction or bound for those configurations with a relatively inaccurate model. These prediction curves are tested on independent sets of flight test data in the next section of this paper.

1983 TIFS Study

Twenty-seven aircraft configurations representing large transports and the Space Shuttle Vehicle (SSV) during landing were flown by Calspan on the TIFS aircraft during August and September 1983. Seventeen of the configurations are pitch rate command systems with T_{θ_2} variations. Accurate transfer functions obtained from in-flight frequency sweeps were used to calculate LSP values for each of the 27 aircraft.

Table 4 presents the results, and pilot ratings in column 7 were predicted from curve 1 in Fig. 7. Figure 8 plots actual vs LSP-predicted pilot ratings for all configurations. Predicted ratings for 22 of the 27 aircraft configurations were within two rating units of the flight test pilot ratings. One of the five mispredicted points was called "suspect" by the flight test report.

Following a technique used in Ref. 8, if ratings are converted to handling qualities "levels" using the conversion in Table 5,

Table 3 Loop separation parameter comparison summary for nine LAHOS configurations

(1) LAHOS configuration	(2) $\hat{\omega}_{\text{LSP}}$, rad/s	(3) $\omega_\theta - \omega_\gamma$, rad/s	Average pilot opinion ratings: overall (4) Reference (6)	Average pilot opinion ratings: approach[a] (5) Reference (6)
1-1	6.38	2.1	4	2
2-C	9.57	4.1	2.5	3
2-1	6.16	3.8	2	3
2-7	2.33	3.5	6.5	3.5
3-C	8.38	4.0	3	4.5
3-1	4.55	2.1	6	7
4-10	1.01	2.0	9	6
6-1	0.78	0.6	10	——[a]
6-2	5.81	5.2	2	——[a]

[a]Approach-only rating not assigned.

Table 4 Loop separation parameter prediction summary for 27 TIFS configurations (1983 study)

Aircraft configuration	$1/T_{\theta 2}$, s^{-1}	ω_{nSP}, rad/s	Actual average pilot rating Cooper-Harper	Level	$\hat{\omega}_{LSP}$, rad/s	Predicted pilot rating Cooper-Harper	Level
1-1-1	0.38	2.79	6.0	2-3	2.407	4.5	2
1-2-2	0.72	2.76	6.8	2-3	2.22	5	2
1-3-7	1.0	2.73	4.5	2	2.21	5	2
2-1-1	0.38	1.78	6.0	2	1.56	7	2-3
2-2-2	0.72	1.75	3.8	1-2	1.56	7	2-3
3-1-3	0.38	——[a]	5.8	2	2.72	4.05	2
3-2-4	0.72	——[a]	3.8	2	2.52	4.5	2
4-1-1	0.38	2.79	3.8	1-2	2.94	3.7	1-2
4-2-2	0.72	2.76	2.5	1	2.73	4	1-2
4-3-7	1.0	2.73	7.0[b]	3	2.42	4.7	2
4-3-7-1	1.0	2.73	4.0	2	2.56	4.2	2
5-1-1	0.38	1.78	4.5	2	2.71	4.1	2
5-2-2	0.72	1.75	2.5	1	2.48	4.5	2
6-1-1	0.38	2.27	5.0	2	0.86	8	3
6-1-1-1	0.38	2.27	3.0	1	0.91	8	3
6-2-1	0.38	2.27	3.7	1-2	2.3	5	2
6-2-1-1	0.38	2.27	3.0	1	2.46	4.5	2
7-1-4	0.72	2.84	2.8	1	2.86	4	1-2
8-1-5	0.4	1.45	5.2	2	2.51	4.5	2
8-1-5-1	0.4	1.45	2.0	1	2.73	4	1-2
8-2-5	0.4	1.09	7.7	3	1.91	6	2-3
8-2-5-1	0.4	1.09	7.0	3	2.27	5	2
8-3-5	0.4	1.45	6.7	3	1.03	8	3
8-3-5-1	0.4	1.45	3.0	1	1.27	7.5	3
8-4-6	0.4	1.47	1.0	1	3.35	3	1
8-5-5	0.4	1.45	6.0	2	2.03	6	2
8-5-5-1	0.4	1.45	4.0	2	2.23	5	2

[a]No dominant short-period mode. [b]Suspect pilot rating (Ref. 7).

