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EVOLUTION OF TRANSPORT AIRPLANE STRUCTURAL DESIGN CRITERIA TO INCORPORATE ADVANCES IN TECHNOLOGY

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Abstract

Structural design criteria are constantly being re-evaluated in order to maintain the delicate balance between adequate strength and minimum weight, while maintaining the same or improved levels of safety. The need or opportunity to change structural design criteria may be recognized by the introduction of complex computer technology. However, it could also be due to a change in operational procedures. The intent of this paper is to discuss how these advances in technology and changes in operation are handled, without going into detail about the actual rule change procedure

Background

The introduction of new technology can, in some cases, invalidate the existing structural design criteria. Although it takes many years to change the Federal Aviation Administration (FAA) Code of Federal Regulations, the FAA must recognize the impact of new technology and adjust the certification criteria accordingly. (1) For a significant change in technology, the FAA may establish "Special Conditions," for certification. These are published in the Federal Register and public comment is invited. An example of the most recently published Special Conditions is given in Reference 2.(2) These are for the Ilyushin Aviation Complex Model IL-96T Airplane, which has a fly-by-wire control system, load alleviation, and a center main gear.

Advanced Technology Areas

The following represent areas where the technology has changed, or where operation has changed, or where a need has been identified to consider a particular effect.

Fly-by-wire controls, load alleviation, large high by-pass ratio turbofan engines, turbulence, landing, and ground handling all have a direct and significant effect on structural design load levels.

Fly-by-Wire Controls The significance of fly-by-wire controls to the structures engineer is not the fly-by-wire (it could be fly-by-light), but the insertion of computer control between the pilot and the aerodynamic control surfaces. Computer control and system complexity give rise to a new series of normal control modes and failure modes which can drive the airplane controls at higher rates and/or to larger deflections than a pilot would command. Since the probability of system failures can be calculated, the FAA allows the structural safety factor of 1.5 to be reduced for airplane loads generated by less frequent system failures, as shown in Figure 1. (2)

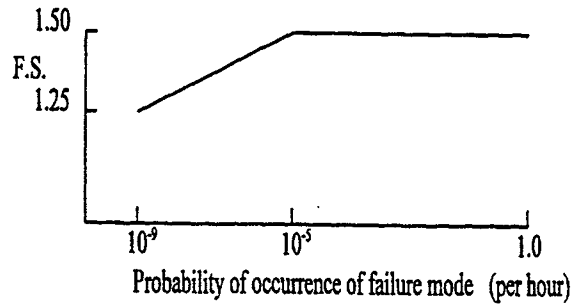


Figure 1. Variation of Factor of Safety at Time of Occurrence

Load Alleviation With a computer control system, it becomes easier to add features such as load alleviation. Airplane parameters such as speed, weight, and acceleration due to maneuver or gust can be monitored, and control surfaces deflected to alleviate or re-distribute the air load. A wing maneuver load alleviation concept using ailerons is presented in Figure 2.

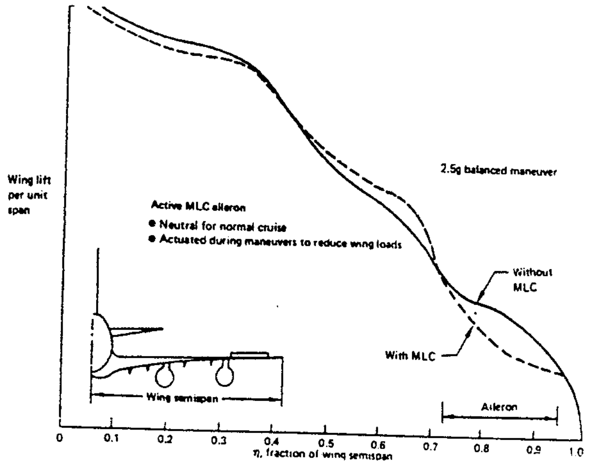


Figure 2. Maneuver Load Control Concept

A wing maneuver load alleviation system using symmetric aileron deflection reduces wing root bending moment by redistribution of the spanwise lift, while the angle of attack must be adjusted to maintain the required total maneuver lift. However, a gust load alleviation system can utilize symmetric aileron deflection to re-distribute and also reduce the wing lift. A gust load alleviation system can also use elevator inputs to reduce gust wing lift.

