DESIGNING A LOAD ALLEVIATION SYSTEM FOR A MODERN CIVIL AIRCRAFT

B W PAYNE
Chief Dynamics Engineer

British Aerospace plc
Weybridge, Surrey, U.K.

SUMMARY

The design of an active control gust load alleviation system is described, with a design objective of making a direct saving on wing weight. The application of this design to the Airbus Industrie A320 is discussed, the first such system to be incorporated in a modern civil airliner from the initial design stage.

The gust is sensed by accelerometers sited in the forward fuselage. These signals are fed as input to the electrical flying control system computers in which are specified the control laws for the load alleviation system. The computer output then moves outer wing spoilers and ailerons. Use of normal flying controls and systems keeps the installation weight penalty to a minimum. Airworthiness objectives are discussed and reference made to two particular aircraft flight test programmes used both in the development of the system, and in establishing confidence in the feasibility and effectiveness of the system.

1 Introduction and Feasibility

A number of studies have been made by British Aerospace in recent years to investigate the alleviation of gust loads and manoeuvre loads on wings of civil aircraft. The two main objectives have been either the direct saving of wing weight, or allowing the possibility of aircraft developments involving increases in A.U.W. which may be introduced without making major changes to an existing wing structure. The general conclusion has been reached that load alleviation for either purpose is both feasible and worthwhile.

A gust load alleviation system has been designed for the Airbus Industrie A320, the first European application of an active load alleviation system to a modern civil transport aircraft, and the first such application world wide to be incorporated from the initial design stage. This application is used in this paper to study the widely varying effects which the implementation of such a system will have on the aircraft, and the constraints which will be found in achieving satisfactory benefits together with an airworthy design.

The design bending moments on the upper surface of an A320 type wing are similar to those shown in Fig.1. Savings in wing weight are possible if the symmetrical vertical gust loads are alleviated to reduce them to the level of the manoeuvre loads, involving a net alleviation of approximately 15% at the wing root. Any further weight saving contemplated would require alleviation of the manoeuvre loads in addition to further alleviation of the gust loads.

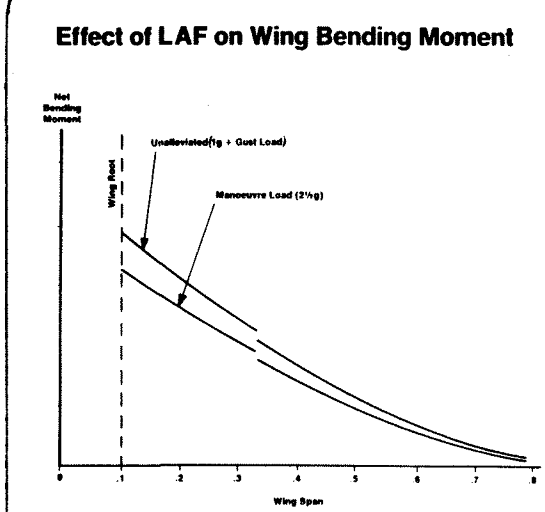

Fig 1

Feasibility studies carried out at the early design stage of the A320 wing examined the use of both gust vane and accelerometer feed-back. Accelerometer closed loop has been found to be more practical, for reasons of reliability and to take advantage of commonality with other control systems on the aircraft. To achieve gust load alleviation, the gust, represented by the feed-back signal, is used to deploy aerodynamic control surfaces which in turn generate their own loads on the wing. These loads then alleviate the gust loads, either by direct loads cancellation or by modifying the wing modal damping or frequency response characteristics. On A320 the principal mechanism will be load cancellation. The most straight forward use of the feed-back signal is to subject it to any filtering and scaling required, and to use it directly as a control demand, forming an 'active' closed loop feed-back control system. However, in general, there is the potential for an active system to exhibit stability problems depending on the structural response contained in the feed-back signal.

Virtually all aerodynamic control surfaces have some capability for load alleviation with a suitable control law. On A320 to achieve the modest design targets with the minimum weight penalty the use of existing controls was chosen as the obvious approach.

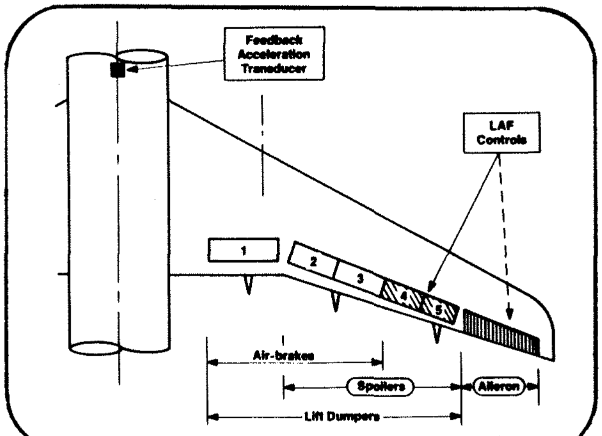

Fig.2

During the feasibility studies both aileron and outboard spoilers were examined, see Fig 2. The two outboard spoilers (spoilers 4 and 5) were found to be considerably more effective than the aileron, although as may be seen from Fig 3, to achieve balanced loading the aileron is more effective in producing load over the outer part of the wing.

