NASA/FRC WAKE TURBULENCE FLIGHT TEST PROGRAM - RIDE QUALITY ASPECTS

Memorandum Report
National Aeronautics and Space Administration
Grant No. NGR 47-005-181

Memorandum Report 403225
Short-Haul Air Transportation Program

Submitted by:

David A. Deptula

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1. INTRODUCTION

On 15 October 1975 the NASA Shuttle Carrier Aircraft Boeing-747 (N905NA) (Figure 1) was flown on a wake vortex test flight at the Flight Research Center, Edwards AFB, California. This flight was a continuation of a series of test flights to determine the characteristics of vortex wake turbulence caused by aircraft in flight. In particular, this flight was concerned with determining how much vortex alleviation could be provided by incorporating spoilers.

An extensive summary of recent wake turbulence flight tests may be found in Tymczyszyn and Barber 1974. The last tests discussed in that report showed that vortices could be alleviated by reducing the deflection of the outboard flaps on the B-747 aircraft. The results of these tests indicated that the magnitude of the vortex alleviation was such that it could reduce required aircraft spacing in terminal areas by a factor of 2 or greater. However, dissipation provided by span lift alterations was significantly reduced by certain factors required in terminal area operations such as landing gear extension, reduced aircraft thrust, and aircraft sideslip (Tymczyszyn and Barber).

Since that series of tests another flight has taken place in which it was determined that deflecting particular combinations of spoilers on the B-747 alleviated the wake vortex of the aircraft in the landing configuration (Figure 2). Unfortunately, disrupting the vortex in this manner creates buffeting and degradates the ride quality of the aircraft. In order to determine how much the ride quality was affected at various spoiler settings, the University of Virginia PEMS II (Portable Environmental Measuring System) was used to measure the motion aboard the flight of 15 October 1975. PEMS II measures acceleration in the vertical, transverse and longitudinal directions as well as angular rates in pitch, roll, and yaw.

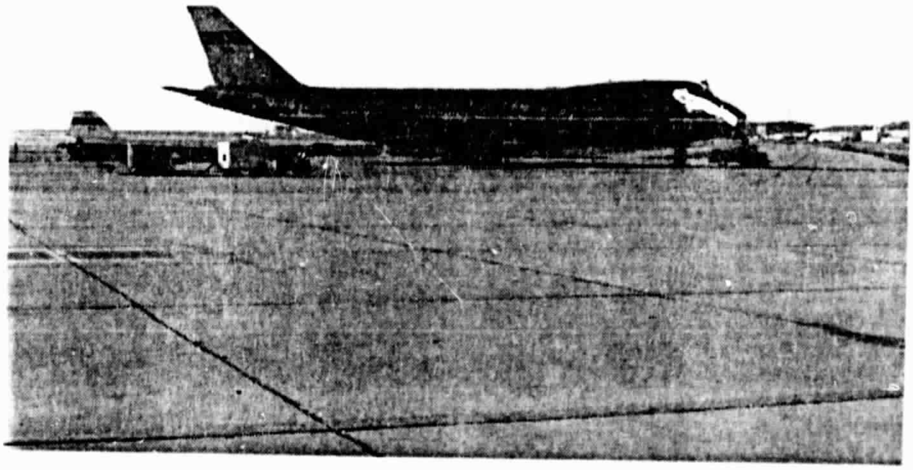

Figure 1 NASA Shuttle Carrier Aircraft

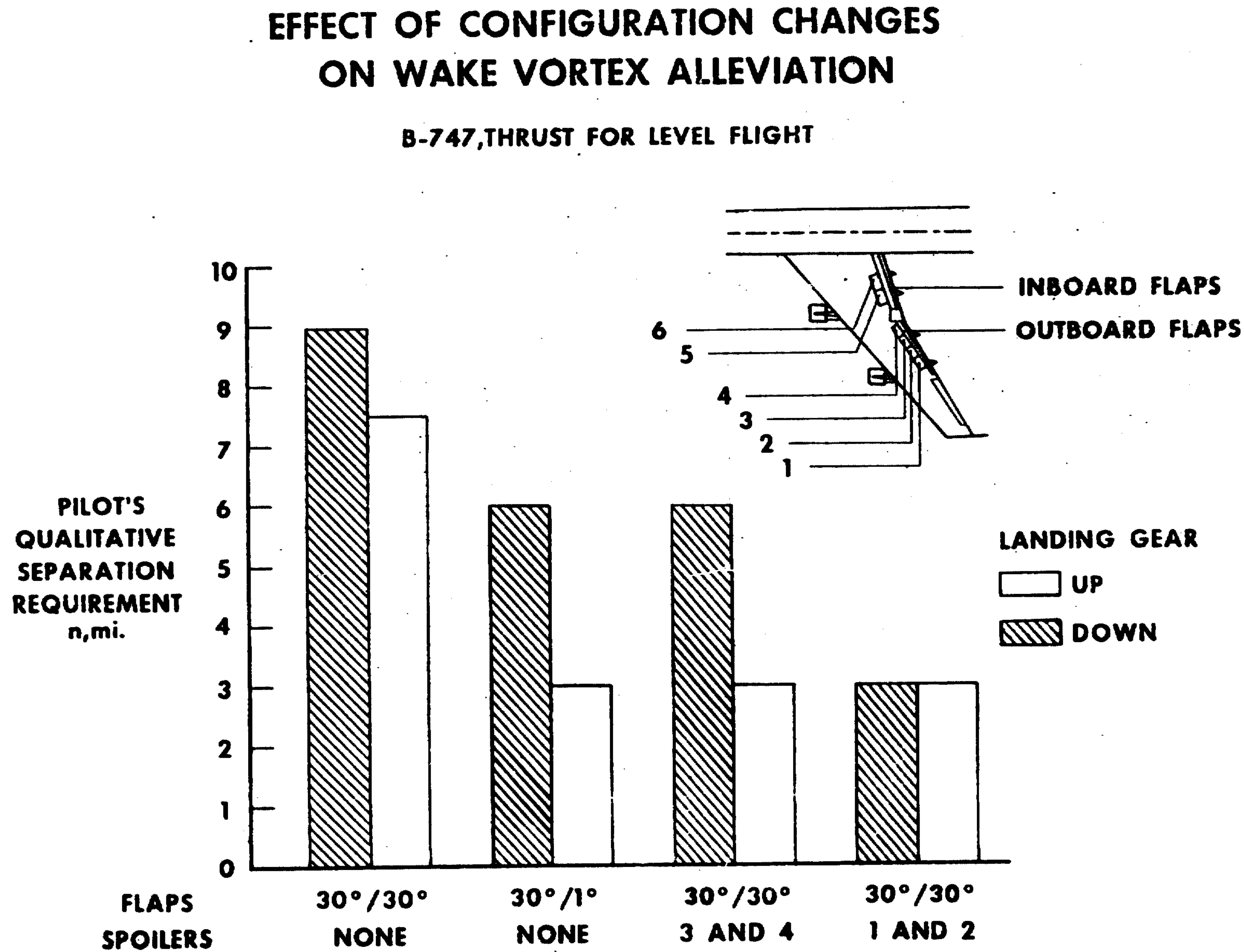

Figure 2 Effect of Configuration Changes on Wake Vortex Alleviation

The data acquired by that instrumentation package combined with the airline passenger comfort model developed by Jacobson and Richards 1974, will give an indication of how passengers would react to the motion induced by flying in a vortex alleviation configuration. This report deals with the results of the 15 October 1975 Vortex Alleviation Test Flight with respect to ride quality aspects and the implications of those results.

