AERODYNAMIC LOW SPEED BUFFET BOUNDARY CHARACTERISTICS OF A HIGH SPEED BUSINESS JET

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Abstract

Low speed buffet boundary flight testing of a highly swept-wing high-speed business jet has been conducted. The test data covered a Mach Number range of 0.2 to 0.65, a Reynolds Number range of 8x10^6 to 16x10^6, and pitch and incidence (angle-of-attack) rates of –0.5 to +4 degrees per second. The types of buffet onset manoeuvres included straight 1g flight, straight stalling manoeuvres of 0.75 knot/sec deceleration, low-angle of bank turns, steep turns and rapid pitch-up manoeuvres. In each case, the aerodynamic coefficient characteristics of buffet onset have been analysed. Buffet levels were more observable in fluctuations and mean value changes in C_D rather than in C_L. The highest buffet levels occurred during low altitude stalling manoeuvres. As expected, the analyses highlighted differences in C_L and C_D buffet characteristics with incidence for low and high pilot-induced pitch and incidence rates, and with Mach Number. However, no definite variation of buffet onset incidence, nor characteristics, with Reynolds Number were observed. Of particular interest were the different aerodynamic characteristics for the combination of near-zero incidence rate, -0.1 to 0.4 degrees per second, and correspondent manoeuvre pitch rates of zero to 4 degrees per second, over the buffet Mach Number range of 0.5 to about 0.6 and a high altitude range of 32,000 to 35,000 feet.

1 Introduction

For the Type Certification of ‘turbojet’ Transport Category aeroplanes, in accordance with the regulations of FAR 25[1] or the requirements of JAR 25[2], the high (Mach) and low speed (pre-stall) buffet boundaries must be defined and scheduled in the Approved Flight Manual for the aeroplane Type.

The high speed Mach buffet boundary is defined by the occurrence of buffet due to shock-induced boundary layer flow separation, and is therefore, generally critical at design-dive Mach Number as validated in flight (M_{DF}) at maximum certificated operating altitude. The low-speed buffet boundary is defined by the occurrence of buffet due to high-lift-induced boundary layer flow separation. As such, it can be associated with Mach Number effects, but the principal effector is Reynolds Number.

Nevertheless, in both cases, flight-path dynamics can have significant effects upon the occurrence of buffet onset (which defines the buffet boundary). An example of the first order importance of flight dynamic considerations upon low-speed buffet onset is examined, using aerodynamic flight test data, and the potential implications for Type Certification flight test are discussed.

2 Experimental Details

2.1 Flight Test Aeroplane and Instrumentation

The aeroplane used for the gathering of flight data was an intermediate capacity highly swept-wing high-speed business jet.

Two inertial data measuring systems were used on-board the flight test aeroplane:

(1) an angular rate and linear acceleration measurement system; and
(2) a six-component Inertial Measurement Unit (IMU) developed by the NRC[3], consisting of a Honeywell HG1700 FOG and a data reduction and processor unit (DRP), used to bound and minimise the IMU inertial sensing errors (based upon Kalman filtering of FOG output and GPS reference inertial information), and to data stream and record the inertial data; the NRC IMU/DRP system has very high sampling rate potential (600 Hz); furthermore, the data is minimally filtered prior to being data-bussed for recording, and is therefore sensitive to acceleration loads induced by buffet occurrences; on this occasion, a data sampling rate of 64 Hz was used for data acquisition.

2.2 Flight Test Manoeuvres

The range of flight test manoeuvres from which low-speed buffet onset boundary data has been analysed, included:
(1) flap-UP stalling (AUTO-slat extension at stall-warning stick-shaker activation was a Type Design characteristic);
(2) straight and level flight, at low angular rates of pitch and incidence, α;
(3) low angle-of-bank, ϕ, turning flight;
(4) medium ϕ turning flight;
(5) high ϕ turning flight; and
(6) dynamic '2311' pitch-up manoeuvres.

2.3 Data Reduction

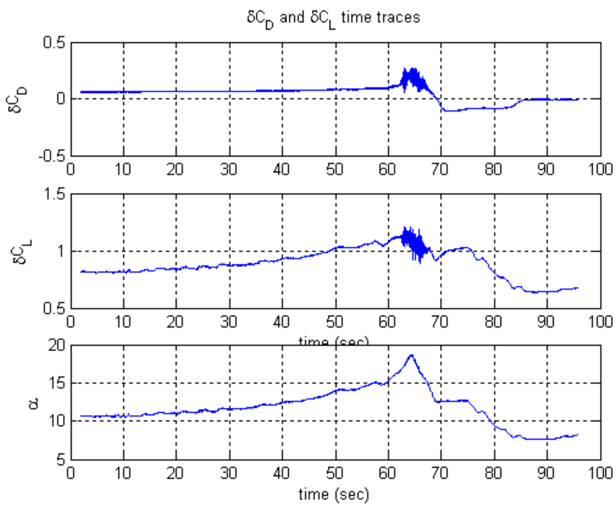
Data has been reduced by the application of the quasi-steady equations of motion for aerodynamic normal and axial forces, Z and X respectively, decoupled from the lateral/directional equations of motion. No thrust model has been used for the data reduction, therefore with the exception of stalling manoeuvres, the C_L and C_D data has been presented in 'Δ' form, with reference to an initial quasi-steady trim condition, for which $X=T=T_o$, the initial thrust condition. Therefore, for cases where thrust has changed due to significant air data changes during manoeuvres, or due to thrust lever angle (TLA) changes, step offsets are observed in ΔC_L and ΔC_D characteristics.

In the case of stalling manoeuvres, such a data reduction process results in mostly negligible ΔC_L with increasing α, thereby validating the subsequently applied assumption that IDLE engine thrust is negligible compared to X_o. Hence, for stalling manoeuvres the data reduction provides C_L and C_D time-trace relationships with α. Buffet onset incidence is designated as α_B.

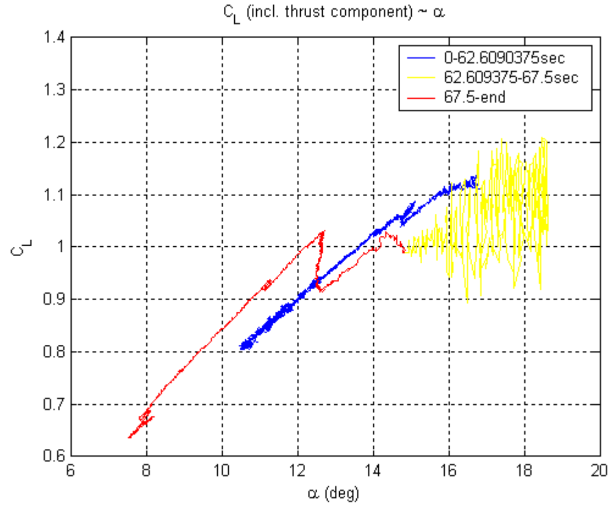
3 Results and Discussion

3.1 Stalling Manoeuvres

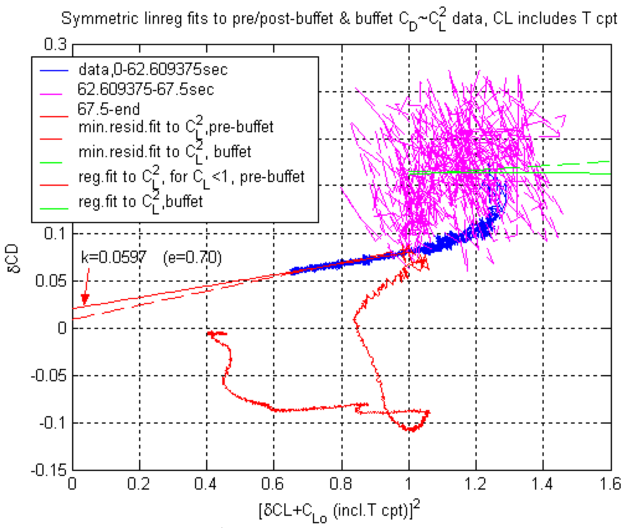
Figures 1 and 2 show the time-trace and C_L, C_D characteristics for flap-UP stalling manoeuvres, conducted at 12-13,000 feet, with mean deceleration rates of about ¾ knots per second. Associated pitch and incidence rates were low to moderate, up to about 2 deg/sec. Because of the IMU sensitivity to unsteady axial and normal linear accelerations, a_X and a_Z, the occurrence of buffet is highly visible in the estimated C_L and C_D time-trace waveforms, for example in Fig.1 between times of 63 and 67 seconds. Following the onset of buffet, the buffet levels were quite high, equating to C_L variations of ± 0.05 and C_D variations of ± 500 drag counts. In the Fig.1 manoeuvre, a thrust lever advance was used during the recovery, whereas there was no change during the Fig.2 manoeuvre.