Large High By-pass Ratio Turbofan Engines The current design criteria were developed for the first generation of turbojet engines, where a shaft seizure was considered a significant load-producing condition. Now, with large fans with relatively few blades, the loss of one blade produces significant forces as a result of the failure, and continues to produce significant unbalanced forces for the rest of the flight. The combination of large engines and long flights (especially for the twins) has given rise to the need to evaluate and re-define the design criteria.

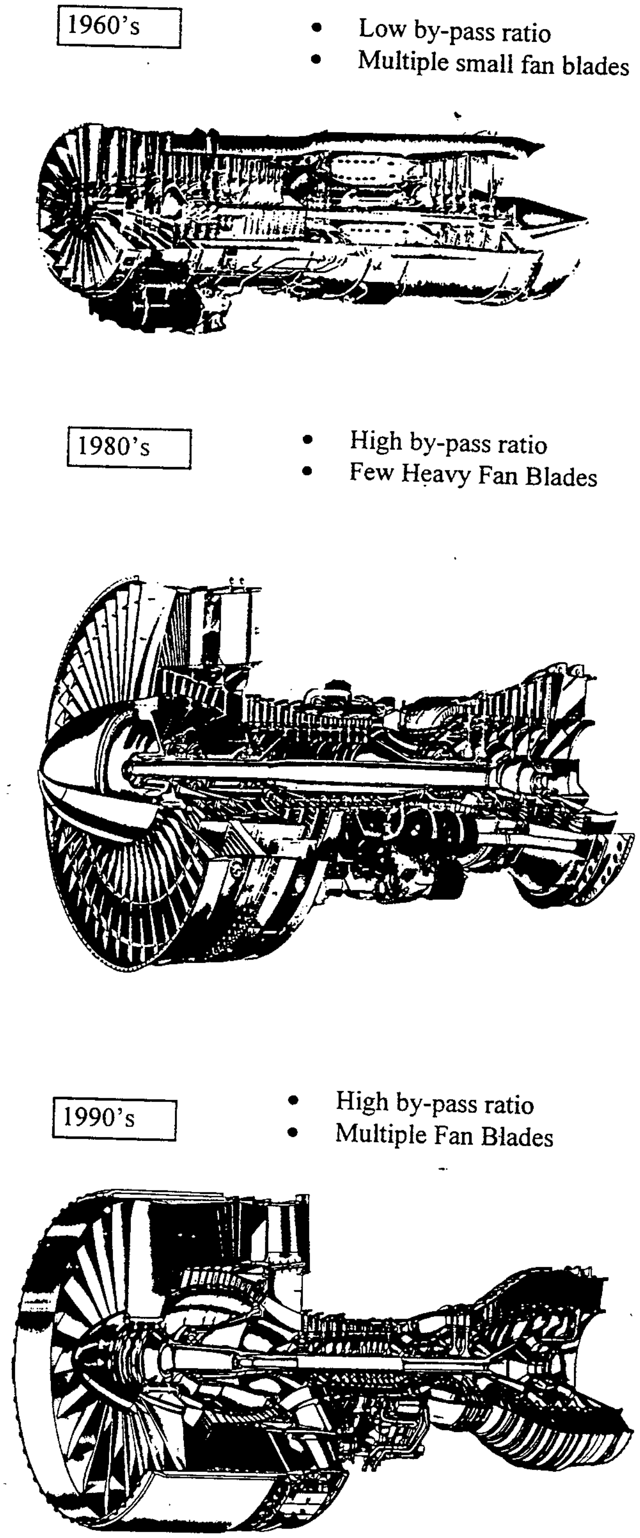


Figure 3. Engine Configuration Changes that Affect Structural Design Criteria

A typical approach has been used to develop interim certification criteria for these new engine/flight operation combinations — a combination of new engine specific data, and prior operational statistics. Each new engine type that is certified must comply with FAR Part 33.94, "Blade containment and rotor unbalance tests." (3) This usually involves a highly instrumented test which explosively releases a fan blade at maximum engine r.p.m.