2. FLIGHT DESCRIPTION

The actual flight plan for the 15 October 1975 Wake Votex Test is reproduced in Figure 3. It is modified from the original plan to indicate what was actually flown.

The 747 was flown at maximum landing gross weight (564,000 lbs.) in landing configuration (flaps 30°/30°, Gear Down) during each run. The 747's vortex was probed by the T-37 wake vortex probe aircraft. A system of smoke generators located along the wing of the 747 provided visual identification of the vortex and associated turbulence for the T-37 aircraft.

The PEMS II and recorder were located approximately 31 feet aft of the aircraft's CG. Data was recorded from taxi through the complete flight plan. The segments identified in Figure 4 are those for which the analog data was digitized for input into the comfort model. The segments are arranged in chronological order.

Spoilers were deflected in the range of 0 to 45°. Figures 5 and 6 indicate the location of the spoilers used. In Figure 5 there is 0° spoiler deflection. Figure 6 shows spoilers up during a test run.

747 WAKE VORTEX FLIGHT PLAN									FLIGHT DATE 10/15/75
RUN NO.	CONFIGURATION			SPOILERS	WEIGHT	AIR-SPEED	C_L	ALTI-TUDE	COMMENTS
	FLAPS	GEAR	THRUST	1,2,11&12	K lbs.	KTS		K ft.	
1	30/30	Dn	Level	20,25,30, 35,40,45°	≈ 564	≈ 146	1.4	5	Pilot and crew determine buffett level that passengers would tolerate.
2	30/30	Dn	-3°	25,35, 40,45°	≈ 564	≈ 146	1.4	8→5	Pilot and crew determine buffett level that passengers would tolerate.
3	30/30	Dn	-3°	41°	≈ 564	≈ 146	1.4	8→5	Determine sideslip (ball) during 3-engine approach (outboard idled).
4	30/30	Dn	Level	0°	≈ 564	≈ 146	1.4	1 AGL	Building Flyover
5	30/30	Dn	Level	41°	≈ 564	≈ 146	1.4	1 AGL	Building Flyover
6	30/30	Dn	Level	25°	≈ 564	≈ 146	1.4	1 AGL	Building Flyover
7	30/30	Dn	Level	41°	≈ 564	≈ 146	1.4	1 AGL	Building Flyover with sideslip determined in Run 3
8a	30/30	Dn	-3°	41°	≈ 564	≈ 146	1.4	12 → 8	T-37 Parallel Probes
8b	30/30	Dn	Level	41°	≈ 564	≈ 146	1.4	12	T-37 Parallel Probes
8c	30/30	Dn	-3°	41°	≈ 564	≈ 146	1.4	12 → 8	T-37 Parallel Probes
9a	30/30	Dn	-3°	25°	≈ 564	≈ 146	1.4	12 → 8	T-37 Parallel Probes
9b	30/30	Dn	-3°	35°	≈ 564	≈ 146	1.4	12 → 8	T-37 Parallel Probes
10a	30/30	Dn	-3°	41°	≈ 564	≈ 146	1.4	12 → 8	T-37 Parallel Probes with sideslip determined in Run 3
10b	30/30	Dn	-3°	41°	≈ 564	≈ 146	1.4	12 → 8	T-37 Parallel Probes

Figure 3 747 Wake Vortex Flight Plan

Figure 4 Test Segment Descriptions

Segment	Spoiler Setting	Segment Description	Run #
1	N/A	Taxi	N/A
2	N/A	Take-off	N/A
3	N/A	Climb	N/A
4	20°	S&L	1
5	25°	S&L	1
6	30°	S&L	1
7	35°	S&L	1
8	40°	S&L	1
9	45°	S&L	1
10	30°	Right Turn	N/A
11	25°	3°GS	2
12	35°	3°GS	2
13	40°	3°GS	2
14	45°	3°GS	2
15	41°	3°GS/Sideslip	3
16	0°	S&L	4
17	41°	L/Sideslip	7
18	41°	S&L	8B
19	35°	½(S&L)/½(3°GS)	9B
20	41°	½(S&L)/½(3°GS)	10B

N/A - Not Applicable

S&L - Straight & Level

GS - Glide Slope

Sideslip - Enough to hold aircraft on course during 3 engine approach.