(a) C_L , C_D and α time-traces

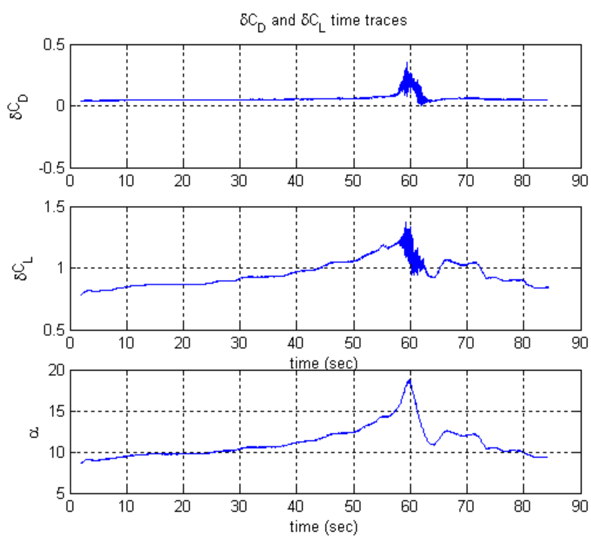


(b) lift curve with α: before (a=3.301) (auto-slat extension at α=15°), during buffet (a=1.697) and post-buffet (a=4.554, lower incidence) (auto-slat retraction at α=14.7°, thrust advance at α=12.6°).

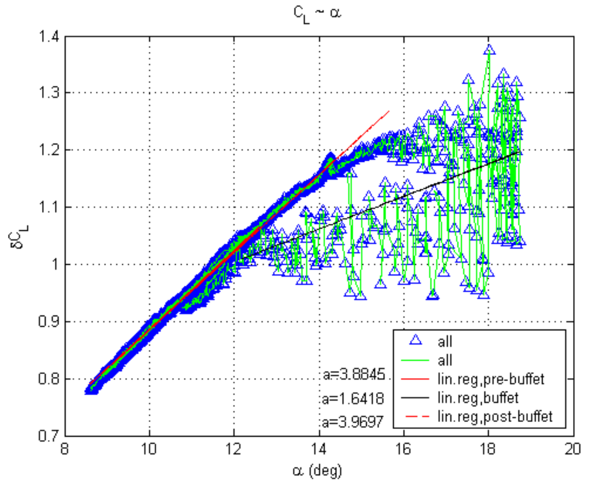


(c) C_D with C_L^2 ('pre-buffet' defined as t=0-62.6sec)

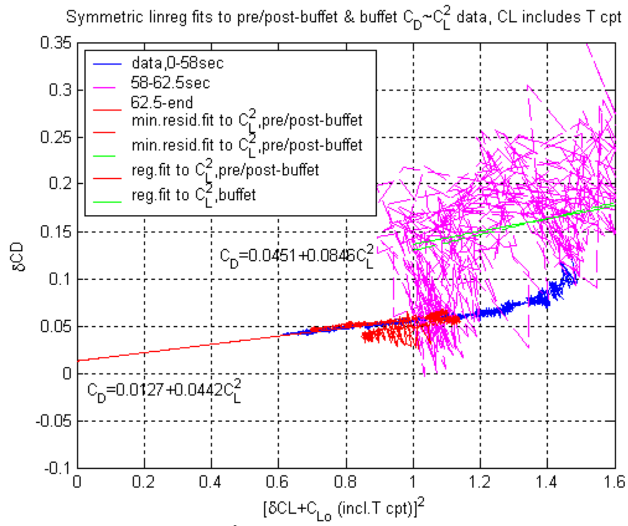
Figure 1 – buffet characteristics, stalling manoeuvre, thrust lever angle (TLA) advance upon recovery: **Pa=13,062ft; M=0.267; Rec=12.99x10^6; W=29,270 lb; flap UP stall; α_B=16.84° at [q ∂α/∂t]=[0.65 1.2]**



(a) C_L , C_D and α time-traces



(b) lift curve with α: before (a=3.005) (auto-slat extension at α=14.3°), during buffet (a=1.642) and post-buffet (a=3.970, lower incidence); greater buffet hysteresis on reducing incidence compared to Fig.1 stalling manoeuvre.



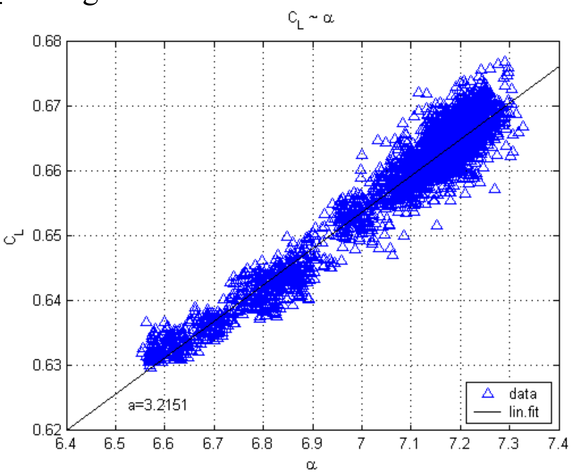
(c) C_D with C_L^2 ('pre-buffet' defined as t=0-58sec)

Figure 2 – buffet characteristics, stalling manoeuvre, constant TLA: **Pa=12,252ft; M=0.241; Rec=11.66x10^6; W=27,274 lb; flap UP stall; α_B=15.7° at [q ∂α/∂t]=[1.2 2]**

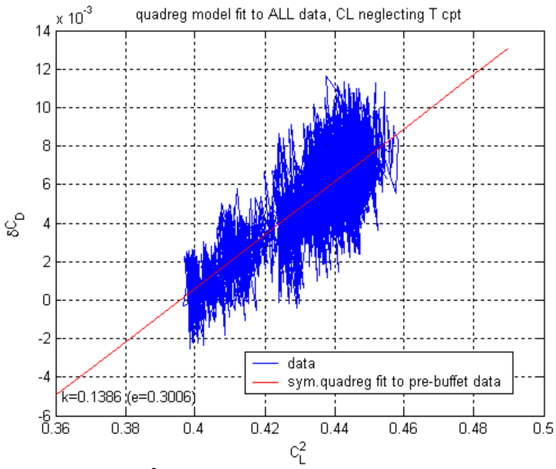
Comparing the drag characteristics of the two manoeuvres (Fig.1 and 2), conducted at differing weights but similar airspeed decelerations, it is seen that the C_D buffet hysteresis loop was greater for the second manoeuvre, for which the C_D ~ C_L relation recovered post-stall to overlay the pre-stall linear drag polar segment for $C_L^2 \leq 1$; the pre-stall linear segment slopes were different for the two manoeuvres, in part probably due to differing flight-path effects, including that of thrust decay at the higher airspeed of the first, heavier-weight, manoeuvre.

