ON THE CONFIGURATION BUFFET OF A TRANSPORT AIRCRAFT

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Abstract

This paper presents a detailed investigation of a "configuration buffet" phenomenon on a transport aircraft. Buffet occurred during low speed approach with the trailing-edge flaps fully deployed. Buffeting of the aircraft was characterised as discomfort in the cabin and large amplitude vibration on both the flaps and the tailplane. Investigations were initially carried out in the wind tunnel using both 2- and 3-dimensional semi-rigid models. It was found that changes in the wing and flap relative geometry at the flap joint where the flow separated, could result in dramatic changes in the level of model buffeting. A "shroud extension" modification on the model was found to reduce the level of buffet significantly. Flight test evaluation of this solution showed that the level of overall aircraft buffeting was also significantly reduced.

1. Introduction

When flow separates from the surface of an aircraft, an unsteady aerodynamic force may be induced on the aircraft structure which can cause considerable airframe response. This unsteady aerodynamic force is defined as buffet and the subsequent uncoupled structural response as buffeting[1]. The phenomena of buffet and buffeting have received increasing attention on both combat and transport aircraft since the investigation of the first buffeting incident[2]. However, most works published in the recent AGARD meeting on this subject were towards combat aircraft, with the main emphasis being placed on the buffet at high speed and large angles of attack[3]. As for transport aircraft, there were little in the recent literature even on the buffet at high speeds, and hardly anything at low speeds.

Transport aircraft are designed to cruise below the buffet onset boundary, and transient buffeting caused by a gust or turbulence is usually not a concern. The characteristics of a transport wing are a high aspect ratio and low/moderate sweep back. Thus a 2-dimensional airfoil can usually provide good representation in the process of predicting flow behaviour. In the pre-design stage, such an airfoil is usually studied with the advanced Computational Fluid Dynamics(CFD) tools combining the empirical data from a series of wind tunnel tests. This provides a sufficient prediction of the buffet margin for the wing to achieve its performance requirements without any severe buffet. Such aircraft are designed to be free from buffet at the design cruise Mach number. However, the aircraft is often equipped with multiple leading- and trailing-edge devices to achieve the high-lift requirements at take-off or landing. The extension of these devices sometimes causes flow separation and induces a buffet force, which may cause heavy aircraft buffeting if its frequency coincides with one or more of structural modal frequencies. Since it is related to a specific aircraft configuration, it is often referred to as "Configuration Buffet". Although no detailed studies of such phenomena have been reported, failures of the trailing-edge flaps on several types of transport aircraft have been observed.

The "configuration buffet" under this study is distinguished from the well-known cruise buffet in two aspects. Aerodynamically, it occurs at a low speed involving a complicated geometry of multiple elements configuration. The type of flow separation is a bubble. Hence the induced buffet force is random in nature and contains a range of frequencies dominated by a peak associated with the bubble length[4]. However the separation for cruise buffet at high speed is more likely to be shock-induced and the buffet forces may be more concentrated at one frequency. Structurally, the aircraft usually responds to the buffet force at the mode of the component from which flow separates or that emerges in the separated wake. For the cruise buffet, buffeting occurs usually at the aircraft first wing bending mode. The complex excitation and structural response are impossible to predict or simulate either analytically or numerically. Due to the complexity of bubble, the scale effects may vitiate attempts to extrapolate from a wind tunnel model to an aircraft.

This paper presents a detailed investigation into the "configuration buffet" experienced on one transport aircraft in its early development phase. Severe buffeting was first experienced in initial flight tests on a low speed approach. This was a result of local flow separation on the flap surface. Various modifications were sought and tested in flight to reduce the buffeting to an acceptable level. The investigation continued both in flight and in wind tunnels, aiming at a better understanding of the buffet sources and at developing a buffet prediction method using a wind tunnel model. A modification was discovered that reduced the buffet force significantly on the wind tunnel model and which was then tested in flight. A direct Comparison of buffeting responses with and without the modification proved that this modification can reduce the level of buffeting significantly, typically upto 40% in the cockpit.