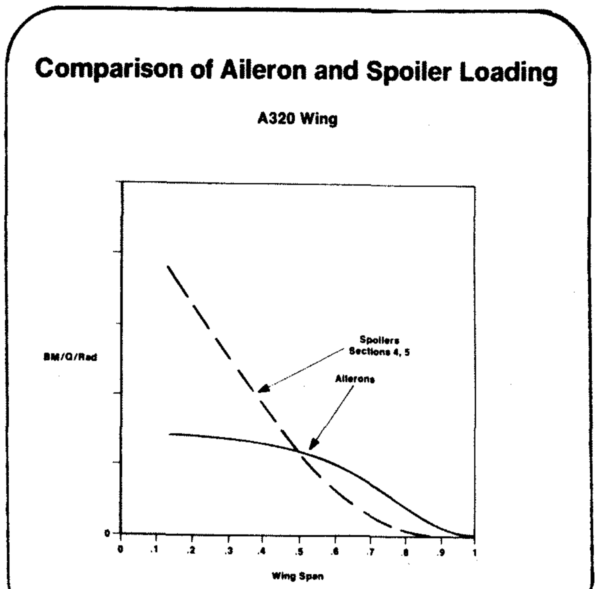

Fig.3

As part of the feasibility studies full dynamic calculations were carried out on the preliminary A320 structural model, which allowed full symmetric flexibility of the structure. A block diagram is given in Fig.4 which shows a rectangle representing the aircraft equations of motion, together with the closed loop feed-back of fuselage vertical acceleration, through flight control computers and control actuators, back into the equations of motion.

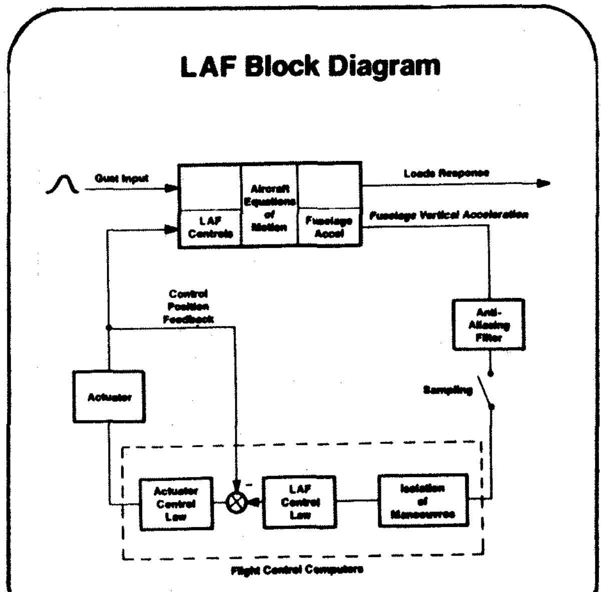

Fig.4

Two of the important features to establish at this feasibility stage were the degree of alleviation possible from particular actuator rates and gains in the feed-back loop, and the stability of the system under all flight conditions. Considering the response to a (1-cosine) discrete up gust, a series of calculations were undertaken in which the spoiler actuator rate and the gain were varied. Fig.5 shows carpets which give the % of incremental alleviation for wing bending moments at the wing root, the wing pylon position and the wing mid span.

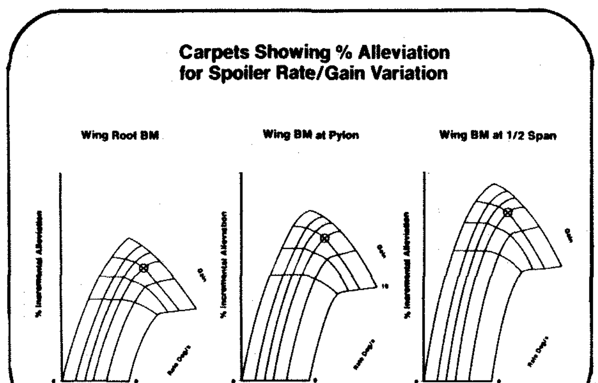

Fig.5

Studies which examined the stability of the system and the interaction with the structural modes, showed that for high gains the positioning of the feed-back accelerometer on the structure was important. The regions in the aircraft where it was suitable to place the accelerometer, and the system gain and hence alleviation possible, could be restricted by stability considerations.

Also at this feasibility stage, calculations were carried out both for the discrete gust requirements and for the continuous turbulence requirements contained in both the European and FAA Airworthiness Requirements.

This paper will now discuss some of the problems which have arisen from the decision to fit load alleviation to the Airbus Industrie A320. The sections that follow will cover the implications of load alleviation on the A320 system design, the Airworthiness Requirements for such a system or function, the effect on flutter and/or structural stability and some particular problems which have arisen because of the inherent non-linearities of the system. Flight test programmes on two different aircraft have been used in the development of the system and some of the implications on the A320 flight programme are discussed.