The results of this test are used to develop a forcing function which is applied to the engine, struts, and airframe. The forcing function is typically applied at several different angles to represent blade loss at any radial location. The resulting loads on the engine and strut are considered as ultimate, and those applied to the adjacent airframe structure are multiplied by 1.25 to obtain ultimate loads.

For continuation of the flight, which is of special concern for twin engine extended over water operations, data from previous fan blade events were collected to provide a statistical basis for developing acceptable criteria in terms of proportion of complete fan blade loss versus time to destination.

Turbulence Two models of atmospheric turbulence are used for structural design — discrete and continuous. Since turbulence encounters are a combination of the actual turbulence and the airplane being there, the actual levels of turbulence encountered will vary with the type of operation. In the past, NACA, and more recently, NASA, has conducted routine surveys to collect normal operational turbulence data. Now this work is being conducted by the FAA.(4, 5) In addition, the UK-CAA Data Recording Program (CAADRP) has provided results of events (indicating turbulence) for use in defining new gust design criteria. Discrete gust design criteria have been updated, and continuous turbulence criteria are expected to follow.

The 50 feet/second 1-cos 25 chord gust, and the optional gust load formula were finally replaced by a more rational dynamic tuned discrete gust analysis criterion as defined on Figures 4(a) and 4(b).

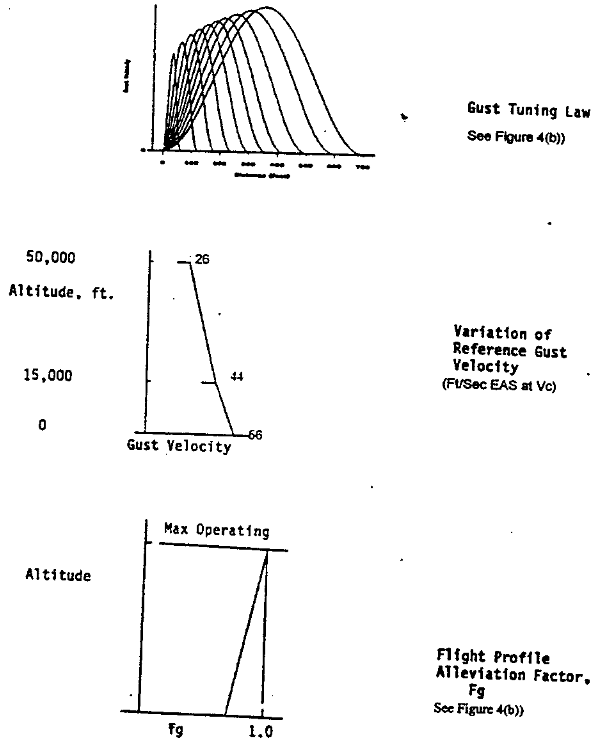


Figure 4(a) Current FAR 25 Tuned Discrete Gust (§25.321 Amdt. 25-86, 1996)

Gust Tuning Law

The shape of the gust must be:

$$U=\frac{U_{ds}}{2}\left[1-\mathrm{Cos}\left(\frac{\pi s}{H}\right)\right]$$

for $0 \le s \le 2H$
where—
s=distance penetrated into the gust (feet);
U_{ds}=the design gust velocity in equivalent airspeed specified in paragraph (a)(4) of this section; and
H=the gust gradient which is the distance (feet) parallel to the airplane's flight path for the gust to reach its peak velocity.

(3) A sufficient number of gust gradient distances in the range 30 feet to 350 feet must be investigated to find the critical response for each load quantity.