2. "Configuration Buffet"

During initial flight tests, the aircraft experienced severe buffeting during approaches for landing with its flaps extended to the maximum allowable angle. It was commented by the test crew that the level of buffeting vibration felt in the cockpit was unacceptable. It was also reported by flight engineers that large amplitude vibration of flaps was visible during the incident. These were confirmed by the measurement of accelerometers located on various components of the aircraft. The measurement also revealed that not only the fuselage and flaps sustained a high level of vibration, but also that large vibration was found on the tailplane. The level of buffeting provoked concerns for crew and passenger comfort, together with the possibility of fatigue damage to the flaps and tailplane.

The wing of this aircraft was designed with leading-edge slats and trailing-edge flaps across the wing span. It was thought that the flow on the flap upper surface was separated due to the three-dimensional flow interaction at the "kink" joint of inboard and outboard flaps at a large flap angle. Fig. 1 illustrates the local geometry at the flap joint together with a typical cross-section. Flow visualisation using tufts revealed that the flow on the upper surface of the flaps was indeed separated at the joint region as shown in Fig. 2. Further tests of the aircraft showed that the tailplane was submerged in the wake of the separated flap flow, which accounted for the vibration. It was also found that the area of separation on the flaps could be reduced by retracting the flaps to the second largest setting. Then the vibration levels on the aircraft were significantly reduced. Various modifications were also implemented with the flap retraction from the maximum setting to the second largest so that the levels of vibration on the aircraft were greatly reduced whilst the required performance at landing was maintained. Thus the buffeting vibration on the aircraft was no longer a concern for crew and passenger comfort or for the structural fatigue of the airframe and all its components.

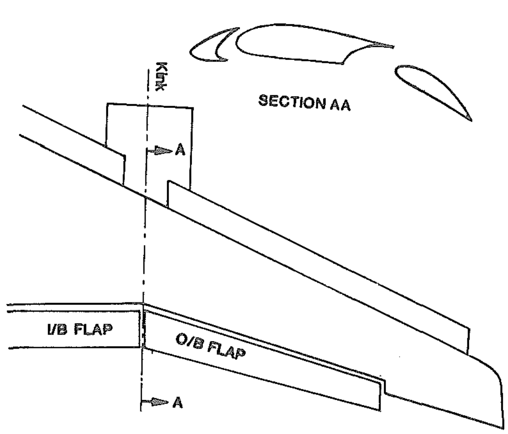


Fig. 1 Illustration of the local geometry at flap joint and a cross-section.

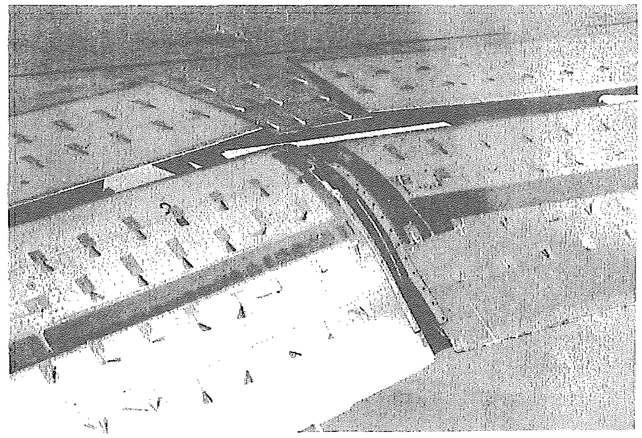


Fig. 2 Tuft visualisation of flow separation on the flaps at the maximum flap angle.

Whilst the use of a reduced landing flap angle proved adequate to achieve the required airfield performance, use of the originally designed maximum setting would offer improvements in landing distances for potential development of the aircraft. The experience on this aircraft also raises interest in a better understanding of the phenomena and a possible prediction method in the design stage. It was therefore decided to complete the initial investigation to restore the maximum flap setting and to improve the prediction of "configuration buffet" for future aircraft projects.