3.2 Straight and level flight buffet onset

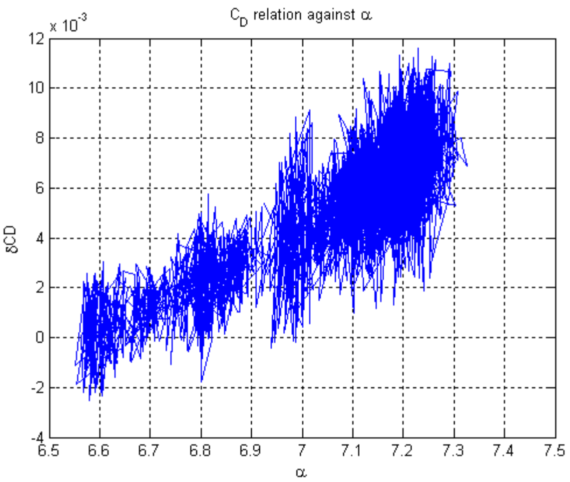
Figure 3 presents the aerodynamic characteristics for buffet onset during a very slow deceleration in level flight, at 43,000 feet. The buffet onset abruptly affects C_D, but to a lower magnitude than stalling flight; compared to drag variations before buffet onset, the buffet level equates to ΔC_D of about $\pm$20 drag counts.



(a) lift curve with α (linear regression, a=3.215 rad^{-1})



(b) C_D with C_L^2 (linear fit pre-buffet, k=0.1386, e=0.3006)

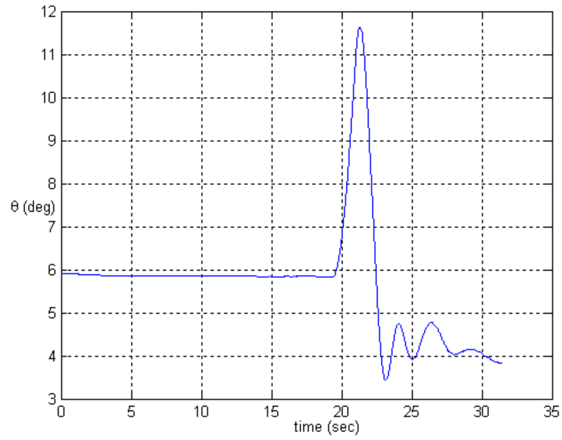


(c) C_D with α ($\alpha_{BUFFET} \approx 7°$)

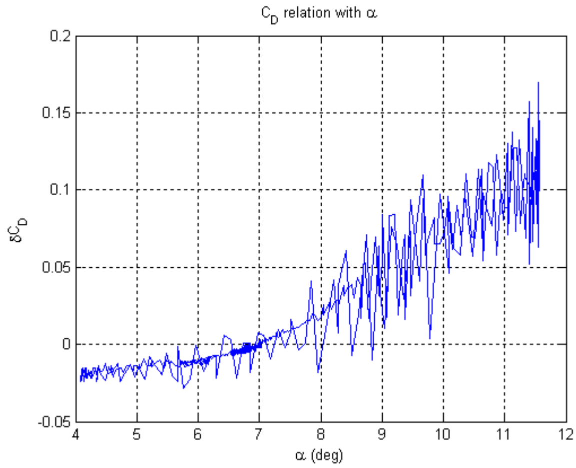
Figure 3 – buffet characteristics, straight and level flight.
Pa=43,000ft; M=0.638 ; α_B=6.95° at [q ∂α/∂t]=[0 0] °s^{-1}

3.3 Pitch-up manoeuvre buffet onset

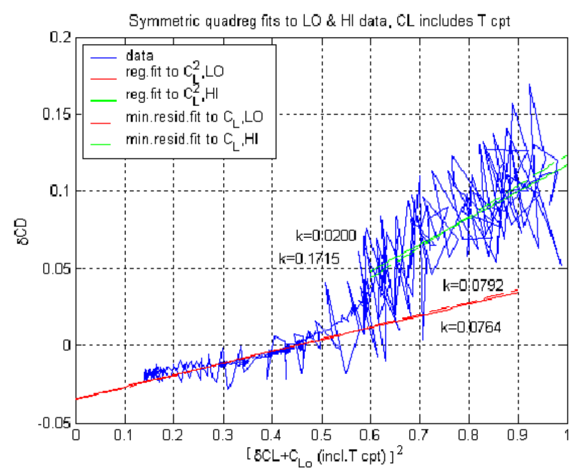
Figure 4 presents the C_L and C_D characteristics for an abrupt pitch-up manoeuvre, conducted at 43,000 feet. The incidence rate, $\partial\alpha/\partial t$, delayed the onset of buffet, however the buffet onset was sharp (in terms of C_L and C_D variations), and the level somewhat greater than that which occurred in straight and level flight, equating to C_L variations of $\pm$0.035 and C_D variations of $\pm$40 drag counts.



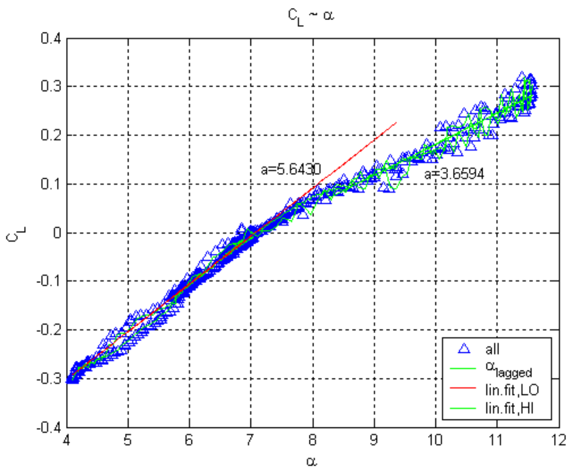
(a) pitch angle timetrace



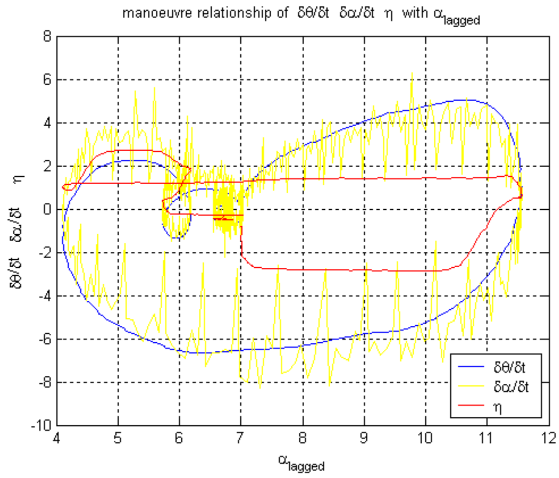
(b) derived C_D characteristics with α.