2. A320 Design

An early decision was taken to equip the A320 with an electrical flying control system (EFCS) and advantage was taken to also incorporate a Load Alleviation Function (LAF) into the EFCS.

The aim of LAF was to reduce the symmetric gust upward bending moment by 15% net at the wing root and thus permit a saving in the structural weight of the top skin of the wing. By setting the alleviation at this fairly modest level the technical risk would be kept at a low level with a minimal decrease in reliability, and by using the existing control surfaces and control system the adverse installation weight penalties would be kept to a minimum.

Appreciable weight savings have been made possible on A320 by introducing LAF from the early stage. Experience gained in the design of LAF may be of use in designing future aircraft developments, without major modifications to the wing structure.

It should be noted that where "% alleviation" is quoted, this is a net value which gives the % reduction in the total wing load of incremental gust load plus 1g. "% incremental alleviation" is also referred to in some parts of the paper.

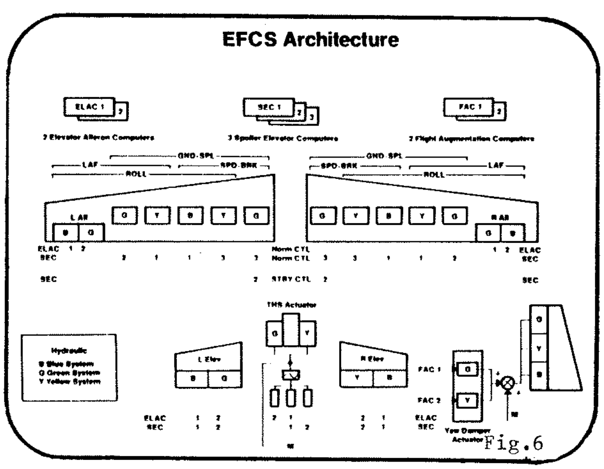

Fig.6

The EFCS architecture is shown in Fig.6, for reference. Also contained in the flight computers is the C* pitch command law used for handling, and which uses both aircraft vertical acceleration and pitch rate feed-back. The system therefore already contains a vertical acceleration signal which is available for LAF.

The accelerometer position in the fuselage although important for LAF, is not important for C*, and there is no conflict when deciding on the position. Requirements for replication and monitoring are similar for the two functions.

All of the A320 flying controls are hydraulically activated. The hydraulic requirements have been reviewed against the additional demands of LAF, and as shown in Fig.7 the system carries only a few modifications to meet the LAF requirements. The two spoilers each require increased valve sizes on the actuators to permit the increase in control surface rate demanded by LAF. An increase in the diameter of hydraulic return pipes has also been introduced, and the addition of hydraulic accumulators to ensure maintained pressure during repeated demands when flying through a number of turbulence peaks is also required.

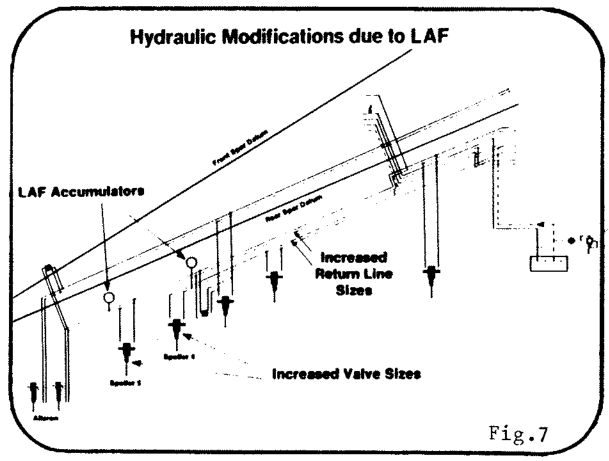

Fig.7

The total weight penalty arising from these system modifications is quite modest and is small relative to the weight saved on the wing.

3. Airworthiness Objectives

Gust load requirements from the different Airworthiness Authorities vary considerably. Fig.8 show a simplified summary of the gust load requirements for a conventional aircraft when being certificated to the European requirements of JAR, the UK national variant and the FAA requirements. JAR calls for discrete (1-cosine) gust calculations for a fixed wavelength together with a continuous turbulence requirement involving a power spectral density (PSD) analysis. The CAA in the UK, in addition to the PSD approach, calls for an investigation of (1-cosine) gusts for a fully flexible aircraft over a wide range of gust wave lengths to find tuning effects. This

Airworthiness Gust Requirements

GUST REQUIREMENTS				
		JAR	UK Nat Variant	FAA
Pratt		Formulae		Formulae
	U_{de}	OR		OR
Discrete Gust		(1-Cos) 12.5$\bar{c}$ Constant	0.9 x tuned 1 - cosine $(h/100)^{1/6}$	(1-Cos) 12.5$\bar{c}$ Constant
	U_{de}	66/50/25 $V_B/V_C/V_D$	66/50/25 $V_B/V_C/V_D$	66/50/25 $V_B/V_C/V_D$
PSD		Mission or Design Envelope Analysis	Mission or Design Envelope Analysis	Mission or Design Envelope Analysis
	U_σ^*	85 ft/sec	85 ft/sec	85 ft/sec (75 ft/sec)

* Supplementary DEA U_σ = 66 ft/sec

Fig.8

requirement is a straight addition to JAR rather than a replacement for part of the requirements. The US requirements tend to accentuate the PSD approach which then needs to be supplemented by a discrete gust investigation. Therefore whereas the Europeans call for a full flexible mode analysis for both discrete gust and continuous turbulence, the US only insist on such an analysis for the continuous turbulence investigation.

