Abstract of the Plantema Memorial Lecture

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Three Faces of Aeronautical Fatigue

Face 1: We had Eyes but Could Not See

During 1969, an incident occurred at a large aircraft engine company. The company received many orders for a specific aircraft engine model. The demand for these engines was so high, that the company employed subcontractors to manufacture several of the complex engine parts, in parallel with "in-house" manufacturing. Soon after the engines entered service, several airlines reported fatigue cracks and failures of the "high-compressor duct". Analysis of these failures disclosed that *nearly all of the fatigue failures occurred on ducts manufactured by the subcontractor.*

The first step of the investigation was to compare several ducts produced by the subcontractor and those produced in-house, against the design and manufacturing specifications. ***It was found that all the ducts produced in-house, and all those produced by the subcontractor met all the design and manufacturing requirements.***

Engine testing was performed, installing ducts produced by the subcontractor. When the high-rotor reached about 6,800 RPM, the pressure-transducers began "shrieking" at 1350 Hz, while the strain-gages and accelerometers were "dancing" at the same frequency. The peak measured noise levels reached 170 dB while the measured stress levels on the duct were 18 to 20 ksi, which certainly could explain the high-cycle fatigue failures. As the high-rotor speed reached 8,800 RPM, all the measured parameters suddenly quieted down. Engine testing with in-house produced ducts, did not show any of these characteristics.

Subsequent testing showed that the source of the noise and vibration was an *acoustic resonator* that was present in a chamber of the engine. There still were no indications why only the ducts produced by the subcontractor were affected. Eventually, the mystery was solved, but more than sixty high-compressor ducts failed in service. This problem took about ***eight months*** to solve, at a very high cost to the company.

Face 2: Nearly Identical Twins or Distant Cousins?

Over the last half-century, organizations that dealt with fatigue life variability of aircraft structures, generally performed their reliability analyses by using the Weibull distribution. The Log-Normal distribution was considered to be *nearly identical* to the Weibull distribution, and it was less often utilized.

It has been shown in this paper, using several actual examples, that there are *very sizable differences* between the Weibull and Log-Normal distributions, for setting allowable service lives to minimize the probability of failure. *In all cases, the Weibull results are much more conservative than the Log-Normal results.* From these results, it is difficult to say which distribution is the more accurate.

An analysis was performed to determine the allowable service life of a steel landing gear. The results clearly indicate that the Log-Normal distribution predicts a *much lower probability of failure* during its service life than the Weibull distribution.

In 1969 and in 1972, the Boeing Company published the results of a detailed study that was performed on fatigue life variability of aluminum, titanium and steel aircraft structures. Boeing concluded that the Log-Normal model produced an *optimistic assessment* of the fatigue data distribution, while the Weibull model produced an *acceptable assessment* of the fatigue data distribution. The author of this paper found it difficult to accept the above conclusions without further investigation, due to the manner that the test specimens were selected.

A sixty-specimen fatigue test program is proposed in the paper in order to better evaluate the fit of the Weibull and Log-Normal distributions to *actual* fatigue test data.

Face 3: Widespread Fatigue Damage Revisited

During October, 2011, The FAA released AC No. 120-104, which is an advisory circular dealing with "Establishing and Implementing Limits-of-Validity to Prevent Widespread Fatigue Damage". In this document, the FAA *suggested* that the manufacturer perform sufficient fatigue testing and analysis, under typical spectrum loading, to determine the service life at which 50% of the fleet has already failed. This service life is called $WFD_{average}$ in this advisory circular. The advisory circular then *suggests* that 50% of the $WFD_{average}$ be identified as the "Structural Modification Point" (SMP), at which the manufacturer is to implement structural improvements to the structure, in order to ensure that widespread fatigue damage will not occur. This implies that if the manufacturer elects *not to implement any structural improvements,* 50% of $WFD_{average}$ will become the limit-of-validity (LOV) of the aircraft.

This does not seem to be a reasonable suggestion to ensure safety, for two reasons:

(1) Since $WFD_{average}$ is primarily based on the crack-initiation life of the structure, it is basically a return to the "safe-life concept", which has been shown many years ago to be an unreliable method to ensure safety of fatigue critical structures.

(2) Setting the LOV at 50% of the "safe life" is certainly insufficient. Scatter-factors of 5 or more are normally used to provide sufficient safety of safe-life structures.

An alternate approach is presented in this paper to define the LOV of the suspected structure:

(1) Determine the *appropriate* allowable hazard-rate for the structure. AC No. 25.571-1D and other FAA documents *imply* that a hazard-rate of 10^{-9} failures per flight hour will result in sufficient safety. *(Hazard-rate is defined as the probability that the "next flight of the aircraft" will result in a catastrophic failure.)*

(2) Perform probabilistic analyses using INSIM Software to determine the inspection thresholds and intervals that are appropriate for the selected LOV for the "AC No. 120-104" approach as well as the "alternate" approach. The results of these probabilistic analyses will predict the maximum hazard-rate before the LOV is reached. In this way, the results of using the methodology suggested in AC No. 120-104 can be compared to those using the alternate approach described above.

The paper develops these topics and compares the results of the probabilistic calculations, using both approaches. A selected example of a *typical narrow body aircraft* is used for the analysis. Discussion and conclusions are included in the paper.