(c) $C_D \sim C_L$ (with α_{BUFFET}=8.7°)



(d) C_L characteristics



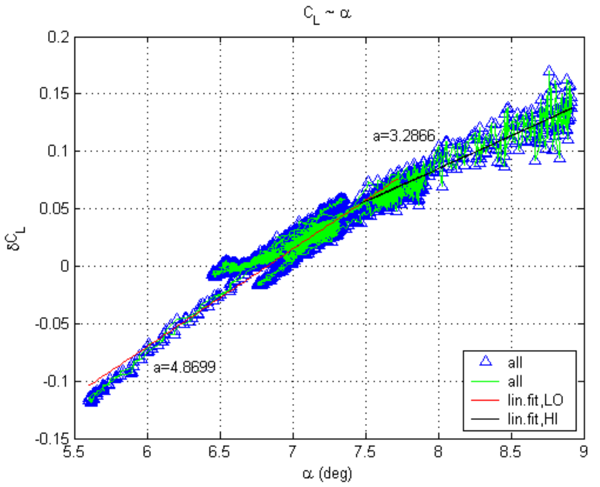
(e) state data: pitch and incidence rates (deg/sec) and elevator deflection (deg)

Figure 4 – buffet characteristics, pitch up manoeuvre.
Pa=43,000ft; M; α_B=8.7°

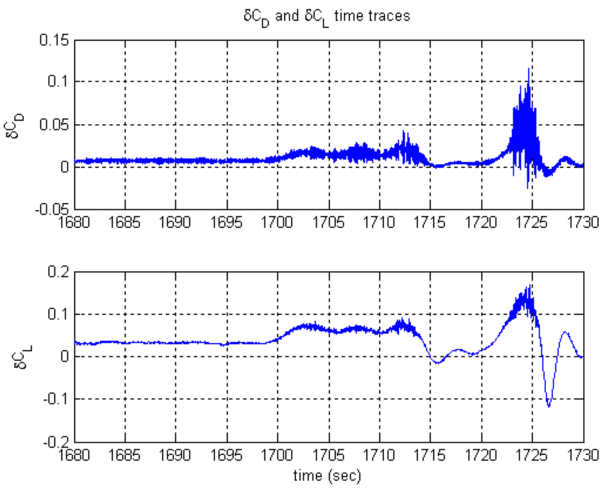
In the pitch-up data analysis presented in Fig.4, the lagging development of unsteady lift force to change in α has been accounted for by applying the Wagner indicial function, as applied to aeroelastic analyses[4], to α, thereafter denoted as α_{lagged}.

3.4 Low ϕ turning flight buffet onset

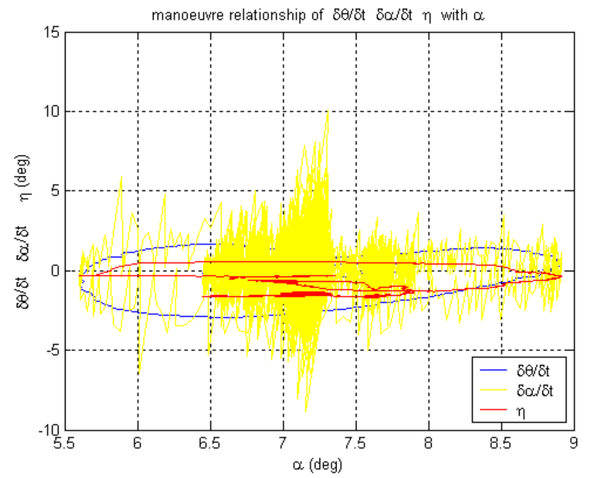
Figure 5 shows the C_L and C_D characteristics for buffet onset in a low angle-of-bank level turn, at an associated low pitch rate of 1-1.5 deg/sec (and a similar incidence rate), conducted at 45,000 feet. Of particular note, the C_L and C_D time-traces and lift / drag curves with α show a sharp low-amplitude buffet onset, followed by progressively increasing buffet levels with increasing incidence, α, to peak values of ΔC_L of $\pm$0.02 and ΔC_D of $\pm$15 drag counts.



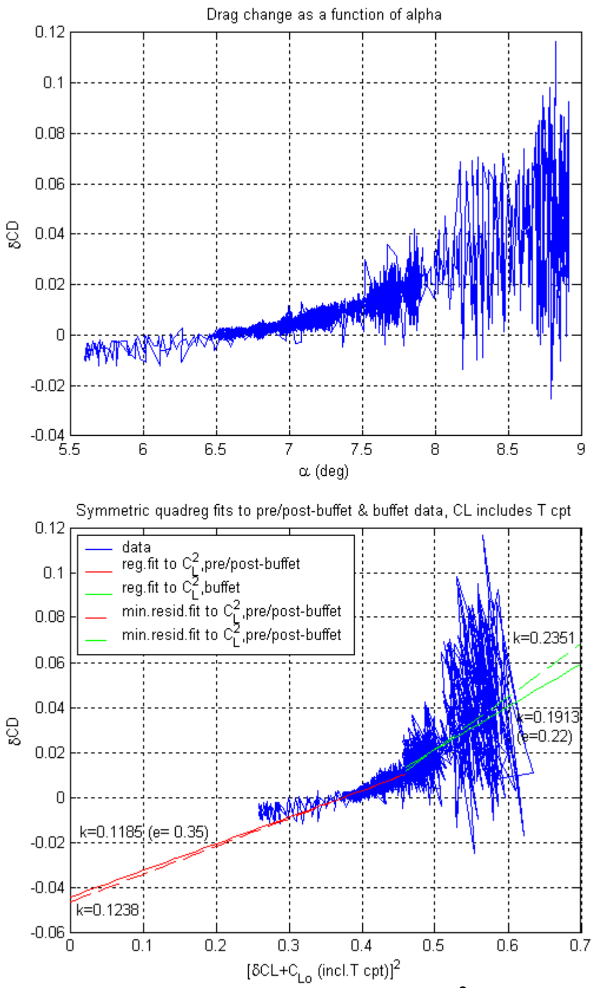
(a) C_L characteristics; in buffet, a 33% loss of lift curve slope occurred.



(b) C_L and C_D timetraces.



(c) maps of incidence and pitch rates (deg/sec) and elevator angle (deg) maps with α

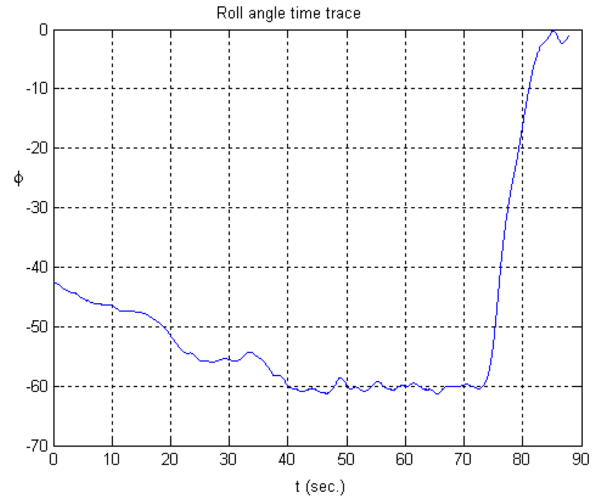


(d) C_D characteristics with α and C_L^2

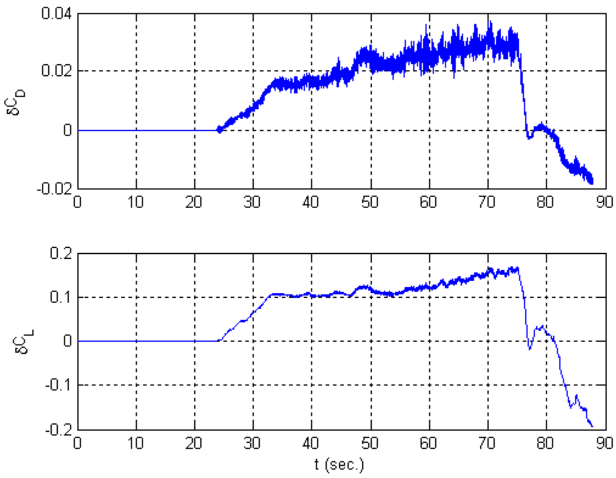
Figure 5 – buffet characteristics in low angle-of-bank level turning manoeuvre; **Pa=45183ft; M=0.6443; Rec=8.6x10^6; W=31,000 lb; α_B=7.5° at [q ∂α/∂t]=[1 0] °s^{-1} and α=8.0° at [q ∂α/∂t]=[0.8 1.2] °s^{-1}.**