The introduction of load alleviation has raised a number of questions in the minds of both designers and authorities. Whereas the requirements have been drawn up and modified over the years to fit in with the development of conventional aircraft, the new design with load alleviation could behave in a sufficiently different manner to call for additional investigations at the design calculation stage.

Some additional criteria have been discussed with the European Airworthiness Authorities. These criteria consider aircraft equipped with systems which directly or as a result of a failure affect the structural performance, and where the influence of these systems and their failure conditions has to be taken into account in meeting airworthiness requirements. These criteria contain a number of primary criteria which consider the determination of limit loads, strength requirements, and systems in failure condition. In addition secondary criteria introduce a consideration of realistic gust fields. The aim is to take account of more realistic representations of gusts and turbulence than those included in the current requirements. Such consideration will provide confidence that design assumptions based on idealised turbulence will not lead to optimistic estimates of the degree of load alleviation likely to be achieved, and to avoid unnecessary constraints on control system design.

4. LAF Law Design

In designing the A320 gust load alleviation system there are a number of basic considerations to be taken into account. The vertical accelerometer should be on the fuselage centre line and should give sufficient phase advance on the wing loads without adversely affecting the flutter stability of the aircraft. Fig.4 shows a flow diagram which represents the load alleviation feed-back loop. The accelerometer signal is first fed through an antialiasing filter to remove the high frequency noise without introducing unacceptable phase lags. This signal is then digitised and sequenced with the computer cycle time to minimise the delay time between control demand and measured input.

The next stage is to process the feed-back signal so as to maximise response to the desired signal source, that is the gust, and to minimise response due to other inputs, for example due to pilot induced manoeuvres. This isolation of the manoeuvre signal is achieved by first feeding it through a high pass filter to remove the low frequency inputs. A threshold of 0.3g has also been introduced before the activation of the load alleviation system to prevent frequent low amplitude actuation of the controls.

The LAF control law is a simple linear gain with amplitude limits. Both controls have limits which as a proportion are about half of the full travel available.

5. Simulation

A digital simulation of the block diagram given in Fig.4 has been prepared for the computer and a number of theoretical solutions have been obtained.

The aircraft is represented by a set of equations of motion written for the symmetric rigid body degrees of freedom and up to 50 flexible modes representing wings, pylons, fuselage and empennage of the A320 aircraft. The frequency range chosen covers all of the modes likely to contribute to the gust response quantities of interest. Unsteady aerodynamic contributions to the equations have been included both in the response equations and in the forcing terms coming from the gust. An account is taken of the indicial lift functions and the gust delays, a Kussner type step gust function being used to represent the growth of the aerodynamic forces due to the gust impact.

The representations of the feed-back control systems that affect the symmetric vertical gust response, include the load alleviation (LAF) and also, due to the possible coupling of the handling laws, the C* flight control system, and these are written to take account of the method of solution.

The aircraft equations may be considered linear, and solutions found in the frequency plane as well as the time plane. The non-linear aspects of the systems, however, may only be represented adequately in a stepwise time plane integration solution, and only linear approximations may be used for the frequency plane solutions. The non-linearities will be discussed further in section 8.

The results of some typical theoretical calculations, solved in the timeplane are given in Figs.9 and 10.

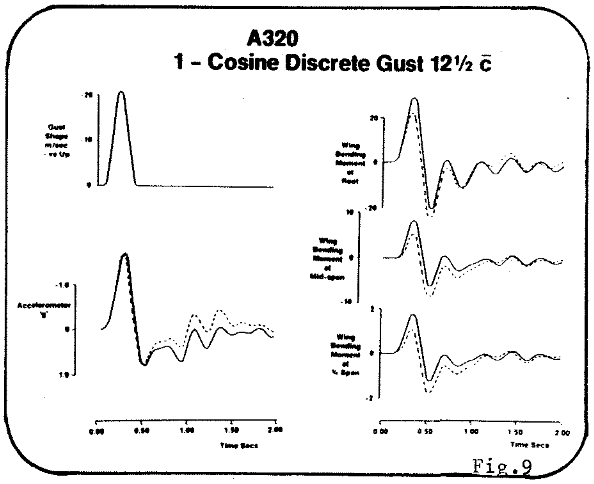

Fig.9

The A320 aircraft equations have been solved at a flight condition of Vc at 23,000 feet and for a high all-up-weight.

Fig.9 shows the response to a (1-cosine) discrete gust of 21 metres/second and gradient length equal to 12½ mean chords. The first trace plotted against time shows the gust shape and the second trace the response of the fuselage vertical accelerometer sited just forward of the wing.