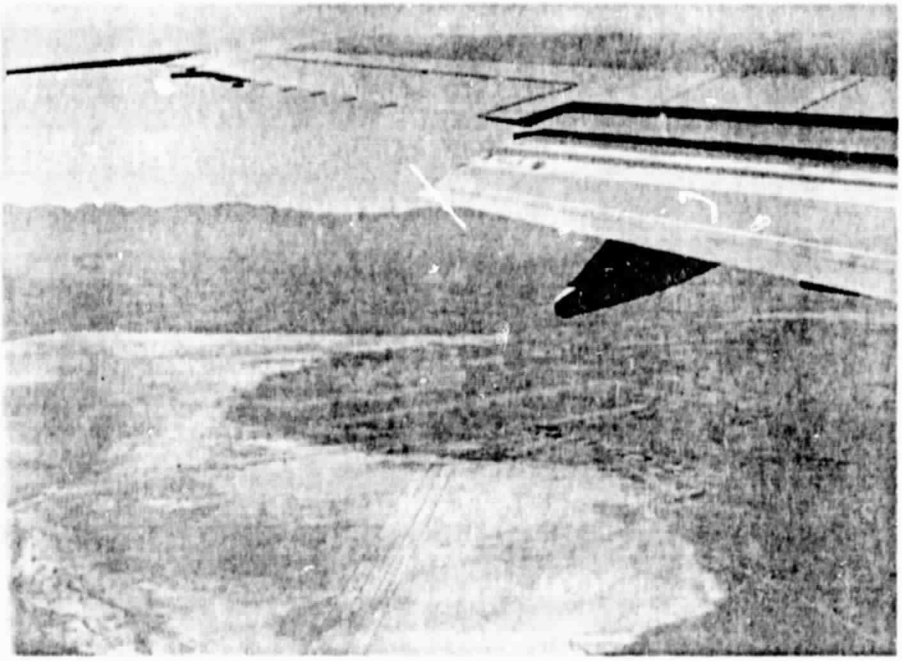

Figure 5 Flaps Being Raised Over Edwards

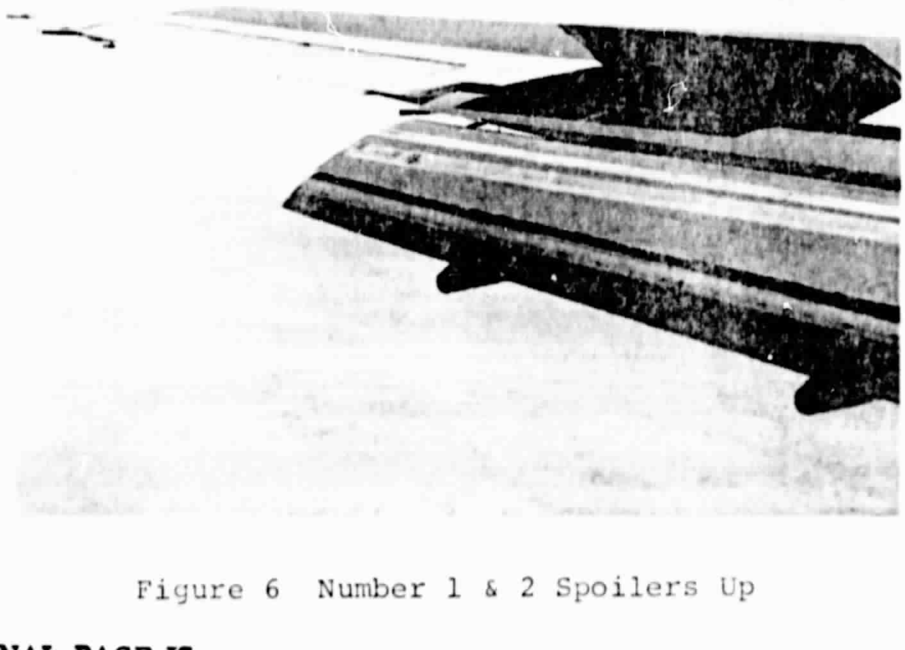

Figure 6 Number 1 & 2 Spoilers Up

3. RESULTS

The PEMS II instrument package recorded the motion data in multiplexed form on ¼-inch magnetic tape. The analog data were then converted to digital form and analyzed at the University of Virginia for each of the segments identified in Figure 4. For each segment the mean and standard deviations of the accelerations and rates, and their cross correlations are obtained. The rms values along with sample analog data may be found in Appendix I and II respectively.

The comfort model was used in this case as a replacement for actual passengers aboard the aircraft in order to determine what passenger reactions would be obtained during the various flight configurations. A detailed description of the development of the model may be found in Jacobson and Richards 1974.

For $\bar{a}_v \geq 1.6\bar{a}_t$ the comfort equation has the form

$$CR = 2.0 + 7.6\bar{a}_t + 11.9\bar{a}_v$$

For the range of accelerations $\bar{a}_v < 1.6\bar{a}_t$

$$CR = 2 + \bar{a}_v + 25\bar{a}_t$$

where $\bar{a}_v$ = rms vertical acceleration

$\bar{a}_t$ = rms transverse acceleration

CR = comfort rating

The comfort ratings have the following designations: 2 - Comfortable; 3 - Neutral; 4 - Uncomfortable; and 5 - Very Uncomfortable.

Figure 7 is a graph of the comfort responses obtained versus the various configurations flown. Actual values are listed in Table 1. They are arranged from smallest (best) to largest (worst) comfort ratings. Figure 8 is a plot of