3. Wind Tunnel Models Investigation

The Increasingly wide application of Computational Fluid Dynamics(CFD) tools in wing design has made possible the prediction of wing performance with acceptable accuracy for a range of speed and incidence. However, to accurately predict flow separation using CFD on such a complex geometry as a transport wing is almost impossible. The most common method of predicting flow separation is still essentially experimental, i.e. wind tunnel tests using scaled wind tunnel models. Perhaps the ideal model for this kind of study is the aeroelastic type with proportional flexibility to the full-scale aircraft. However, the design and manufacture of such models is expensive and takes a long time. An alternative is to make use of semi-rigid models available for aerodynamic performance testing. These models are designed and built to have a geometrical similarity to the aircraft with much higher structural strength than the aircraft. Unsteady dynamic phenomena like buffet may be studied with such rigid models if a theoretical foundation for understanding the dynamics of buffet force and model response is available. Interpretation of such test results should always take consideration of both scale effects and dynamic dissimilarity between the model and the aircraft.

The "configuration buffet" of this aircraft was studied on semi-rigid wind tunnel models (both 2-dimensional and 3-dimensional) in various low speed wind tunnels with Reynolds number ranging from 1.0×10^6 to 9.2×10^6. In this paper results were presented from a 2-dimensional end-plate model and a 3-dimensional half model tested in two different low speed tunnels.

3.1 Two-Dimensional End-plate Model

It is believed that the flow separation at the flap joint is a result of three-dimensional flow interaction due to the complex local geometry. It is possible that changes in the local geometry can significantly affect the flow separation. As shown in Fig. 3, the geometry of the flap and the wing at one local chord is determined not only by the angle of flap but also the relative position of the flap to the wing, which can be defined by two variables, "overlap" and "gap". When the flap retracts from the maximum setting to the second largest, the relative position of the flap to the wing is changed. At the same flap angle, this relative position can also be changed.

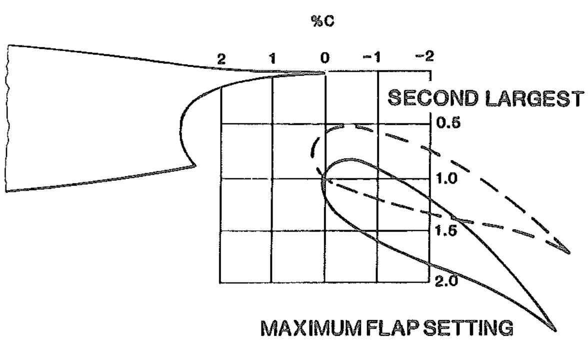


Fig. 3 Relative position of the wing to the flap in a wing cross-section.

This effect was first studied on a two-dimensional end-plate model with its cross-section representing one of the outboard chords of the aircraft wing. The effect of three-dimensionality in the flow was minimised by the end-plates, attached to each side of the model. It was extensively tested in the Reynolds number range of 3.1×10^6 at the pressure of one atmosphere to 9.2×10^6 at the pressure of three atmospheres in two low speed wind tunnels. The tests at different Reynolds numbers in this range showed similar characteristics. The relative position of the flap leading-edge to the main wing trailing-edge (shown in Fig. 3) determined the strength of buffet force and flow separation. In this paper, typical results were given only from the tests at the Reynolds number of 3.1×10^6. Details of the model and the results from whole series of tests can be presented in a future paper[5].

This model was mounted in the low speed wind tunnel at one atmosphere with a free-stream velocity of 60 m/sec. The model was at a typical aircraft approach incidence with the flap at the aircraft maximum flap angle. Whilst the flap was maintained at this angle, the relative position of flap and wing was altered by changing the parameters of "overlap" and "gap" according to the grid in Fig. 3. Accelerometers were mounted on the model at various locations to measure the model response of all modes excited. The data was recorded on-line by a computer for a steady period and analysed after the test.

The frequency spectra were first computed for the model responses measured by the accelerometers. The frequency contents in the spectra showed that various modes of the model were excited. A model resonance test was also carried out to identify each modal frequency of the model and its components at zero speed. It was shown that the largest frequency contents at the flap accelerometers were the mode of the flap excited by the aerodynamic force. Then the amplitude of this frequency at the accelerometer was regarded as a typical response of the model to the buffet force exerting on the flap. It is known that the rms amplitude of a mode is proportional to the buffet force parameter[6]. The rms spectral amplitude at this frequency can then be a measure of the buffet force at this frequency. Fig 4 is a contour of the amplitude at this frequency of a flap accelerometer response for the grid of "overlap" and "gap" tested at the aircraft maximum flap angle. It shows that, the minimum buffet force can be achieved by setting the "overlap" in the region of 1.0–2.0 and the "gap" in the position of one percent of the chord. Outside this region, the buffet force can increase dramatically. For the equivalent setting on the aircraft at the flap joint, an average of 0.5 percent of "overlap" and 1.5 percent of "gap" was selected. This setting in the two-dimensional case would give rise to a buffet parameter of about 40% more than the minimum.