The dotted line gives the response of the 'datum' aircraft, that is the aircraft with LAF fully operational. The full line shows the response of the 'complementary' aircraft, in this case an identical aircraft with LAF non-operational.

The remaining three traces show incremental wing bending moments for a number of wing stations and indicate the amount of alleviation being achieved in the up bending sense.

Fig.10 shows the response of the aircraft for the same flight condition and to a measured turbulence input. The turbulence was measured during a data recording programme on a number of civil aircraft and is noted as an event where a number of gusts have occurred in sequence. The peak has been scaled to the same level as the discrete gust used in the previous figure and the response of the wing bending moment at two stations is shown.

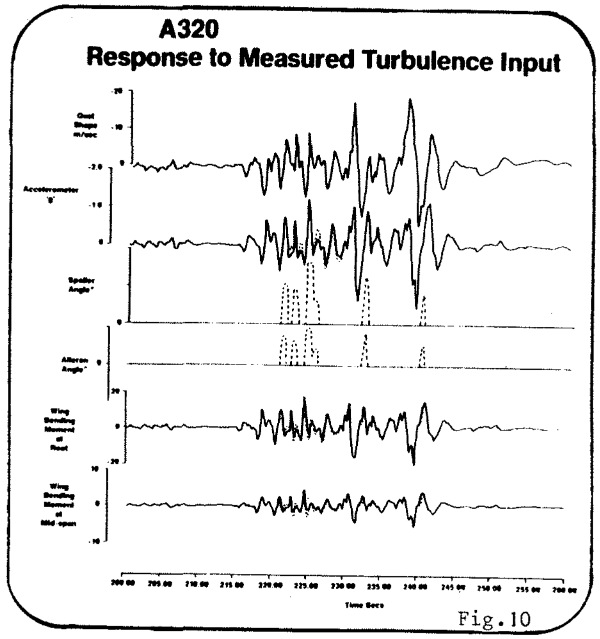

Fig.10

6. Stability

From the earliest studies on load alleviation carried out in British Aerospace at Weybridge and continuing up until the latest studies on A320, one of the major difficulties foreseen has been the problem of structural stability. For a closed control loop between a control surface and an accelerometer fitted to the aircraft structure, there is feed-back at all frequencies at which the structure at that point will respond.

Early calculations indicated that a problem existed in siting the accelerometer in a position where for high gains the structural flexibilities did not introduce instabilities. High response on the outer wings made such a site unsuitable and the lower response of the central fuselage area made that position possibly the only acceptable position, assuming high gain would be used. Use of notch filters to filter out response at certain discrete frequencies was not satisfactory because of shifts in frequency and nodal points in the flexible mode shapes occasioned by different payload and fuel conditions and different flight conditions.

It should be noted that the structural frequencies fed back by the accelerometer tend to be frequencies of the fuselage modes, together with frequencies of the local structure and mountings. In addition to potential instabilities arising purely from the closed loop feed-back of the LAF loop, there is also the possibility of LAF reducing the damping in the critical flutter modes such that flutter instabilities can occur at lower speeds than for the aircraft with LAF non-operational.

A typical calculation of an open loop response is now considered. For this calculation the system was assumed linear and spoilers were assumed to be able to move in both directions about a mean position. The open loop response is shown as a Nyquist plot in Fig.11. The response at 3.1 Hz indicated by the loop on the left will have a gain margin depending on the position along the X axis of the -1 point. If the -1 point is at the position marked 'A' then the gain margin would be three. This means that the response vector would have to be increased by a factor of three or more before the clockwise loop encircled the -1 point, thus indicating an instability of the closed loop system.

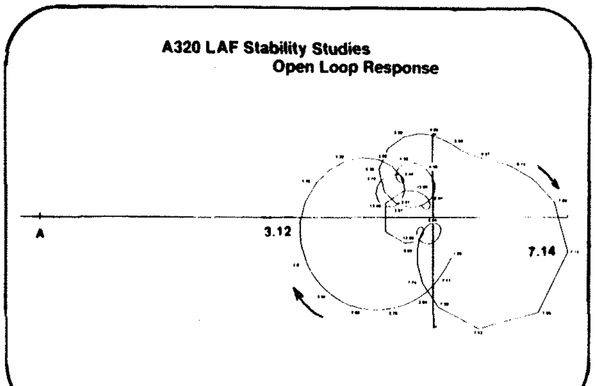

Fig.11

The results from a conventional flutter calculation also need to be considered to establish any potentially critical flutter modes. The results for the 'complementary' aircraft with no LAF need to be found and then the change in damping found for the 'datum' aircraft when the LAF is made operational as a linear system. This damping can then be compared with the Nyquist approach.

Summarising the situation on A320, for the greater majority of flight time the LAF will be inactive and no structural stability considerations can arise involving LAF. However, when LAF is active in the linear regime of the control law then the flutter requirements and the requirements for the linear loop gain margins must be met. It will be necessary to demonstrate stability in flight and the aircraft flight test programmes already completed and which will be discussed in section 10 will discuss this matter further.

