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 $8 \times 10^6$ to $16 \times 10^6$, 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\textsuperscript{1} or the requirements of JAR 25\textsuperscript{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:
an angular rate and linear acceleration measurement system; and

(2) a six-component Inertial Measurement Unit (IMU) developed by the NRC\textsuperscript{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, $\alpha$;
(3) low angle-of-bank, $\phi$, turning flight;
(4) medium $\phi$ turning flight;
(5) high $\phi$ 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 ‘$\Delta$’ form, with reference to an initial quasi-steady trim condition, for which $X=T=T_0$, 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 $\Delta C_L$ and $\Delta C_D$ characteristics.

In the case of stalling manoeuvres, such a data reduction process results in mostly negligible $\Delta C_L$ with increasing $\alpha$, thereby validating the subsequently applied assumption that IDLE engine thrust is negligible compared to $X_0$. Hence, for stalling manoeuvres the data reduction provides $C_L$ and $C_D$ time-trace relationships with $\alpha$. Buffet onset incidence is designated as $\alpha_B$.

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 $\frac{3}{4}$ 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 $\pm 0.05$ and $C_D$ variations of $\pm 500$ 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.
Symmetric line fit to pre/post-buffet & buffet \( C_D - C_L \) data, all includes T cp

Symmetric line fit to pre/post-buffet & buffet \( C_D - C_L \) data, all includes T cp

Data: 62-6000.675 sec
- 62 6932.557 sec
- 57 sec (a)
- fit C_D to \( C_L \) pre-buffet
- fit C_D to \( C_L \) post-buffet
- fit C_D to \( C_L \) pre-buffet
- fit C_D to \( C_L \) post-buffet

\( \alpha_B = 15.7° \) at \( \frac{\partial \alpha}{\partial t} = [1.2, 2] \)

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 $\Delta C_D$ of about ±20 drag counts.

### 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 ±0.035 and $C_D$ variations of ±40 drag counts.

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**Figure 3 – buffet characteristics, straight and level flight.**

$Pa=43,000\text{ft}; M=0.638 ; \alpha_B=6.95^\circ$ at $[q \partial \alpha / \partial t]=[0 \ 0] \text{^\circ s}^{-1}$

**Figure 4 – buffet characteristics, abrupt pitch-up manoeuvre.**
In the pitch-up data analysis presented in Fig.4, the lagging development of unsteady lift force to change in \( \alpha \) has been accounted for by applying the Wagner indicial function, as applied to aeroelastic analyses\(^4\), to \( \alpha \), thereafter denoted as \( \alpha_{\text{lagged}} \).

### 3.4 Low \( \phi \) 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 \( \alpha \) show a sharp low-amplitude buffet onset, followed by progressively increasing buffet levels with increasing incidence, \( \alpha \), to peak values of \( \Delta C_L \) of \( \pm 0.02 \) and \( \Delta C_D \) of \( \pm 15 \) drag counts.
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 $4 \,^\circ\text{s}^{-1}$. Once again, the buffet onset was sudden (to a $\Delta C_D$ level equating to $\pm 30$ drag counts), followed by a mild and progressive rise in buffet level with increasing incidence, to about $\pm 60$ drag counts.
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 α_2. 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: \( Pa=32,820 \text{ft} \); \( M=0.527 \); \( Rec=13.50 \times 10^6 \); \( W=28,717 \text{ lb} \); steep turn; \( \alpha_B=8.5^\circ \) at \( q \frac{\partial \alpha}{\partial t}=[2.8 \ 0] \); and \( \alpha_B=8.1^\circ \) at \( q \frac{\partial \alpha}{\partial t}=[2.65 \ 0] \).
medium $\phi$ 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.

### 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...
Finally, when compared to the buffet onset Mach Number scheduled for the Type Design (against the parameter vector of \([W \text{ Hp } a_z(g)]\)), 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.

### 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 \([M \text{ Rec } q \partial a/\partial t]\), it is sufficient to make some parametric observations. Firstly, there is no consistent variation with buffet Reynolds Number, \(\text{Rec}_B\). Secondly, the buffet-onset incidence, \(\alpha_B\), varies inversely with Mach Number, as shown in Figure 10.

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**Figure 9** – buffet characteristics, medium rate turning flight manoeuvre; \(\alpha, \beta, \phi\) (deg), \(N_1\) (%), \(a_x\) ('g'), \(\partial \theta/\partial t, \partial \alpha/\partial t\) (deg/sec); \(P_a=42,576\text{ft}; M=0.630; \text{Rec}=9.72\times10^6; W=33,519\) lb; medium rate turn; \(\alpha_B=7.2^\circ\) at \([q \partial a/\partial t]=0.4\]

**Figure 10** – variation of buffet onset incidence, \(\alpha_B\) (deg), with Mach Number

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