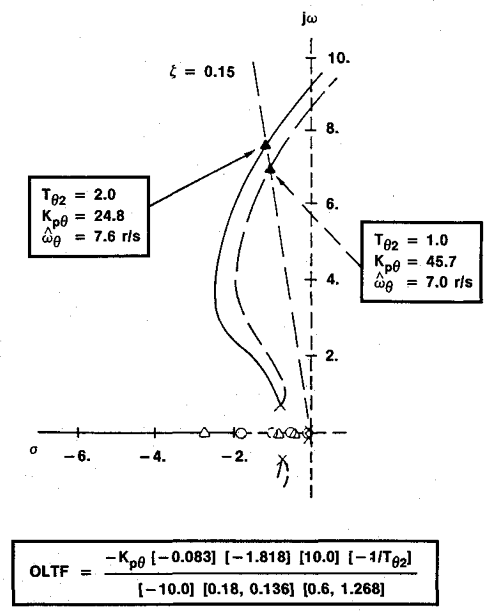


Fig. 9 Effects of T_{θ_2} on predicted pitch attitude control resonant frequency for LAHOS configuration 1-1.

Table 5 Pilot rating conversion, Ref. 8

Cooper-Harper rating point range	Handling qualities rating 'level'
1.0–3.0	1
3.0–4.0	1-2
4.0–6.0	2
6.0–7.0	2-3
7.0–10.0	3

Table 6 Prediction success summary for 27 TIFS configurations (1983 study)

Criterion	Percent ≤ 1 level error
Bandwidth criteria (on θ)	48
Equivalent systems criteria	55
Neal-Smith criteria (on θ)	50
Bandwidth criteria (on $\dot{h}$)	68
Time domain criteria[a]	85
Modified LSP	70

[a]Criterion not independent of Data.

columns 5 and 8 of Table 4 show that the LSP criterion correctly predicts 70% of the flying qualities levels within one rating level. Table 6 shows a direct comparison of the LSP prediction success with the success of other flying qualities criteria proposed for the Handling Qualities Handbook. The MIL-F-8785C criterion for short-period response predicts that all 27 configurations will receive a level-1 rating (Cooper-Harper ratings of 1–3.5). A set of time-domain criteria from the 1983 TIFS study correctly predicts 85% of the cases, but this new criterion was developed directly from these configurations. Thus, the LSP criterion is shown to be as good or better than all other predictive criteria for landing when applied to an independent data base.

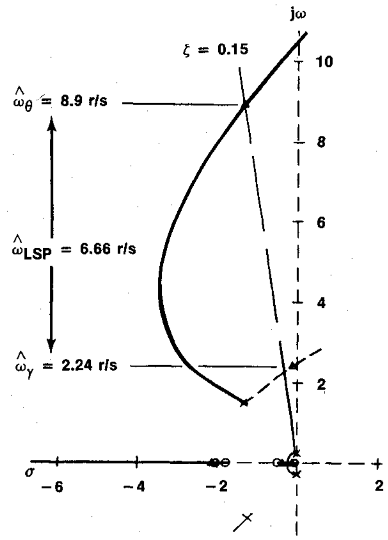
1985 TIFS Study

Landing flying qualities evaluations for five additional TIFS configurations became available in 1986 following late-1985 flight tests by Calspan.[9] These configurations represent diverse aircraft types, with noted inaccurate models, and received widely varying pilot opinion "levels." Flying qualities levels predicted by the LSP criterion (curve 1 of Fig. 7, converted to levels by Table 5) are shown in Table 7. Predictions from curve 2 are included because of the suspect accuracy of the dynamics models.