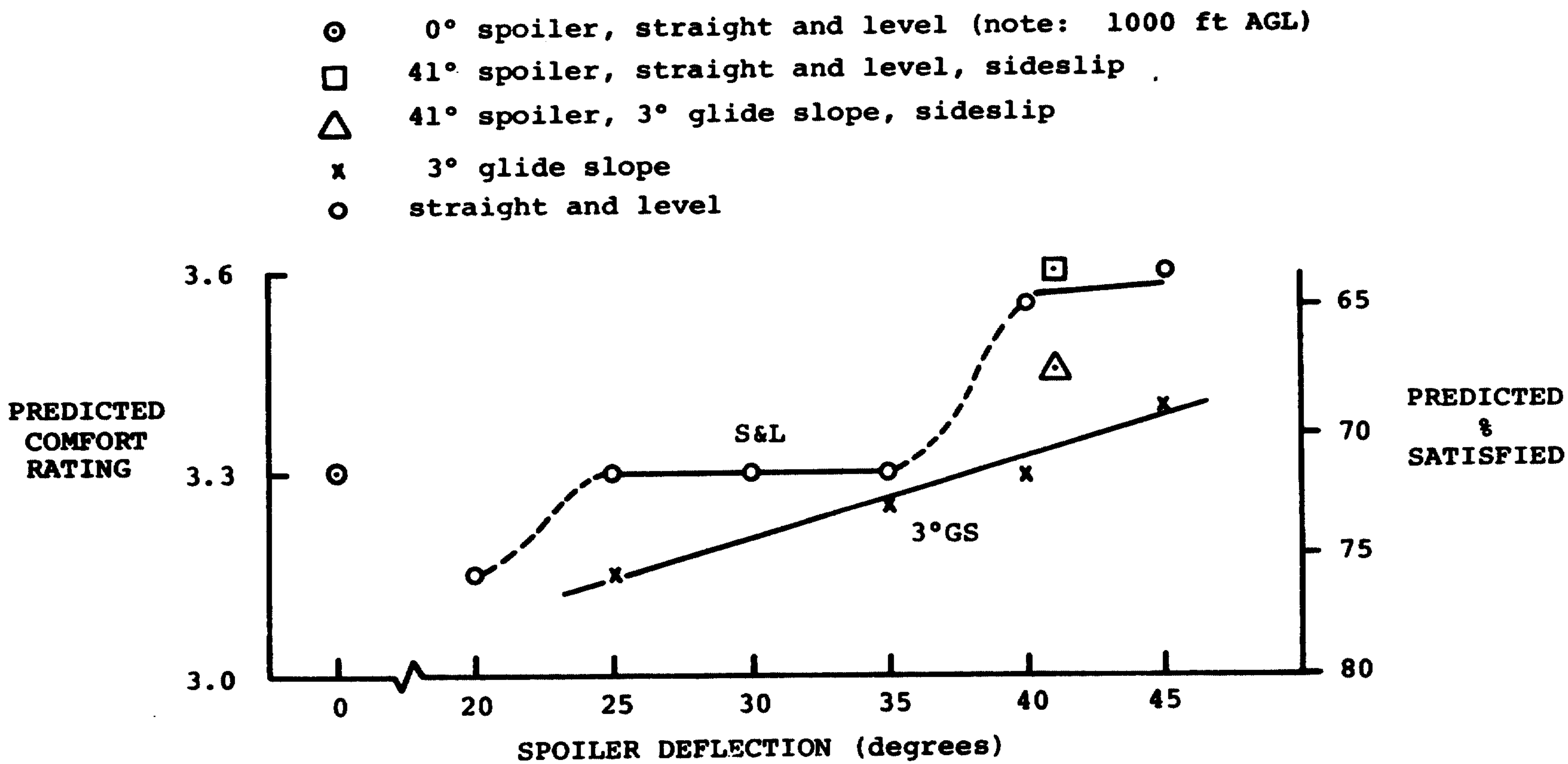

Figure 7 Comfort and Satisfaction Levels by Spoiler Deflection

Table 1 (Predicted Comfort Responses)

	Segment	Comfort Response
3	Climb	2.75 ± .05*
11	25°S/3°GS	3.15
4	20°S/S&L	3.15
12	35°S/3°GS	3.25
16	0°S/S&L	3.30
6	30°S/S&L	3.30
5	25°S/S&L	3.30
7	35°S/S&L	3.30
13	40°S/3°GS	3.30
19	35°S/½(S&L)/½(3°GS)	3.35
20	41°S/½(S&L)/½(3°GS)	3.35
14	45°S/3°GS	3.40
10	30°S/Right Turn	3.40
15	41°S/3°GS/Sideslip	3.45
18	41°S/S&L	3.50
8	40°S/S&L	3.55
9	45°S/S&L	3.60
17	41°S/L/Sideslip	3.60
1	Taxi	3.75
2	Take-off	5.00

* Error estimate based on predicted data accuracy.

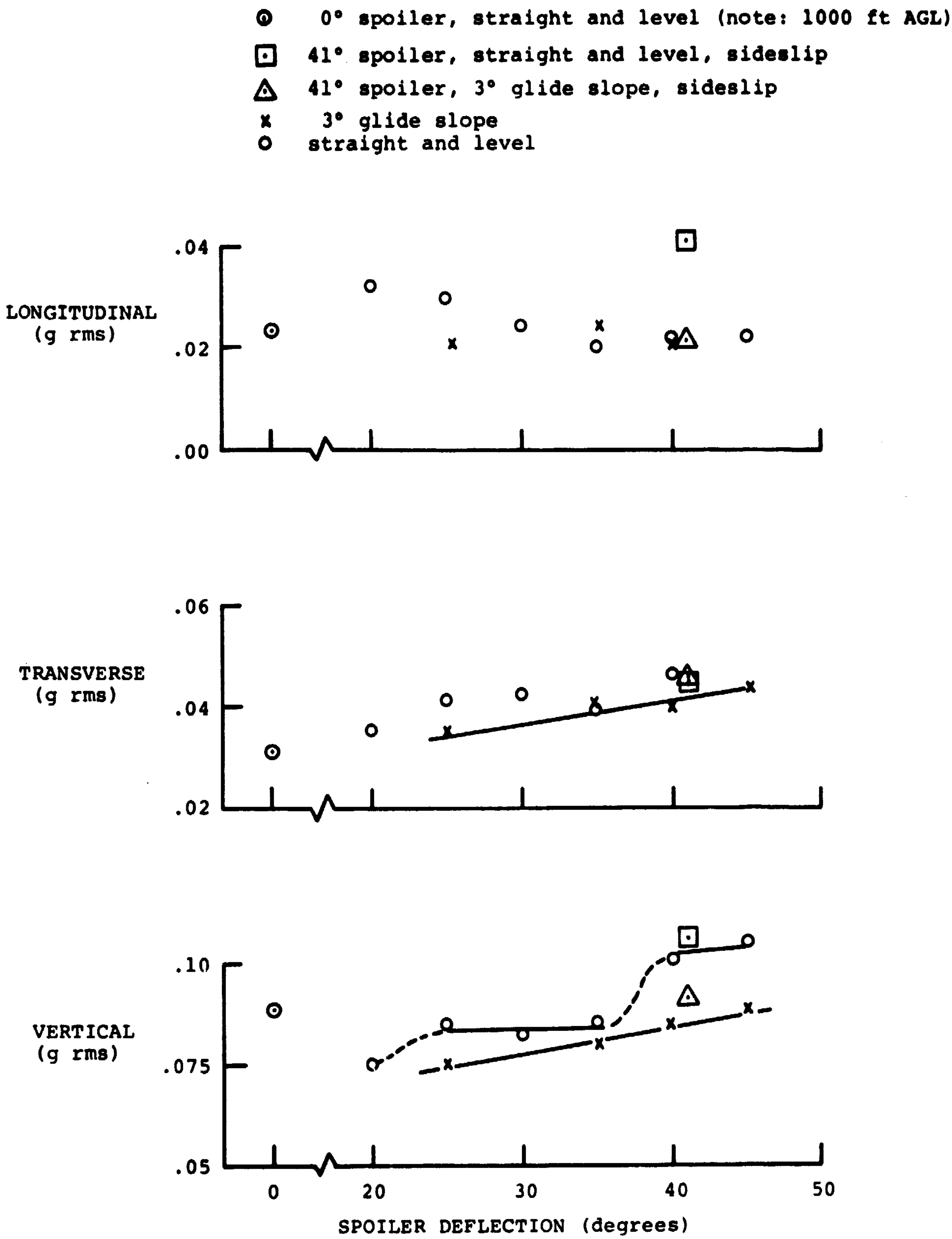

Figure 8 RMS Accelerations

actual rms accelerations in the vertical, transverse, and longitudinal directions while Figure 9 is a plot of actual rms angular rates in pitch, roll, and yaw.