3.5 Steep turning flight buffet onset

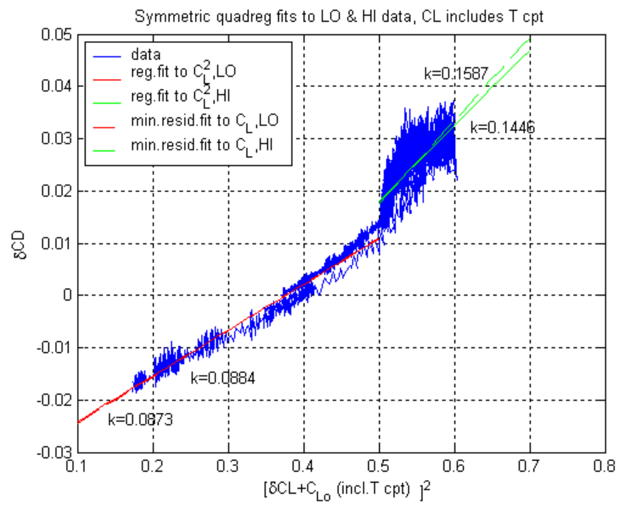
The buffet onset characteristics during steep turn are presented in Figure 6. The manoeuvre was conducted at 45,000 feet, with a quasi-steady pitch rate of 4 °s^{-1}. Once again, the buffet onset was sudden (to a ΔC_D level equating to ±30 drag counts), followed by a mild and progressive rise in buffet level with increasing incidence, to about ±60 drag counts.



(a) angle of bank time trace



(b) derived δC_D and δC_L timetraces



(c) C_D against C_L^2 relationship

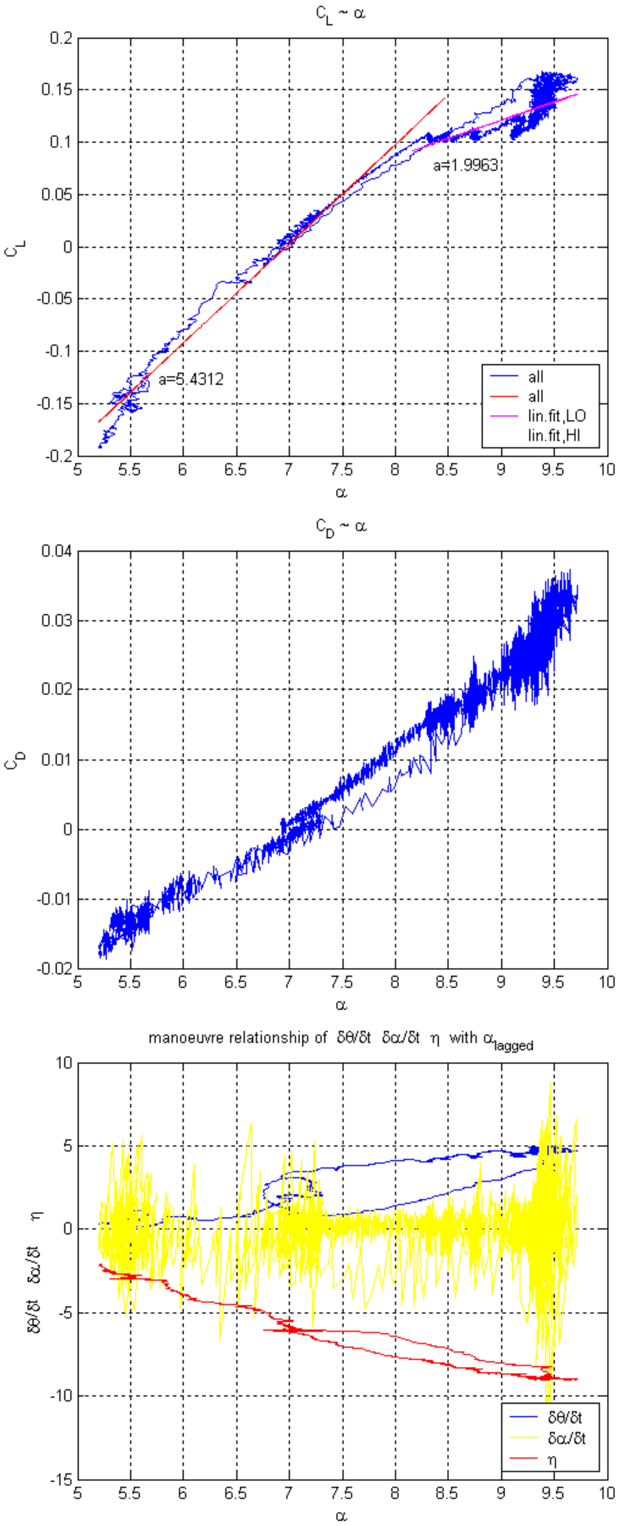
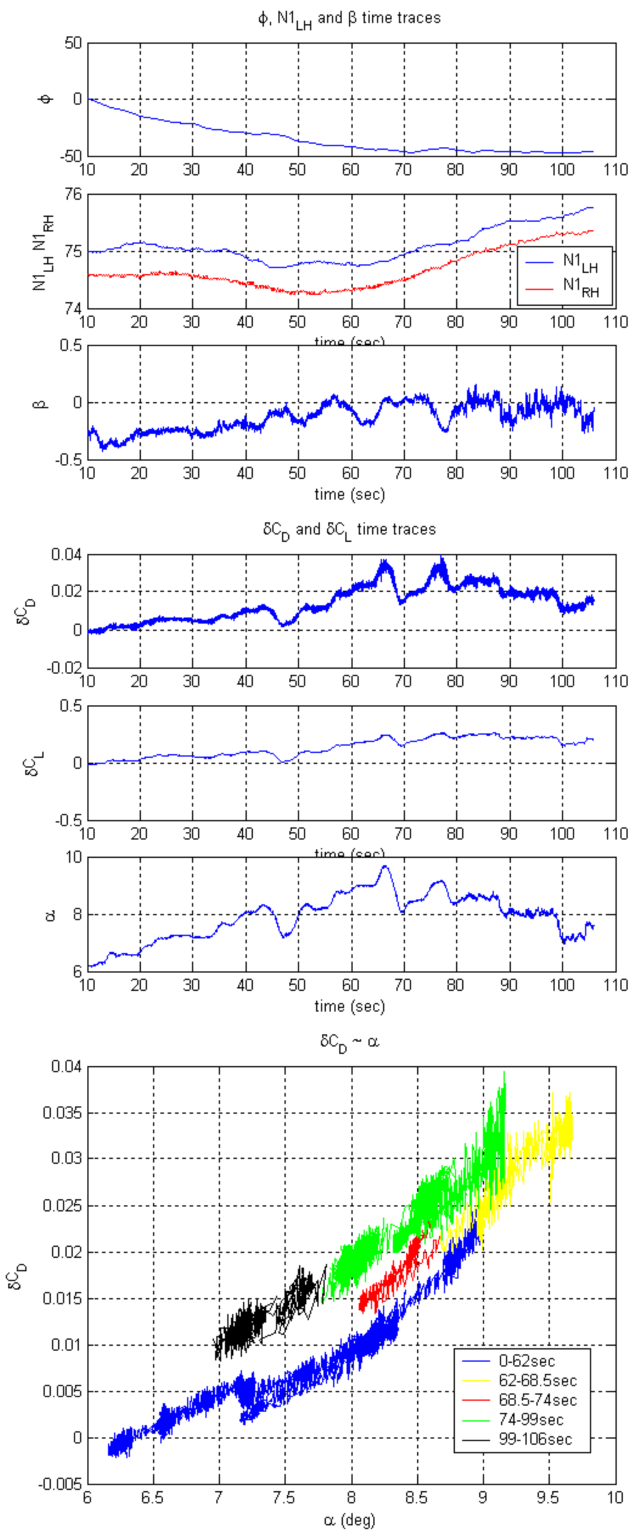
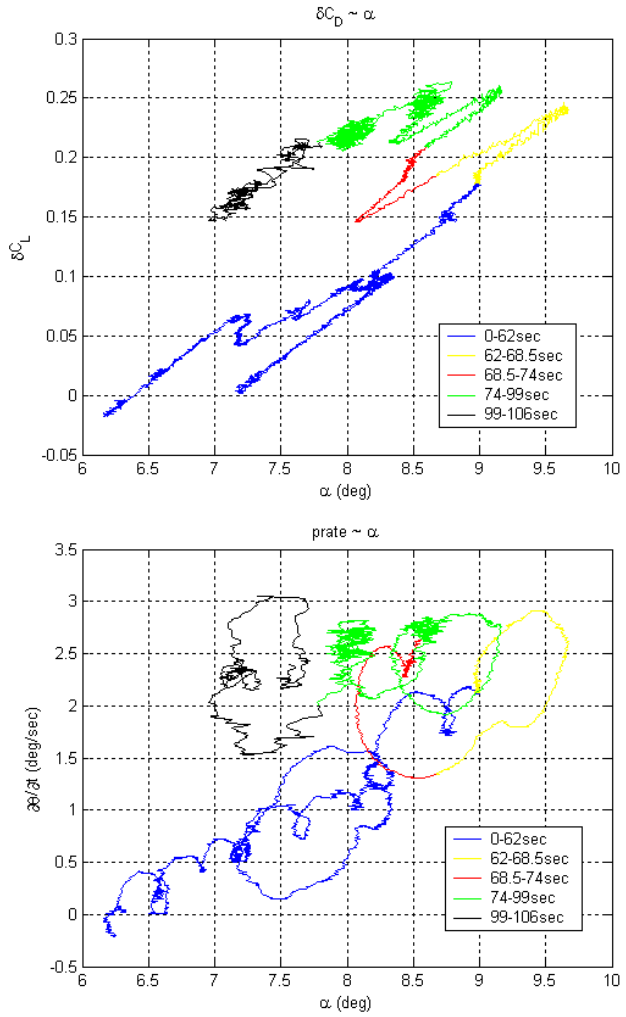