7. Failure Cases

One of the overiding considerations in designing the LAF has been the one of safety. In the case of failure of any part of the system the principle of equivalent safety has been used and the objective in the system safety analysis has been to show that the frequency of exceedance of the design limit load for an aircraft fitted with LAF shall be no greater than for an aircraft of similar characteristics designed without LAF. In establishing the safety it has been necessary to consider flight with LAF

- o operational and operating
- o partially operational and operating
- o operational but not operating
- o non-operational

Probabilities of loss of function and partial loss of funtion have to be established and safety analysed at the time of the failure, for the duration of the flight, and in the possibility of dispatch in a known failure condition.

For A320 the assessment is currently under discussion both within Airbus Industrie and with the Airworthiness Authorities.

8. Non-Linearities, the Effect on Gust Calculations

The load alleviation function developed for A320 is of necessity non-linear in character, the spoilers operate in one direction only from the neutral position, and can only be used to alleviate up gusts. The threshold, the control limits and the actuator control law all add to the non-linear nature of the system.

The non-linear characteristics do have an influence on the theoretical analyses, the major one being that theoretical loads and response calculations can only reasonably be carried out in the time plane. Any solutions in the frequency plane can only be run for linear approximations.

A major consideration therefore is the procedure to be adopted for carrying out continuous turbulence calculations because the requirements are written in terms of a power spectral density (PSD) approach.

A technique has been developed which takes solutions in the time plane for the 'datum' (non-linear) and 'complementary' (linear) aircraft to determine the relationship between the two aircraft states due to LAF and C* control systems. By referring this to a conventional frequency plane calculation for the linear 'complementary' aircraft, consistent results can be obtained for the 'datum' aircraft. Problems in the time plane arise from the length of time required to represent the true random nature of turbulence, the magnitude of the turbulence, and the resolution of low frequencies and their effect on the response.

In practice, the time plane and frequency plane results for the linear 'complementary' aircraft for the same standard of mathematical model have demonstrated identical results and the procedure developed will be used for the 'datum' aircraft.

9. Implications for Flight Testing

Gust statistics show that the probability of the aircraft exceeding the threshold value of vertical acceleration is signifcantly less than once per flight. The ability to find flight conditions which will adequately test the system is therefore severely limited. It will hardly be an economic possibility to flight test for a sufficient number of hours to build up a reasonable statistical sample of results as required by the random nature of turbulence, and the chances of finding a gust magnitude close to the design limit level will be of the order 1 in 100,000 hours.

The approach to be adopted on A320 is therefore the only sensible one which is available. As for any conventional aircraft the wing loads arising from gusts are calculated. The loads arising from the load alleviation system and which subtract from the gust loads are measured by exercising the system for a synthetic input and the effectiveness of the system judged from these measurements when compared with predictions.

However, allowing for some possibility of finding turbulence, the A320 will be instrumented to measure the response to any real turbulence and if suitable turbulence is found then the results will be analysed in terms of exceedance counts with and without LAF.

The test approach to be used on A320 includes

- o establishment of LAF for
  - alleviation performance
  - stability
- o measurement of incremental loads (as noted above) for
  - substantiation of methods and data
  - comparison with predictions
- o measurement of gusts (if met in normal flight and as noted above) for
  - correlation with predictions

Establishment of LAF will involve testing throughout the flight envelope to establish the parameters used in the LAF Law and adjust them if necessary. Excitation will be applied to the aircraft in open loop through the ailerons and outer spoilers, both separately and together. Data will be analysed both for performance and stability. The closed loop LAF gain margins will be established for some flight points by transfer function analysis in the open loop condition. For all flight points and conditions, satisfactory gain margins will be demonstrated explicitly in the closed loop condition. These tests will be closely integrated with the aircraft flutter tests and handling tests.

This approach has been developed in flight on the A310 and the results of this programme together with a complementary programme on the BAC 1-11 are discussed in the next section.

10. Aircraft Test Programme

10.1 A310

The Airbus Industrie owned prototype A310, aircraft 172, was made available to carry out LAF testing in flight. Outboard ailerons are not fitted to the production A310 on which lateral control is by electrically signalled inner ailerons and spoilers, a step towards the full fly-by-wire system of the A320. As shown in Fig.12 aircraft 172 has outboard ailerons fitted and although normally locked since the first flights of the A310, these ailerons were made available for the LAF testing. Also available were the two outboard spoilers, in this case spoilers 6 and 7. The on-board computer and the spoiler actuators both had a reduced performance relative to A320, but nevertheless the value of flight testing and the comparison of this testing with calculations for the A310 were considered to be an essential part of the development programme.