In order to be able to interpret these results the comfort levels are related to a more value oriented variable. This quantity being the percentage of passengers satisfied with the ride. This value transfer function is described in detail in Richards and Jacobson 1975, and Jones 1975. The form of the relationship is as follows:

$$S = \frac{-B - \sqrt{B^2 - 4C(A - CR)}}{2C} \qquad CR < 3$$

$$A = -159/11$$

$$B = 26/55$$

$$C = -0.035/11$$

$$S = 162.5 - 27.5CR \qquad CR \geq 3$$

where S = % of Passengers Satisfied with the Ride

CR = Comfort Rating

Figure 7 also indicates S versus the various configurations flown. Actual values may be found in Table 2.

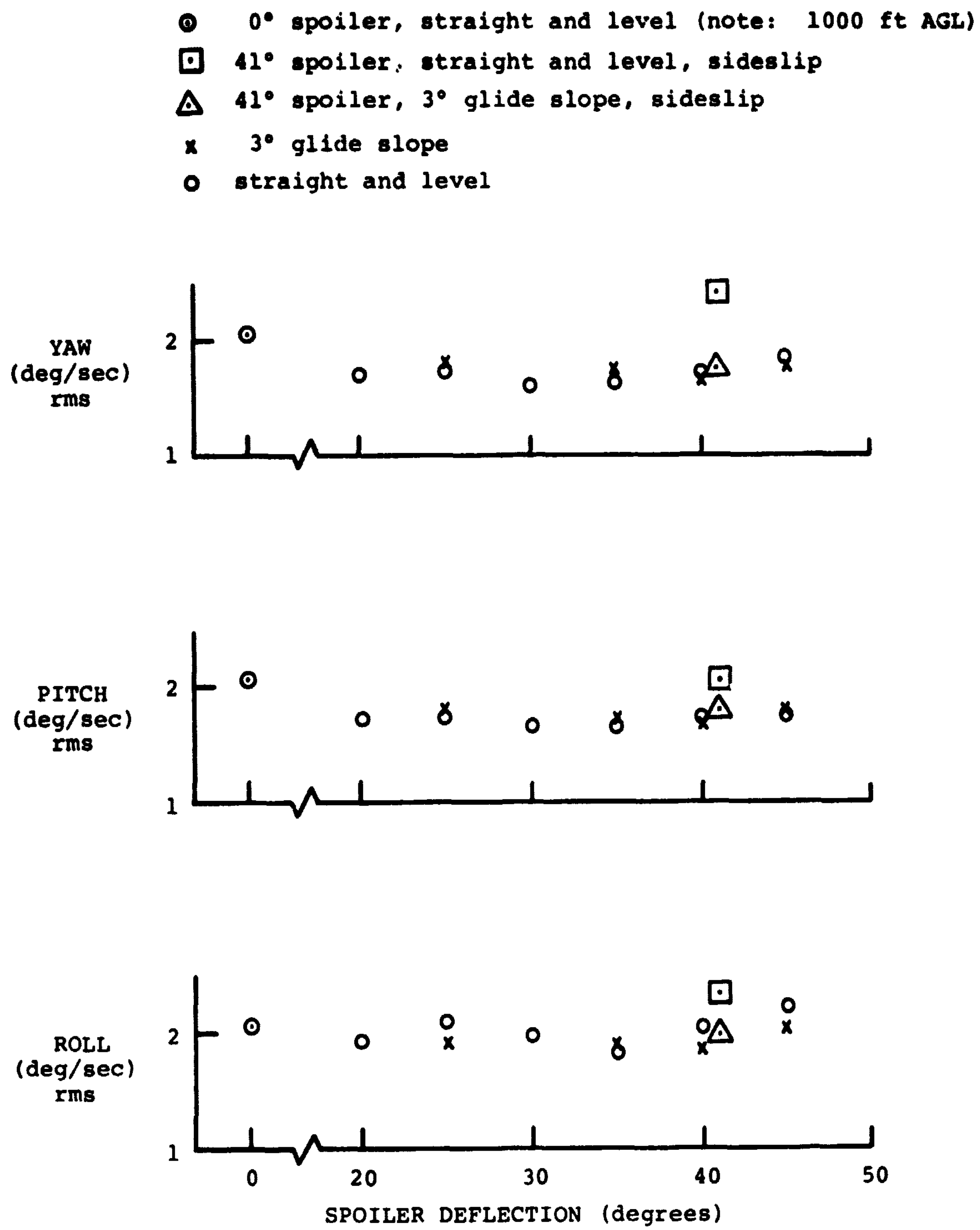

Figure 9 RMS Angular Rates

Table 2 (% Satisfied with Ride)

Segment	S (%)
3	85 ± 1*
11	76
4	76
12	73
16	72
6	72
5	72
7	71
13	72
19	70
20	70
14	69
10	69
15	68
18	66
8	65
9	64
17	63
1	59
2	25

* Error estimate based on predicted data accuracy.

4. DISCUSSION

The results as presented in section 3 lend themselves to interpretation in three areas: 1 - General range of comfort responses predicted; 2 - Effects of aircraft attitude; and 3 - Significance with respect to satisfaction levels.

General Range of Comfort Responses Predicted

As can be seen in Figure 7 all the segments involving spoiler extension fall within one-half a comfort response of each other. This range being between the neutral and uncomfortable levels. Only four of these segments can be interpreted as being uncomfortable segments: 18-41° Spoiler, Straight and Level; 8-40° Spoiler, Straight and Level; 9-45° Spoiler, Straight and Level; and 17-41° Spoiler, Level with Sideslip.

From the location of these segments and the next lowest spoiler setting during straight and level flight, 35° (Segment 7), it appears that for straight and level flight the transition region between a neutral response and an uncomfortable one is 35° - 40° spoiler.

During straight and level flight the responses for 25°, 30°, and 35° spoiler setting are identical. This is significant in that 10° more spoiler can be flown over 25° with no degradation in comfort level. It is also interesting to note that segment 16 (0° Spoiler, Straight and Level) results in a comfort response at a similar level as the 25°, 30° and 35° segments. However, segment 16 was flown at 1000 ft. AGL while the other segments were flown at higher altitudes.

Effects of Aircraft Attitude

Looking at Figures 7 & 8 the effect of flying a 3° glide slope at equivalent spoiler settings as during the straight and level runs can be seen. In each case (25°, 35°, 40°, 45°) the comfort level is improved (lower response) when flying the 3° approach. Flying the 3° approach allows approximately

5° more spoiler to be added over straight and level flight with no sacrifice in comfort response. For example, flying 35° spoiler straight and level results in a comfort response of 3.30. In the 3° glide slope, 40° spoiler results in the same response. Straight and level at 40° spoiler gives a comfort response of 3.55. The 3° approach at 45° spoiler results in a comfort response of only 3.40.