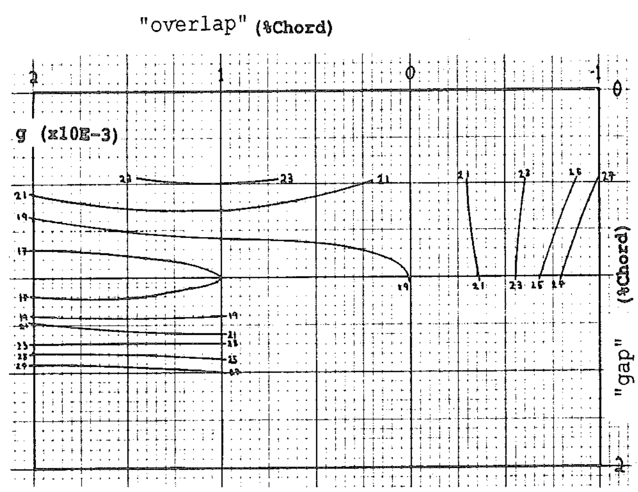


Fig. 4 Contour of the buffet force parameter for the variations of "overlap" and "gap".

The setting of "overlap" and "gap" for the aircraft was optimised in the design stage by taking the performance parameters at high and low incidences into consideration. An optimised setting for the performance may not lead to the lowest buffet. It is possible that a certain comprise between the concerns of performances and buffet would lead to a dramatic reduction in the level of buffet whilst the performances can be maintained.

3.2 Three-Dimensional Half Model

The study of the 2-dimensional model provided understanding of the buffet phenomena and suggested that geometrical changes in flap and wing could result in a significant reduction in the level of buffet. However, the degree of understanding and the solution from a 2-dimensional study was not sufficient for a modification to be practically tested on an aircraft. Such a modification has to be well-studied in more sophisticated tests with various 3-dimensional wind tunnel models, and the Reynolds number of the tests has to be large enough to minimise the scale effect. Several 3-dimensional semi-rigid models have been tested in various low speed wind tunnels, and various modifications have also been assessed. In this paper, only the tests on a 3-dimensional half model conducted in a low speed wind tunnel are presented. A future paper will review the whole series of tests, including those on a complete model at higher Reynolds numbers[7].

The model was built to represent the right-hand half of the aircraft with a model scale of 1:13.6. It was mounted vertically in the wind tunnel working section with the free-stream velocity maintained at 20 m/sec. Most of the tests were concentrated on the configuration that represents the aircraft with flaps extended to the maximum angle. An accelerometer was mounted at the wingtip inside the wing to measure the structural response of the model throughout the test. Data was recorded on an analogue tape recorder for analysis after the test.

The first test aimed at better understanding of the buffet phenomena on the model using the wingtip accelerometer. The model was tested over a range of incidences from -4° to that at stall. While the model was maintained steady at one incidence, response from the accelerometer was recorded and later computed into frequency spectra. Fig. 5 illustrates the variations of model response at various modes with the model incidence. Most modes show a steady variation with the model incidence, except that the mode at 145 Hz becomes dominant in the incidence range from 7° to 14°. In this incidence range, the aerodynamic excitation at about 145 Hz was much greater than elsewhere. This could be the result of a sudden bursting flow separation. A model resonance test showed that the 145 Hz is the bending mode of one of the flap supporting tracks. It was evident that the flap was experiencing severe buffeting due to a large excitation at about 145 Hz. Also, separated flow on the flap upper surface at the flap joint was revealed by flow visualisation, similar to that observed on the aircraft.