Figure 6 – buffet characteristics in a steep turning flight manoeuvre ~ α (deg); **Pa=31,190ft; M=0.578; Rec=15.67x10^6; W=28,717 lb; steep turn; α_B=8.3° at [q ∂α/∂t]=[4 0.3].**

Additional buffet onset C_L and C_D data during a further steep turn manoeuvre is presented in Figures 7 and 8. Fig.7 covers buffet onset during the first half of the manoeuvre, Fig.8, during the second half. Included in the figures is additional state data of sideslip angle, β, engine rotational speed, N1, and a_z. The N1 data is presented to qualitatively indicate changes in the state of engine thrust during the manoeuvre. Given that no accounting for engine thrust changes was included in the C_L and C_D derivation, actual changes in thrust tracked through as apparent changes in C_L and C_D, amidst buffet-induced variations.





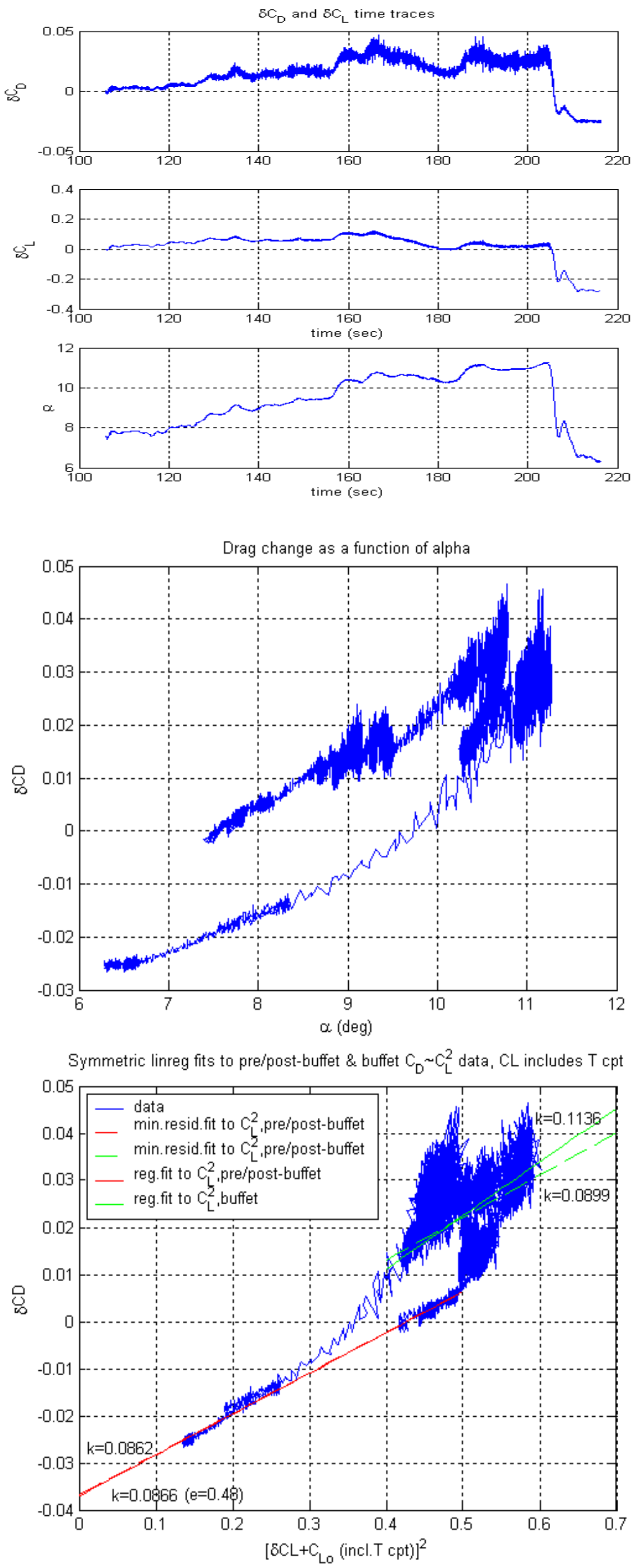
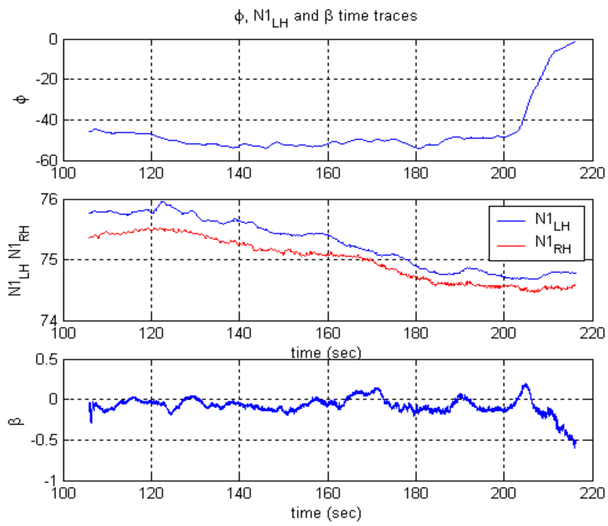


Figure 7 – buffet characteristics, further steep turning flight manoeuvre, pt.1; **Pa=32,820ft; M=0.527; Rec=13.50x10^6; W=28,717 lb; steep turn; α_B=8.5° at [q $\partial\alpha/\partial t$]=[2.8 0]; and α_B=8.1° at [q $\partial\alpha/\partial t$]=[2.65 0].**