This is significant in that where maximum spoiler deflection is necessary (i.e., terminal areas) one is most likely to be flying the 3° approach and can use the higher spoiler settings without causing an uncomfortable ride. However, other factors affecting aircraft attitude during approach may diminish the comfort level such that a reduction in spoiler setting would be necessary to prevent the ride from becoming uncomfortable.

During segments 10, 15, and 17 the effects of perturbations on the normal flight path of the aircraft are measured. Segment 10 is a right turn with 30° spoiler. Segments 15 and 17 are runs with 41° spoiler with sideslip necessary to hold the aircraft on course with an engine out during a 3° approach and level flight respectively. In each case the above segment's predicted comfort response is worse than their respective segment's response without the maneuvers. (Segment 13 is the comparison for Segment 15.) In each case the maneuver response is approximately 3% worse than the corresponding segment response without the maneuver. Therefore, if one knows that certain maneuvers are to be performed, the the pilot should be aware that these will decrease the comfort level of the passengers at a given spoiler setting.

Significance with Respect to Satisfaction Levels

While the above deals with comfort responses, one needs to know how these levels relate to overall passenger satisfaction. Referring to Table 2 the spread in passenger satisfaction levels for the spoiler segments is 13%. This is certainly a significant value. How significant, however, requires a judgment by the airlines on whether or not a decrease in passenger satisfaction of this magnitude is acceptable with respect to the FAA's value of decreasing aircraft separation. Looking at segment 16 (0° Spoiler, Straight and Level) the passenger satisfaction level is 72%. From the above discussion it was seen that during a 3° approach the comfort responses were decreased. While no segment consisted of 0° spoiler during a 3° approach, taking the mean of the decrease in comfort responses for the differences between straight and level flight and the 3° glide slope for the other segments, subtracting this from the segment 16 response, and obtaining the corresponding satisfaction level, we get 76%. We will interpret this to be the value presently obtained while flying a normal 3° approach in landing configuration with 0° spoiler. If one restricts max spoiler deflection to 41° in the 3° approach then we are talking about a max decrease in passenger satisfaction of about 8% below the present satisfaction level while flying a 3 engine approach.

5. CONCLUSION

Summarizing the results we find that:

1. The general range of comfort levels predicted during the spoiler deflection segments fall between the neutral and uncomfortable responses. This is a band about one-half a comfort response in width lying closer to the neutral response than the uncomfortable response.

2. During straight and level flight, 20°, 25°, 30°, and 35° spoiler all give a similar response with 20° being slightly better than the others.

3. Flying a 3° approach allows approximately 5° more spoiler to be added (over straight and level flight) with no sacrifice in comfort response.

4. Maneuvering the aircraft decreases the comfort level (increased response) by approximately 3%.

5. The range of passenger satisfaction levels for the spoiler deflection segments is 76% (20° Spoiler, Straight and Level) to 63% (41° Spoiler, Level with Sideslip).

6. The maximum degradation of passenger satisfaction over levels now flown and 41° Spoiler, 3° Approach, with sideslip is about 8%.

7. 41° spoiler in the approach mode is the maximum deflection which results in a not uncomfortable mean response allowing for maneuvering during the approach.

Appendix I

(RMS Accelerations, Angular Rates, and Cross Correlations)

APPENDIX I

(RMS Accelerations, Angular Rates, and Cross Correlations)

KEY

Identifier		
5	5	Roll Rate (Deg/Sec)
5	6	Roll-Pitch Cross Correlation $(Deg/Sec)^2$
5	7	Roll-Yaw Cross Correlation $(Deg/Sec)^2$
5	8	Roll-Longitudinal Cross Correlation (Deg/Sec)(g)
5	9	Roll-Transverse Cross Correlation (Deg/Sec)(g)
5	10	Roll-Vertical Cross Correlation (Deg/Sec)(g)
6	6	Pitch Rate (Deg/Sec)
6	7	Pitch-Yaw Cross Correlation $(Deg/Sec)^2$
6	8	Pitch-Longitudinal Cross Correlation (Deg/Sec)(g)
6	9	Pitch-Transverse Cross Correlation (Deg/Sec)(g)
6	10	Pitch-Vertical Cross Correlation (Deg/Sec)(g)
7	7	Yaw Rate (Deg/Sec)
7	8	Yaw-Longitudinal Cross Correlation (Deg/Sec)(g)
7	9	Yaw-Transverse Cross Correlation (Deg/Sec)(g)
7	10	Yaw-Vertical Cross Correlation (Deg/Sec)(g)
8	8	Longitudinal Acceleration (g)
8	9	Longitudinal-Transverse Cross Correlation $(g)^2$
8	10	Longitudinal-Vertical Cross Correlation $(g)^2$
9	9	Transverse Acceleration (g)
9	10	Transverse-Vertical Cross Correlation $(g)^2$
10	10	Vertical Acceleration (g)

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6	9	1.5131427348E-01	1.6275544465E-01	1.5628144145E-01	1.573047063[illegible]
6	10	1.9957197772E-01	2.0253731818E-01	2.0227153619E-01	2.4212916195E-01
7	7	1.8345117569E 00	1.8396358874E 00	1.7577693364E 00	1.7437636925E 00
7	8	1.2545548217E-01	1.3775551319E-01	1.3413046303E-01	1.5401386211E-01
7	9	1.4129387994E-01	1.4697593451E-01	1.4338567853E-01	1.3732739775E-01
7	10	2.3639933785E-01	2.3738847673E-01	2.1893773993E-01	2.5162091951E-01
8	8	2.1773584093E-02	2.9789366580E-02	2.1173235227E-02	2.3926316638E-02
8	9	1.2172157189E-02	1.6653532162E-02	1.4651564881E-02	1.2511697593E-02
8	10	1.4961773555E-02	1.7193732783E-02	1.1945193639E-02	9.9204355589E-03
9	9	4.4336459415E-02	3.9199990031E-02	3.3717811108E-02	4.0059171517E-02
9	10	1.3699431924E-02	1.6782792285E-02	1.3295003213E-02	2.7318146080E-02
10	10	1.2435929594E-01	9.2732455519E-02	7.4843518436E-02	7.9168595374E-02