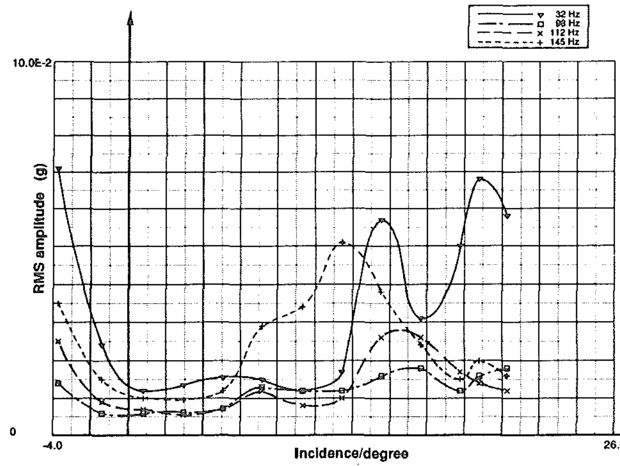


Fig. 5 Model response variation at each mode with incidence.

A number of modifications were made to the model and tested in the wind tunnel at this configuration with a typical incidence of 8°. Most of the modifications showed that the level of buffeting was significantly reduced. Among these, one that extended the trailing edge of the wing over the flap leading edge, called "shroud extension" (as shown in Fig. 6), proved effective and could be readily fitted to the aircraft. Fig. 7 compares frequency spectra of the model responses with and without the modification. It shows that the dominant mode at 145 Hz was significantly reduced. The first wing bending mode at 32 Hz is also reduced. The modification has also slightly improved the lift coefficient at the test incidences.

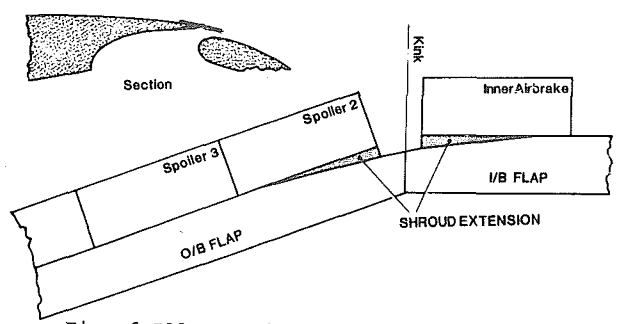


Fig. 6 Illustration of "shroud extension" to the half model and to the aircraft.

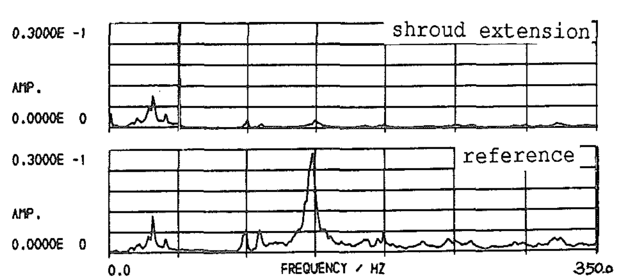


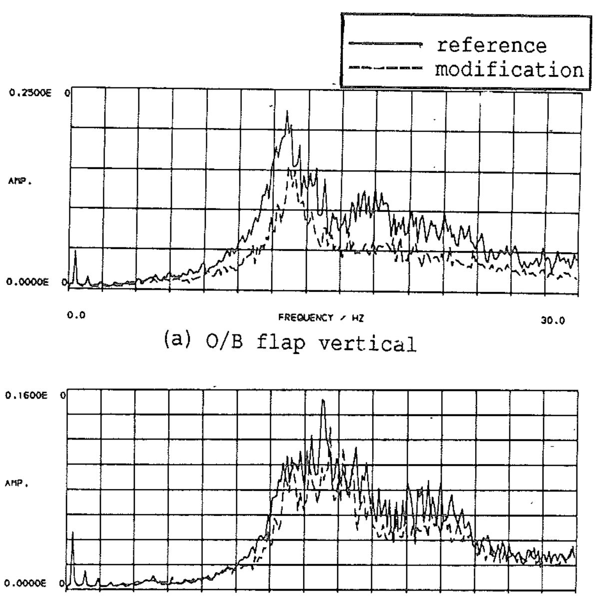
Fig. 7 Spectra of wingtip acceleration with and without "shroud extension" at 8° incidence.