(4) The design gust velocity must be:

$$U_{ds}=U_{ref}F_g\left(H/350\right)^{1/6}$$

where—
U_{ref}=the reference gust velocity in equivalent airspeed defined in paragraph (a)(5) of this section.
F_g=the flight profile alleviation factor

Flight Profile Alleviation Factor

The flight profile alleviation factor, F_g, must be increased linearly from the sea level value to a value of 1.0 at the maximum operating altitude defined in §25.1527. At sea level, the flight profile alleviation factor is determined by the following equation:

$$F_g=0.5\left(F_{gz}+F_{gm}\right)$$

Where:

$$F_{gz}=1-\frac{Z_{mo}}{250000};$$

$$F_{gm}=\sqrt{R_2\,\mathrm{Tan}\left(\pi R_1/4\right)};$$

$$R_1=\frac{\text{Maximum Landing Weight}}{\text{Maximum Take-off Weight}};$$

$$R_2=\frac{\text{Maximum Zero Fuel Weight}}{\text{Maximum Take-off Weight}};$$

Z_{mo}=Maximum operating altitude defined in §25.1527.

Figure 4(b) Tuned Discrete Gust Definitions

The tuned discrete gust criterion reflects the accepted 1-cos gust shape, and the $H^{1/6}$ relationship between gust intensity and wavelength that is found in turbulence at structural design levels.

Landing The landing impact design criteria were established many years ago, and validated using a camera survey shortly after the introduction of jet transports.

With the availability of a new video system, the FAA is conducting a series of airport operational surveys to re-validate the landing design criteria, and provide landing fatigue data to the manufacturers. Some results are available — see Figure 5. If a transport airplane significantly larger than the B-747 is anticipated, then the landing design criteria may need to be re-evaluated due to the trend of higher sink speed with airplane size and/or weight. (6)

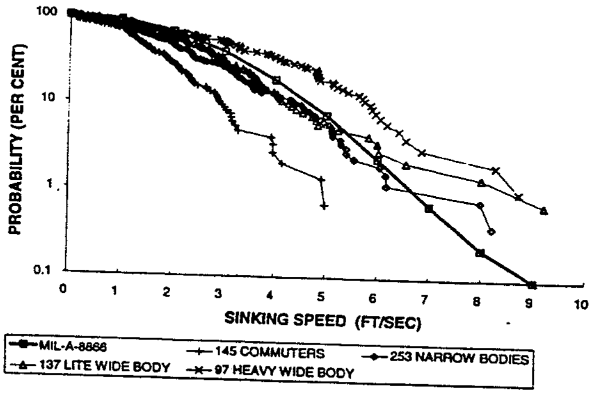
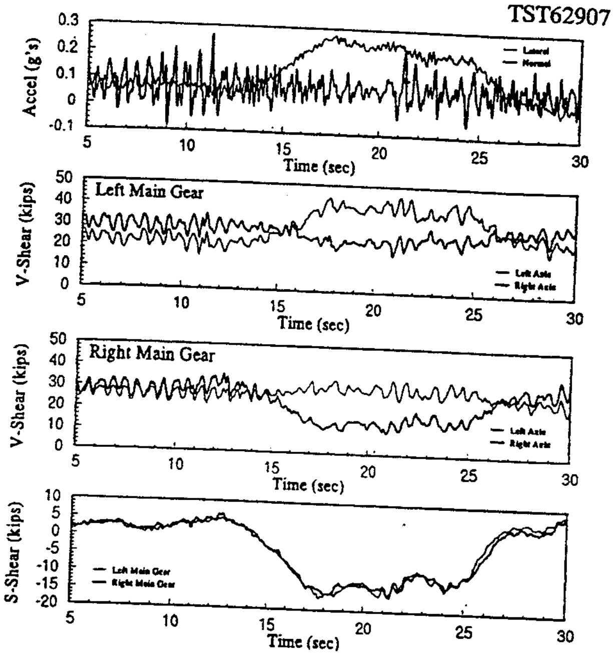


Figure 5. Probability Distribution of the JFK International Airport Survey Sinking Speeds

Ground Handling As with the landing criteria, the ground handling load conditions were established many years ago, and have largely remained unchanged. Especially as airplanes have increased in size and weight, the simplistic "book cases" are being challenged as being unrealistic. Two examples are § 25.495, Turning and § 25.509 Towing Loads. Both are simplistic criteria which have resulted in adequate strength. Some data are available which indicate that both criteria may be conservative.