ORIGINAL PAGE IS
OF POOR QUALITY

IDENTIFIER		SEGMENT NUMBER			
		13	14	15	16
5	5	1.8457023521E 00	2.0113415715E 00	1.9582121086E 00	2.3621874332E 00
5	6	1.6364593365E 00	1.7345532179E 00	1.7083933353E 00	1.9659742327E 00
5	7	1.5765339618E 00	1.6817984561E 00	1.6703661182E 00	1.9249171319E 00
5	8	1.2144450843E-01	1.2629285455E-01	1.2349209934E-01	1.4763394337E-01
5	9	1.7315155263E-01	1.9863609838E-01	1.9138275087E-01	1.5755252144E-01
5	10	2.1414576471E-01	2.1553087631E-01	2.1651712363E-01	2.3256435871E-01
6	6	1.6518665552E 00	1.7762925625E 00	1.7713626895E 00	2.3559997559E 00
6	7	1.5796445608E 00	1.7179152966E 00	1.6936575174E 00	1.9836485516E 00
6	8	1.2324919552E-01	1.2727233768E-01	1.2366221174E-01	1.5410323928E-01
6	9	1.5133538334E-01	1.6443826258E-01	1.5585352480E-01	1.4753074944E-01
6	10	2.1825596204E-01	2.1134771497E-01	2.0338998735E-01	2.0571303345E-01
7	7	1.6239155723E 00	1.8035632434E 00	1.7567549944E 00	2.0514285554E 00
7	8	1.3596692093E-01	1.3956315968E-01	1.3383659723E-01	1.5565679967E-01
7	9	1.2879629433E-01	1.3650368154E-01	1.2923708556E-01	1.3391616943E-01
7	10	2.2966752736E-01	2.4115188423E-01	2.2932569304E-01	2.4571311375E-01
8	8	2.0667143166E-02	2.1323356777E-02	2.3562741126E-02	2.2662833333E-02
8	9	1.1746549630E-02	1.2274883687E-02	1.2625289399E-02	1.3363637035E-02
8	10	5.1362249359E-03	5.7477131486E-03	9.2954917421E-03	4.5603077519E-03
9	9	4.2256589651E-02	4.4355582446E-02	4.5611269772E-02	3.3721335717E-02
9	10	1.8054815551E-02	2.3744968597E-02	2.3593747327E-02	1.2257955930E-02
10	10	8.4053099155E-02	8.7875276834E-02	9.3957103839E-02	8.8658995926E-02

IDENTIFIER | SEGMENT NUMBER

IDENTIFIER		17	18	19	20
5	5	2.3165905716E 00	1.9731501477E 00	2.2340748596E 00	2.0114836693E 00
5	6	1.8255993294E 00	1.6721779138E 00	2.0555509934E 00	1.5753219555E 00
5	7	1.7459793737E 00	1.7836633262E 00	1.9650688171E 00	1.7980922461E 00
5	8	1.7105831434E-01	1.5476737916E-01	1.6364504235E-01	1.7532545328E-01
5	9	2.0823839307E-01	1.9946415722E-01	2.0525377989E-01	1.9132380186E-01
5	10	2.2183282673E-01	2.4185793122E-01	2.4446394036E-01	2.3771737516E-01
6	6	2.0642244816E 00	1.9344719648E 00	2.1018257141E 00	1.9551620483E 00
6	7	2.0982749462E 00	1.6587684155E 00	2.0292222580E 00	1.8628916589E 00
6	8	1.9655077327E-01	1.5788117251E-01	1.7383266985E-01	1.8750639265E-01
6	9	1.9159491360E-01	1.6515317559E-01	1.9217149913E-01	1.7362646759E-01
6	10	3.2265001535E-01	2.4107576907E-01	2.5827169418E-01	2.4993477762E-01
7	7	2.4074645042E 00	1.7947775126E 00	2.1127889156E 00	1.9439586401E 00
7	8	2.2473657131E-01	1.6784007847E-01	1.8300287426E-01	1.9124476132E-01
7	9	1.6085537851E-01	1.5582239628E-01	1.8610298634E-01	1.5772959593E-01
7	10	3.7119609118E-01	2.4516763315E-01	2.8656369448E-01	2.7031257749E-01
8	8	3.9953578254E-02	3.5976231398E-02	3.6283411086E-02	3.9383512573E-02
8	9	1.9347556745E-02	1.7337847531E-02	1.6272766516E-02	1.7227341541E-02
8	10	3.0378463236E-02	1.0422503227E-02	1.7765553666E-02	1.6512630135E-02
9	9	4.5144267358E-02	4.9359476156E-02	4.4175405855E-02	4.3502865189E-02
9	10	2.9352944344E-02	2.3793663108E-02	2.6570532669E-02	2.4436223710E-02
10	10	1.0592260212E-01	9.3793305917E-02	8.5822395930E-02	8.5366709603E-02

Appendix II
(Sample Analog Data)

APPENDIX II

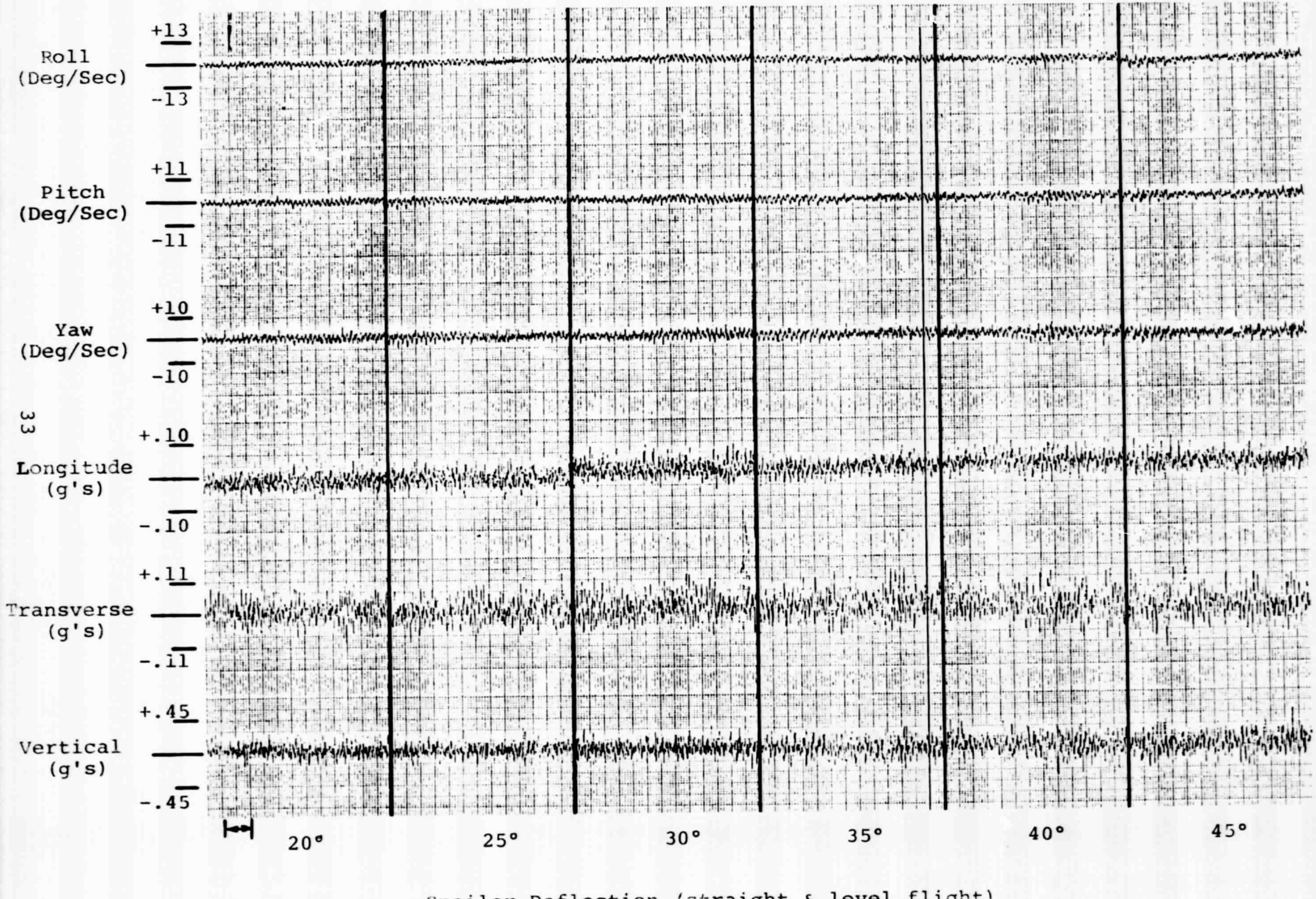
(Sample Analog Data)