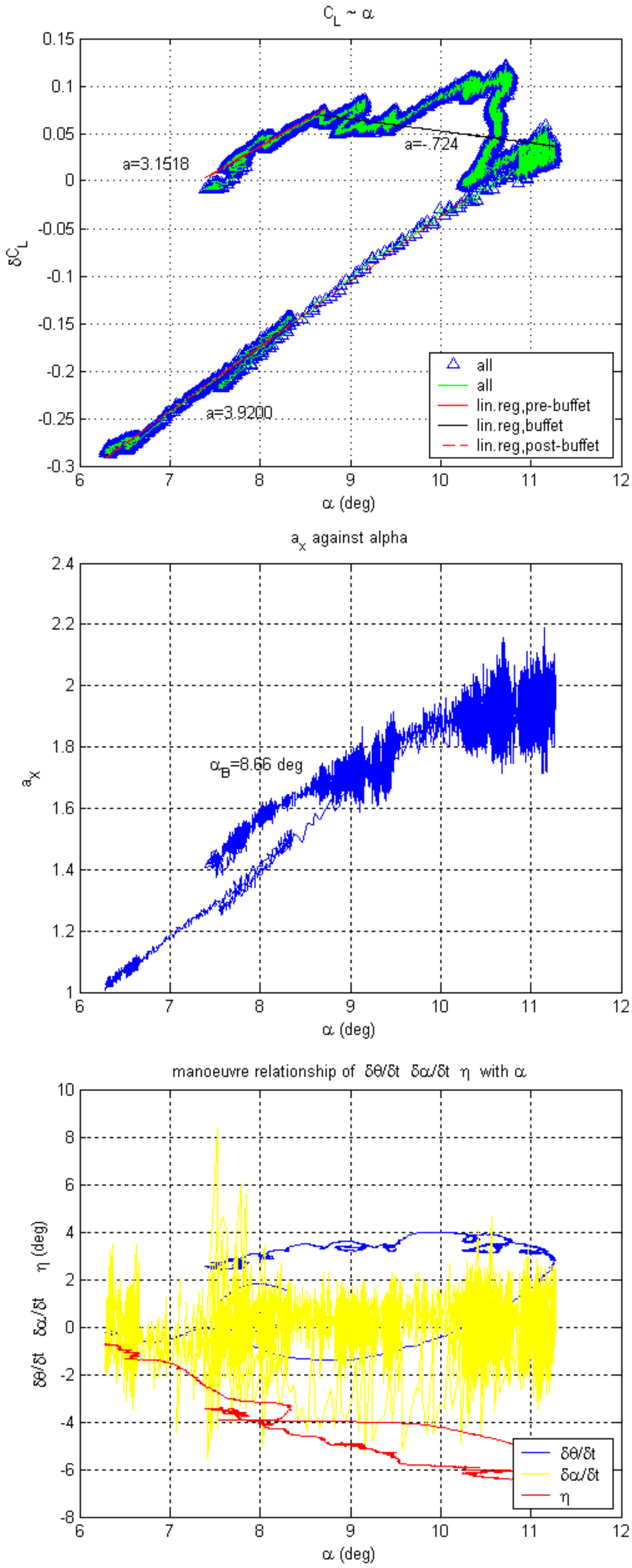
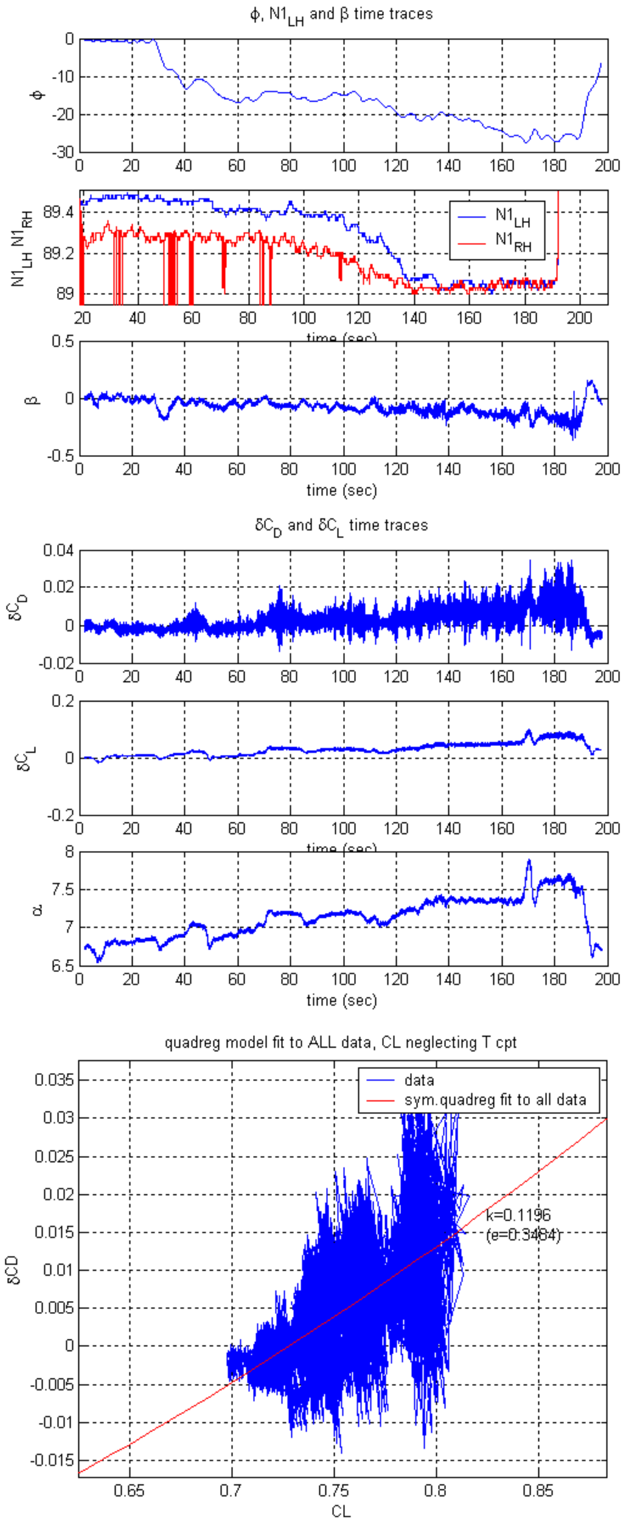


Figure 8 – buffet characteristics, further steep turning flight manoeuvre, pt.2: initial α=7.5°, final α=6.3°; α,β,ϕ (deg), N1 (%), a_X ('g'), $\partial\theta/\partial t, \partial\alpha/\partial t$ (deg/sec); **Pa=32,820ft; M=0.527; Rec=13.50x10^6; W=28,717 lb; steep turn; steep turn; α_B=8.66° at [q $\partial\alpha/\partial t$]=[3.5 0.5].**

3.6 Medium rate turn buffet onset

The occurrence of buffet onset, in terms of buffet effects upon C_L and C_D, during a medium ϕ turn is shown in Figure 9. The medium angle-of-bank level turn was conducted at 43,000 feet, at an associated very low pitch rate of approximately zero.