Data from a highly instrumented B-727 which was conducting ground friction testing were re-analyzed to produce gear loads data, and these data were reported in Reference 7. Of specific interest are the results of S turns and runway exits. Figure 39 is reproduced here as Figure 6, showing that a runway exit at 60 knots results in an airplane c.g. lateral acceleration of 0.28g compared with a design value of 0.5g. (7) In a similar way, Figure 19 which is reproduced here as Figure 7 shows that recorded lateral accelerations in normal operations are less than ± 0.5g. (8)



Data Rate = 30 Hz
F_c = 5 Hz

Figure 6. Multiple Time Trace Data Plot of a Typical Runway Exit at 60 Knots

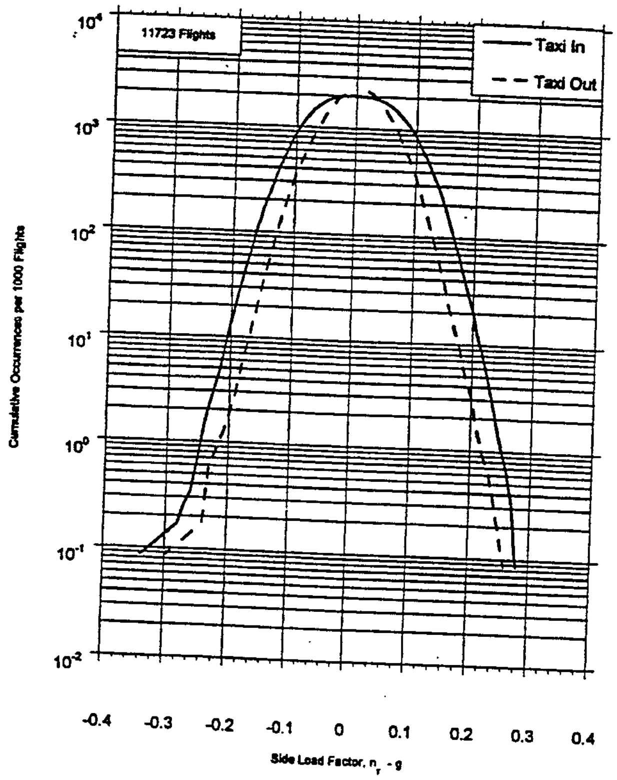


Figure 7. Cumulative Frequency of Maximum Side Load Factor During Ground Turns

For airplanes over 100,000 pounds, the design tow load is 15% of the design ramp weight. Data from actual towing tests indicate that the design value may be conservative. Additional data needs to be collected and analyzed in order to recommend any changes to the established criteria. (9, 10)

Conclusions

The FAA has a system in place which allows for the certification of airplanes which incorporate advances in technology, and which allows for the recognition of changes in operational procedures which may impact structural design criteria.

The FAA is also conducting research which directly or indirectly provides data which can be used to evaluate the structural design criteria against actual usage.

References

1. Code of Federal Regulations, FAR Part 25 - Airworthiness Standards: Transport Category Airplanes.

2. FAA Special Conditions No. 25-ANM-135: Ilyushin Aviation Complex Model Il-96T Airplane, published in the Federal Register January 21, 1998.

3. Code of Federal Regulation FAR Part 33 - Airworthiness Standards: Aircraft Engines.

4. DOT/FAA/AR-95/21, "Flight Loads Data for a Boeing 737-400 in Commercial Operation."

5. Technical Paper, "The FAA Flight Loads Data Collection Program for Commercial Transport Aircraft," presented by Terence J. Barnes, FAA at ICAF '95.

6. DOT/FAA/AR-96/125, "Video Landing Parameter Survey — John F. Kennedy International Airport."

7. DOT/FAA/AR-95/82, "An Analysis of Ground - Flight Loads Measured on the Instrumented B-727 N40."

8. DOT/FAA/AR- / , "Statistical Loads Data for Boeing 737-400 Aircraft in Commercial Operations." (Draft Report)

9. FAA-NA-80-23, "Evaluation of the impact of Towing DC-9 Transport Airplanes at Boston-Logan Airport," May 1980.

10. FAA-NA-80-24, "Evaluation of the Impact of Towing the L-1011 Airplane at Boston-Logan Airport," May 1980.