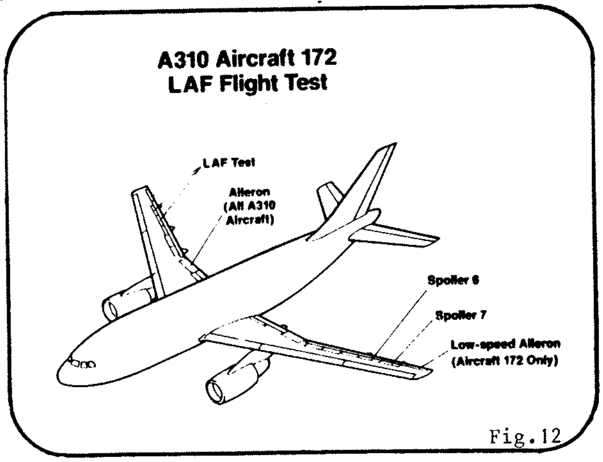

Fig.12

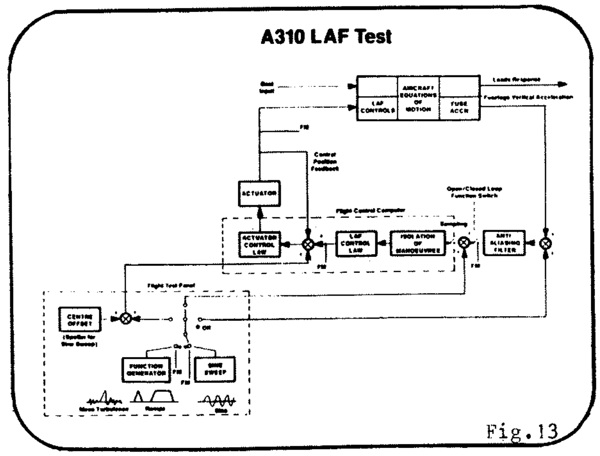

Fig.13

A block diagram representing the test setup is given in Fig.13, which shows a flow diagram not unlike that discussed earlier for A320 (Fig.4). Fig.13 shows the introduction of a switch to open and close the basic loop in the feed-back and a flight test panel from which a number of different inputs can be fed into the system. These include sine wave swept over a particular frequency range, triangular ramps and ramps with dwell, and measured turbulence input.

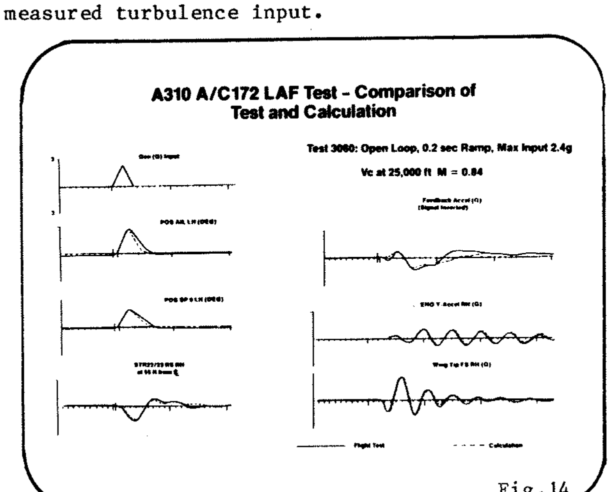

Fig.14

A series of comparisons are given between test and theory for open loop inputs for a particular flight condition and using an equivalent A320 LAF Law. In Fig. 14 the traces for test and theory have been over plotted for a triangular ramp input and the spoiler movement, acceleration and load response is remarkably good. With a measured turbulence input the traces are plotted alongside one another and Fig. 15 and 16 give corresponding traces to those shown in Fig. 14 and again the spoiler movement, acceleration and load response is close.

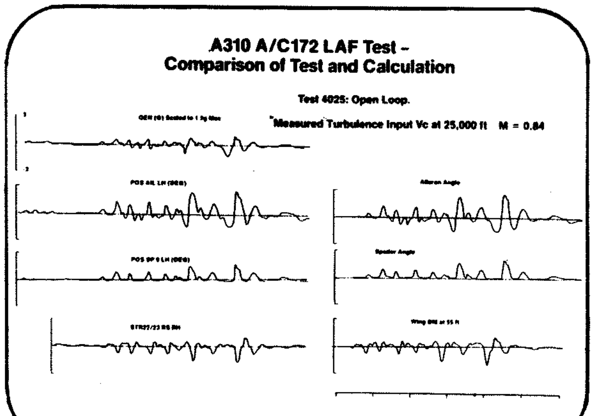

Fig.15

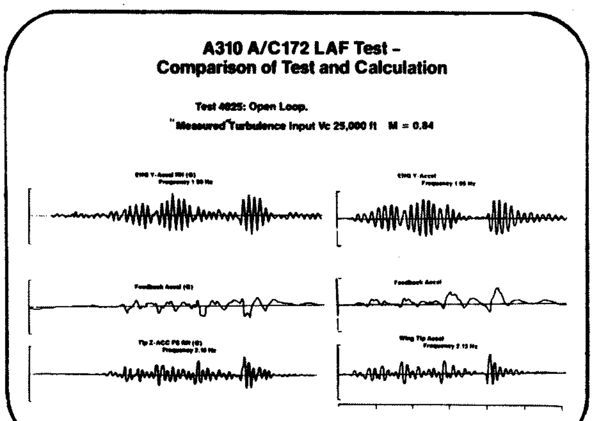

Fig.16

A further test on the aircraft examined the open loop response for a frequency sweep and a comparison of measured and calculated results are given in Fig.17. The Nyquist plots have to be examined fairly closely to see what 'specialists' would recognise as a good comparison in shape and frequency layout, together with gain margin in amplitude and phase.