Thus, this "shroud extension" had proved to have a beneficial effect on the level of buffet and no adverse effect on aerodynamic performance for all the other aircraft configurations. The reduction in model buffeting level and the engineering applicability of this modification has indicated that a flight test on the aircraft was justified.

4. Flight Test with "Shroud Extension"

Flight test evaluation of the effect of this "shroud extension" modification on the buffet was carried out in two separate flights of the aircraft with the same test programme and under the same test conditions. The aircraft first flew with the modification, and then without the modification. The programme of the flights includes tests at various flap settings, several approach speeds and a wide range of incidences. The responses of the aircraft were measured by a number of accelerometers located on various components. In-flight observation of the flap flow and measurements of aircraft performance were also carried out.

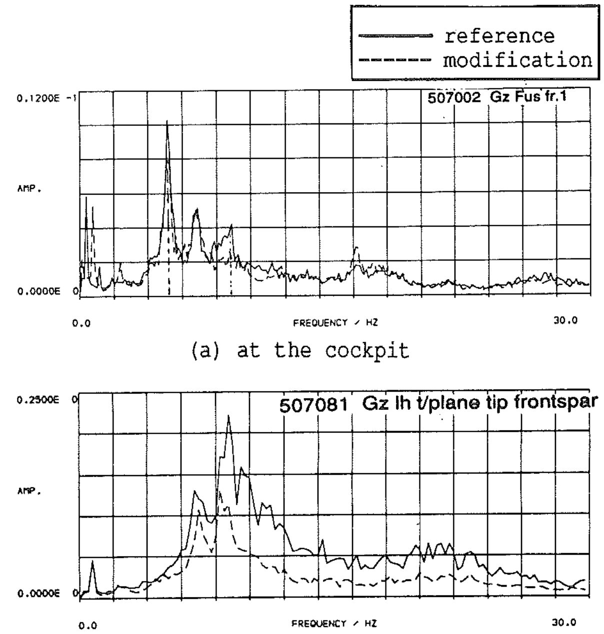
The responses of various aircraft components were analysed and a direct comparison of the frequency spectra of the responses was carried out between the two flights. The results showed that this modification had brought about a significant broad-band reduction in the buffeting at all measured locations and components of the aircraft. Fig. 8 shows that a broad-band reduction was achieved in the flap vibration at a typical approach configuration with the maximum flap angle extended. Fig. 9 shows that there were also significant reductions in the levels of vibration at cockpit and tailplane , being about 40% at the cockpit.



(a) O/B flap vertical

(b) I/B flap vertical

Fig. 8 Comparison of flap buffeting vibration in cases with and without "shroud extension".



(a) at the cockpit

(b) on the tailplane

Fig. 9 Comparison of cockpit and tailplane vibration with and without "shroud extension".

During flight test, flow visualisation using tufts was carried out in both flights with and without the modification. In-flight observation revealed a reduction in the area of separated flow on the flap upper surface at the flap joint in typical approach configurations; being more significant at the maximum flap setting. Measurements of aircraft performance in both flights were also carried out and results showed that the aircraft lift coefficients in the case with modification were slightly increased or at least maintained.

5. Conclusions

A buffet phenomenon on a transport aircraft in a high-lift configuration at low speeds during approach was investigated. This low speed buffet occurred as a result of the large-angle deployment of the trailing-edge flaps and was characterised as "Configuration Buffet". The investigation was carried out both in wind tunnel and in flight, aiming at a better understanding of the phenomenon and possible modifications to reduce the aircraft buffeting level.

The "configuration buffet" was first studied in the wind tunnel using various 2-dimensional and 3-dimensional semi-rigid models. Results from the test of a 2-dimensional end-plate model showed that changes in the relative geometry of the wing and the flap results in a dramatic change to the level of buffet force on the model. The tests of a three-dimensional half model also showed that the "shroud extension", a modification effectively changing the wing and flap relative geometry, brought a significant reduction in the level of buffeting on the model. A flight test of the "shroud extension" on the aircraft proved that the modification brought about a significant reduction in overall level of aircraft buffeting, typically about 40% in the cockpit.

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