Table 7 Loop Separation Parameter prediction summary for five TIFS configurations (1985 study)

Aircraft configuration	Short period dynamics		LSP	Predicted ratings				Actual rating
				Curve 1		Curve 2		
	ζ_{SP}	ω_{SP}, r/s	$\hat{\omega}_{LSP}$, r/s	C-H[a]	Level	C-H[a]	Level	Level
1	0.7	2.0	6.69	2.3	1	4.5	2	1
2	2.1	2.0	9.52	2.0	1	3.0	1	1
8	1.3	2.0	6.78	2.3	1	4.5	2	1
14	——[b]	——	3.26	3.0	1	6.5	2-3	2-3
28[c]	0.7	2.0	1.65	6.8	3	8.5	3	3[d]

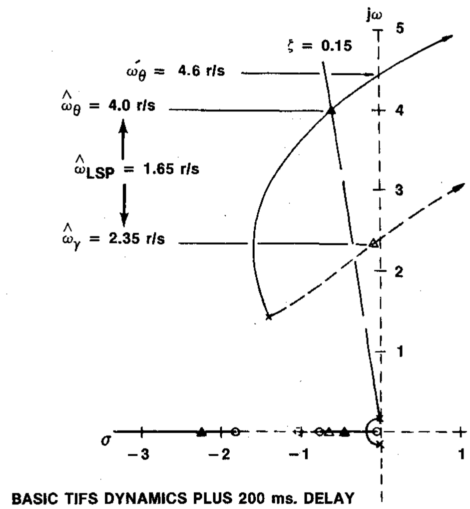
[a]Cooper-Harper pilot opinion rating scale. [b]No dominant short-period roots. [c]Basic TIFS aircraft plus 200 ms delay. [d] PIO during landing flare at 4.5 r/s.



$$\mathrm{OLTF}_\theta(s) = \frac{K_\theta[-0.10]\,[-0.50]\,[-1.82]\,[10.0]}{[-10.0]\,[0.1,\,0.3]\,[0.7,\,2.0]}$$

$$\mathrm{OLTF}_\gamma(s) = \frac{K_\gamma[0.0]\,[-0.955]\,[3.862]\,[10.0]}{[-10.0]\,[0.1,\,0.3]\,[0.7,\,2.0]}$$

Fig. 10 Estimate of loop separation parameter for TIFS configuration 1 (1985 study).



$$\mathrm{OLTF}_\theta(s) = \frac{K_\theta[-0.749]\,[-0.055]\,[10.0]^2\,[-1.818]}{[-10.0]^2\,[0.10,\,0.161]\,[0.7,\,2.0]}$$

$$\mathrm{OLTF}_\gamma(s) = \frac{K_\gamma[-0.054]\,[-1.094]\,[9.282]\,[10.0]^2\,[-6.68]}{[-10.0]^2\,[0.10,\,0.161]\,[0.7,\,2.0]}$$

Fig. 11 Estimate of loop separation parameter for TIFS configuration 28 (1985 study).

The LSP criterion correctly predicts the flying qualities levels for four of the five configurations. It is noteworthy that one of these cases, configuration 28, produced PIO during the landing flare, although the MIL-F-8785C short-period criterion predicted level-1 flying qualities. The poor rating and PIO frequency were correctly predicted by LSP.

Effects of Altitude Lag

Variations of altitude lag, or the numerator time constant T_{θ_2}, are included in the 1983 TIFS configurations. As altitude lag decreases, an aircraft exhibits faster initial response to a command. Normally this decreased response time leads to better pilot opinion ratings, but as shown in columns 2 and 6 of Table 4, large changes in T_{θ_2} resulted in only minor changes in flight test pilot rating for most of these aircraft.[8]

It should be noted, however, that the method used to change the numerator time constant value for a TIFS configuration, direct lift flaps, also changed the position of a pole in the denominator, causing a "marching" pole-zero pair noted in Ref. 8. This results in little change to the *shape* of the root locus branches. Even without this "marching" pair, T_{θ_2} changes LSP only moderately for most aircraft, as shown by the plot in Fig. 9 for LAHOS configuration 1-1. Large changes in LSP will occur only when variation in T_{θ_2} causes significant change in the shape of the root locus.