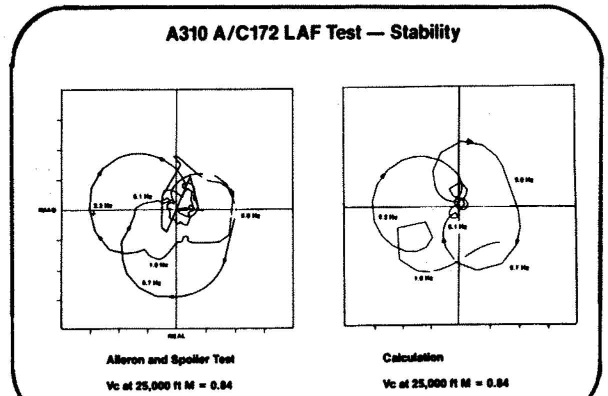

Fig.17

The conclusions from these tests are

(i) the comparison of results supported the theoretical model of control input forces, and of the aircraft simulation and subsequent response.

(ii) the test in fact demonstrated satisfactory LAF operation at a number of speeds ranging from Vb to Vc (not shown).

(iii) the test adequately demonstrated the ability to measure the wing loads arising from LAF operation and these are the loads which will be measured on A320 to demonstrate the effectiveness of LAF.

(iv) the test demonstrated adequate stability margins for an active LAF Law.

10.2 BAC 1-11

The British Aerospace owned BAC 1-11, aircraft G-ASYD, was involved in a programme of Active Control Technology (ACT) tests discussed in Mr Hitch's paper also being presented at this conference. The aircraft shown in Fig. 18 is fitted with an outboard spoiler driven by a high rate actuator. The opportunity was taken in the process of ACT testing to carry out some additional LAF tests using an "A320 type" LAF Law.

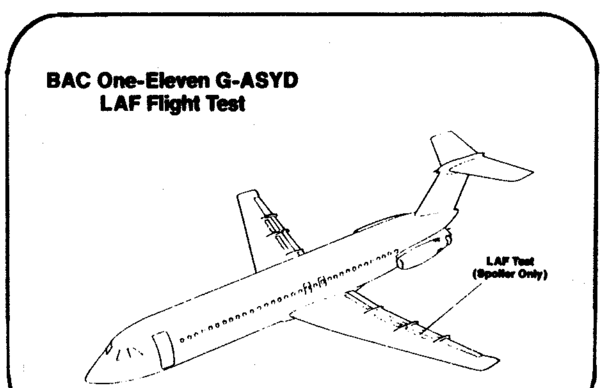

Fig.18

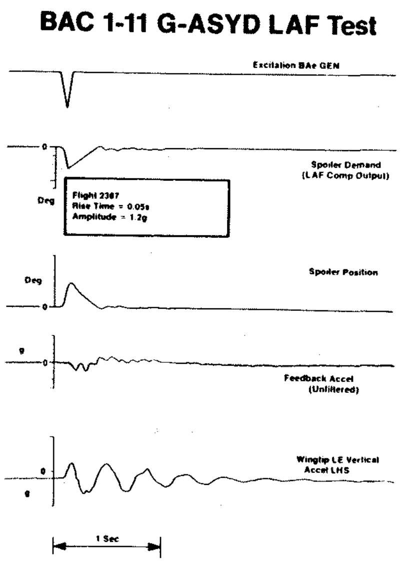

Fig.19

A number of tests were carried out varying flight condition, ramp input amplitude and rise time, threshold and spoiler gain, Fig.19 shows some results obtained on Flight 2367.

The conclusion from these additional 1-11 tests is that, even when fitted with high rate spoiler actuators, adequate stability margins can be demonstrated for an "A320 Type" LAF Law.

11. Concluding Remarks

11.1 The paper has discussed the design of a gust load alleviation function (LAF) for a modern civil airliner, the Airbus Industrie A320, using existing controls and control systems.

11.2 By making use of the electrical flying control system (EFCS) the system modifications to allow the introduction of LAF, and hence the weight penalties, have been kept to a minimum.

11.3 Results of early feasibility studies have been discussed and used to show the degree of alleviation achieved for varying control actuator rates and gains.

11.4 The current Airworthiness Requirements have been examined and reference made to some additional criteria which take account of the system/structural interface and the effect of realistic gust and turbulence fields. No major problems are envisaged in certificating the LAF system.

11.5 The design of the LAF Law has been studied and the results of a sample number of digital computer simulations examined. These calculations indicated that the target alleviation of 15% net at the wing root can be achieved.

11.6 Attention has been given to the structural stability of such a closed loop accelerometer feed-back system, and as a result a satisfactory law developed.

11.7 The flight test implications of LAF have been looked at, and two flight test development programmes referenced which established levels of confidence for the effectivness and the stability of the system.

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