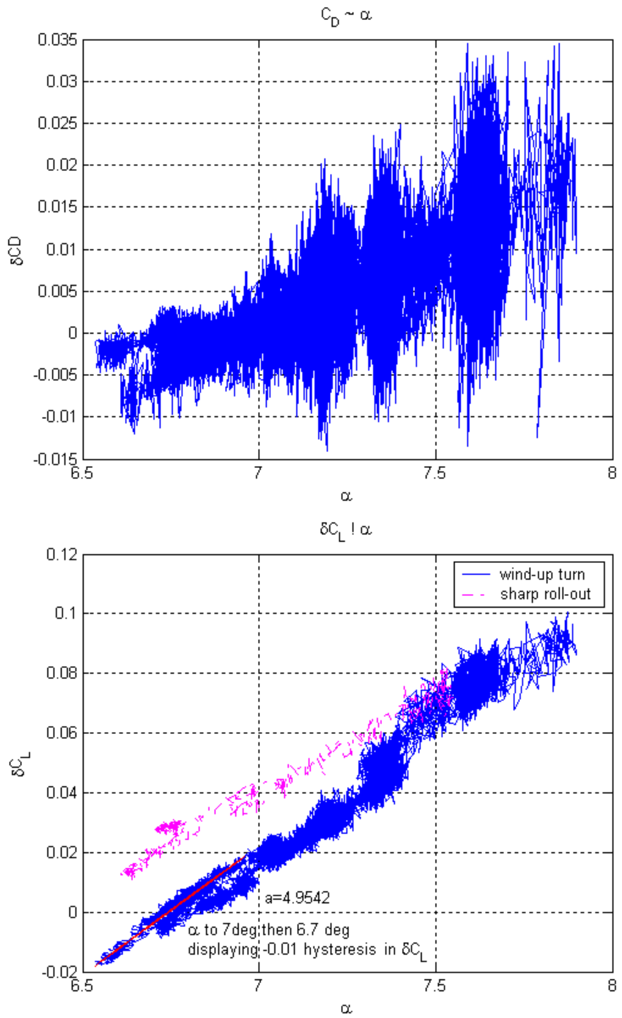


Figure 9 – buffet characteristics, medium rate turning flight manoeuvre; α,β,ϕ (deg), N1 (%), a_X ('g'), ∂θ/∂t,∂α/∂t (deg/sec): **Pa=42,576ft; M=0.630; Rec=9.72x10^6; W=33,519 lb; medium rate turn; α_B=7.2° at [q ∂α/∂t]=[0.4 0]**

3.7 Summary of test point results

A summary of test points appears in Table 1. Although the number of points is not sufficient to conduct parametric identification against a parameter vector of aerodynamic state variables [M Rec q ∂α/∂t], it is sufficient to make some parametric observations. Firstly, there is no consistent variation with buffet Reynolds Number, Rec_B. Secondly, the buffet-onset incidence, α_B, varies inversely with Mach Number, as shown in Figure 10.

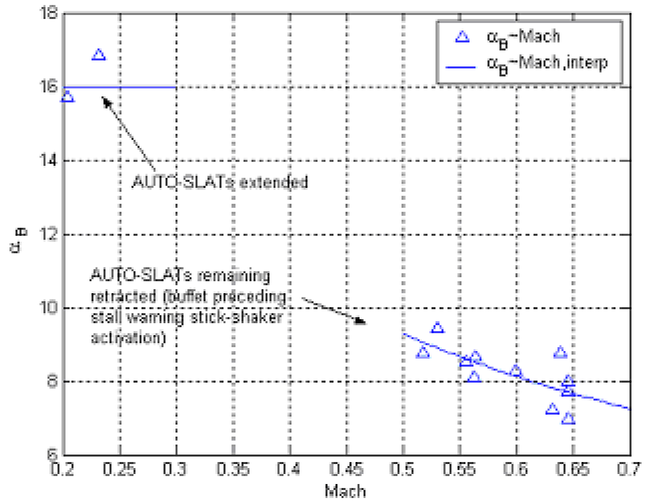


Figure 10 – variation of buffet onset incidence, α_B (deg), with Mach Number

Finally, when compared to the buffet onset Mach Number scheduled for the Type Design (against the parameter vector of [W Hp a_Z(g)]), there are noticeable differences in the Mach Number range of 0.5-0.6 for the manoeuvre flight path dynamics of zero, or near-zero, incidence rate, as indicated in Figure 11. This combination of flight path and buffet Mach Number parameters was obtained over the altitude band of about 32,000 to 35,000 feet. It is noted the Type Certificate Data Sheet (TCDS) for the aeroplane Type recorded an equivalent level of safety against the requirements of FAR 25.201/3/7 for flight above 34,500 feet.

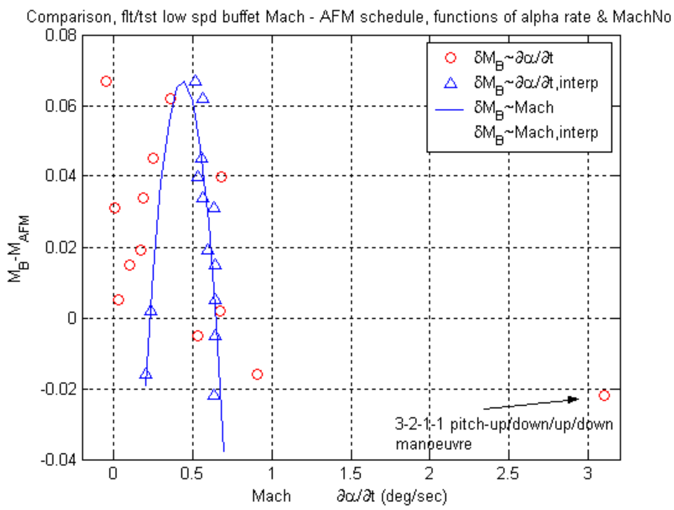


Figure 11 – comparison of low-speed buffet onset Mach Number with flight manual scheduled data.

Case	W (lb)	H_P (ft)	a_Z (g)	M	Re	q (°s^{-1})	$\partial\alpha/\partial t$(°$s^{-1}$)	η_E (elev. angle)	α_B
Stalling	29,270	13,038	0.977	0.232	$11.47x10^6$	0.57	0.67	-6.85°	16.84°
Stalling, -1 kt/sec at buffet onset	27,274	11,832	0.902	0.204	$10.20x10^6$	0.85	0.91	-6.75°	15.7°
S&L	31,000	45,170	0.967	0.645	$8.62x10^6$	-0.01	0.10	-1.56°	6.95°
Pitch-up manoeuvre *	31,000	44,536	1.158	0.638	$8.87x10^6$	3.77	3.10	-2.83°	8.74°
Low rate turn *	31,000	45,212	1.051	0.645	$8.59x10^6$	0.29	0.03	-1.56°	7.50°
Low rate turn *	31,000	45,116	1.085	0.645	$8.63x10^6$	1.19	0.53	-1.30°	8.0
Steep turn	28,717	32,012	1.862	0.598	$15.77x10^6$	4.03	0.10	-7.85°	8.30°
Steep turn	28,717	34,195	1.451	0.555	$13.61x10^6$	2.78	0.25	-4.40°	8.50°
Steep turn	28,717	33,923	1.447	0.562	$13.92x10^6$	2.72	0.36	-4.00°	8.10°
Steep turn	28,717	33,220	1.598 1.603	0.564	$14.28x10^6$ $14.78x10^6$	3.39 3.32	0.19 -0.01	-4.66° -4.71°	8.66°
Medium rate turn	33,519	42,697	1.048	0.631	$9.67x10^6$	0.23 0.22	0.01 0.04	-0.95° -0.94°	7.20°

Table 1 – compendium of test point results

4 Conclusions

Low speed manoeuvre buffet onset and characteristics flight testing of a medium-size swept-wing high-speed business jet has been conducted.

The flight test matrix included buffet onset occurrences during low altitude straight-flight stalling, and high altitude quasi-steady straight flight, turning flight (at various angles-of-bank) and pitching flight. The flight test data covered a Mach Number range of 0.2 to 0.65, a Reynolds Number range of $8x10^6$ to $16x10^6$, and pitch and incidence rates of –0.5 to 4 degrees per second.

The aerodynamic coefficient characteristics of the buffet onset occurrences have been deduced and analysed. As expected, the analyses highlight differences in C_L and C_D buffet characteristics with incidence for low and high pilot-induced pitch and incidence rates and with Mach Number. No definite variation of characteristics with Reynolds Number was observed. Not so expected was the sensitivity of buffet onset behaviour and characteristics for test points conducted at low incidence rates, particularly when buffet onset was compared to the Type Design buffet onset schedule, for the flight test combination of zero incidence rate and pitch rates of 0-4 degrees per second, over the buffet Mach Number range of 0.5 to about 0.65, covering the intermediate high altitude range of 32,000 to 35,000 feet.

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