Effects of Control System Time Delay

The effects of time delay on LSP and predicted pilot ratings are best shown by an example taken from a pair of 1985 TIFS aircraft configurations. Notice in Table 7 the degradation in actual pilot rating from the level-1 rating for configuration 1 to the level-3 rating for configuration 28. These two aircraft configurations have similar dynamics except that configuration 28 has an additional time delay of 200 ms.

The diagrams in Figs. 10 and 11 for configurations 1 and 28, respectively, show both the pitch attitude and flight-path angle dominant root pair branches on one plot. A large separation is achieved for configuration 1 in Fig. 10, but a drastic decrease in separation is caused by the additional time delay for configuration 28, resulting in a degraded predicted rating. The obvious degradation in flying qualities, caused by the addition of control system time delays, is thus reflected in LSP values.

"Stick Pumping" Frequency Prediction

The LSP control loop models predict resonant frequencies which, for some configurations, accurately reflect observed

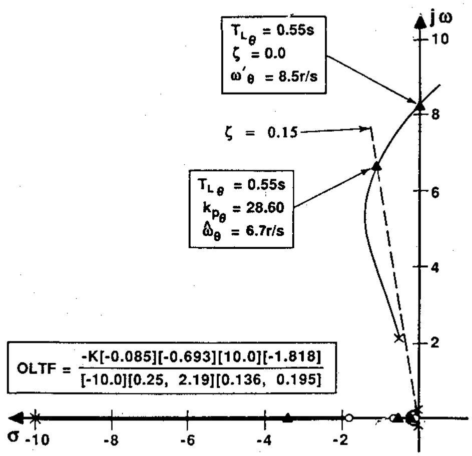


Fig. 12 LAHOS configuration 3-1 pitch attitude loop root locus.

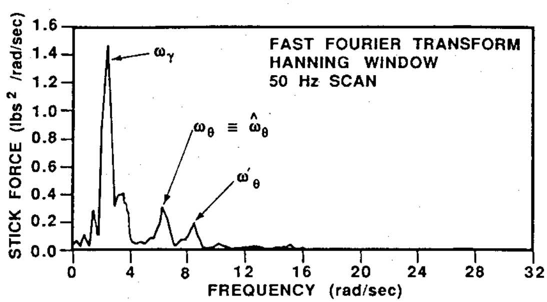


Fig. 13 LAHOS configuration 3-1 landing stick force amplitude spectrum.

"stick pumping" frequencies. The root locus plots for these loops may also be used to predict frequencies that will drive the aircraft unstable. Figure 12 predicts that input frequencies above 8.5 r/s will drive the model of LAHOS configuration 3-1 unstable, and Fig. 13 shows that pilot stick activity did occur at, but not beyond, this frequency during flight test.

As loop separation decreases below 2.0 r/s, the tendency to PIO is increased, and LSP may be used to predict the frequency of oscillation. TIFS configuration 28 experienced PIO during the flare at a frequency of 4.5 r/s (see Table 7). As seen in Fig. 11, LSP predicts that an input frequency of 4.6 r/s will drive configuration 28 unstable in pitch.

IV. Conclusions

An evaluation of the Loop Separation Parameter flying qualities criterion has been accomplished using data for diverse aircraft types. Predicted Cooper-Harper pilot ratings correlate well with pilot ratings received in front-side landing tests. Although developed from data for fighter-type aircraft, LSP has been shown to successfully predict landing flying qualities for large transports and Space-Shuttle configurations. The theory of loop separation can also be used to predict dominant longitudinal control frequencies for the landing task, including PIO frequencies. Ease of use and prediction success make the Loop Separation Parameter a candidate for addition to the Flying Qualities Handbook.

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