Straight & Level Flight - 20°, 25°, 30°, 35°, 40°, 45° Spoiler Deflection

Climb

3° Glide Slope - 25°, 35°, 40°, 45° Spoiler Deflection

3° Glide Slope - 41° Spoiler Deflection - Sideslip


Roll (Deg/Sec)
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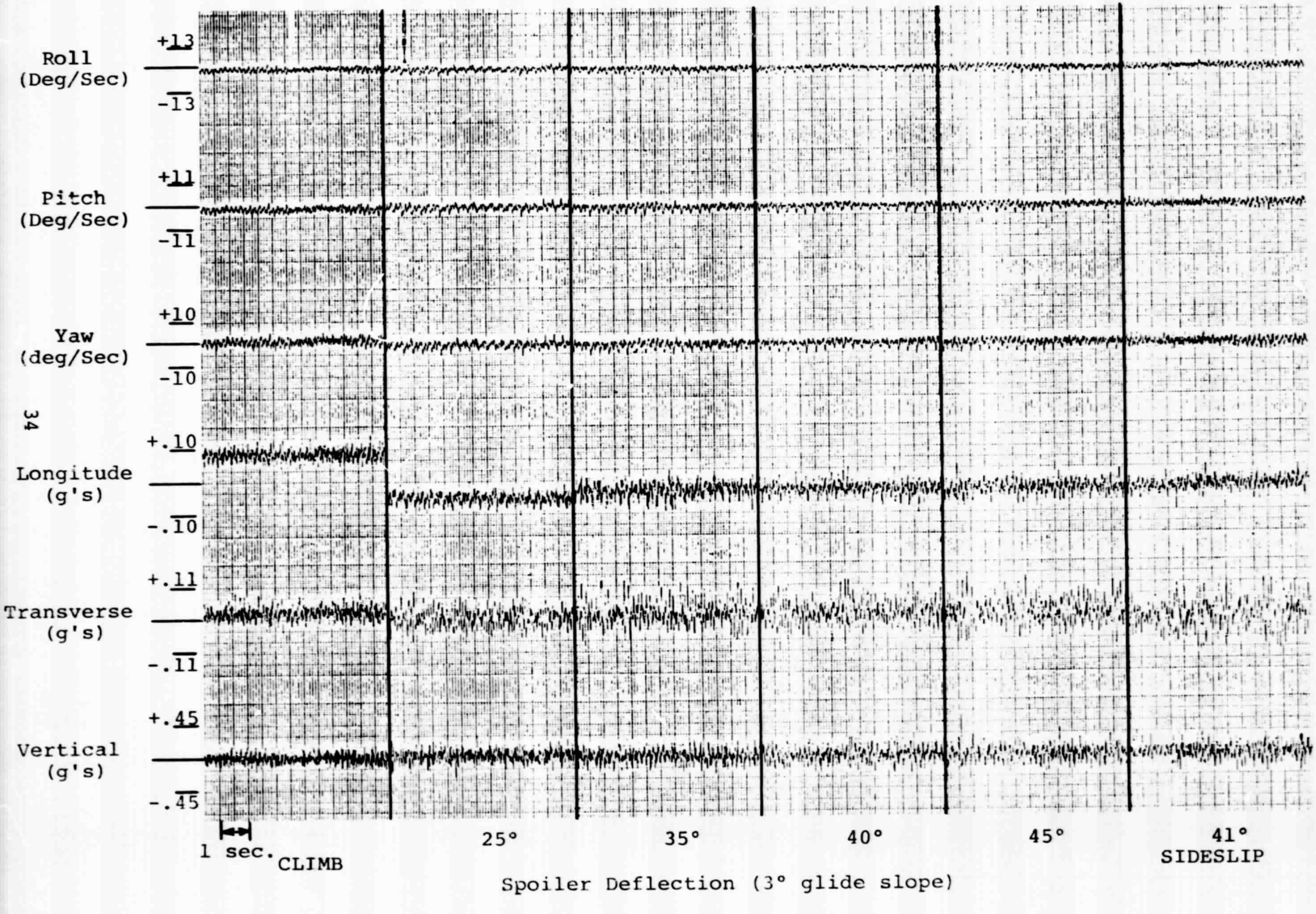
-13
Pitch (Deg/Sec)
+11
-11
Yaw (Deg/Sec)
+10
-10
Longitude (g's)
+.10
-.10
Transverse (g's)
+.11
-.11
Vertical (g's)
+.45
-.45
20°
25°
30°
35°
40°
45°
Spoiler Deflection (straight & level flight)


Roll
(Deg/Sec)
+13
-13
Pitch
(Deg/Sec)
+11
-11
Yaw
(deg/Sec)
+10
-10
Longitude
(g's)
+.10
-.10
Transverse
(g's)
+.11
-.11
Vertical
(g's)
+.45
-.45
1 sec.
CLIMB
25°
35°
40°
45°
41°
SIDESLIP
Spoiler Deflection (3° glide slope)

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