"THREE APPLICATIONS OF MONTE CARLO SIMULATION TO THE DEVELOPMENT OF THE F100 TURBOFAN ENGINE"

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Problem Attacked

The development through Qualification Test of any turbojet or turbofan engine typically clears the "average engine. The limited number of engines used in a development program reduces the possibility of encountering the extremes of the tolerances, material properties and trim bands. Once in service, these 3 sigma problems surface. These engine failures and malfunctions are serious and disappointing after years of development tests. The engine manufacturer is asked why weren't these problems uncovered earlier?

One reason is that there are rare failure modes that have small probability of detection within the development test program. Figure 1 shows the probability of detecting failure modes that have 0.1, 0.01 and 0.001 probability of occurrence in a typical development engine build of 100 test hours. Figure 2 shows that although some failure modes will be detected with high probability before PFRT, others will not appear until long after MQT even when we assume all testing is relevant. New technology is needed to detect these failures early to prevent operational problems and costly retrofits.

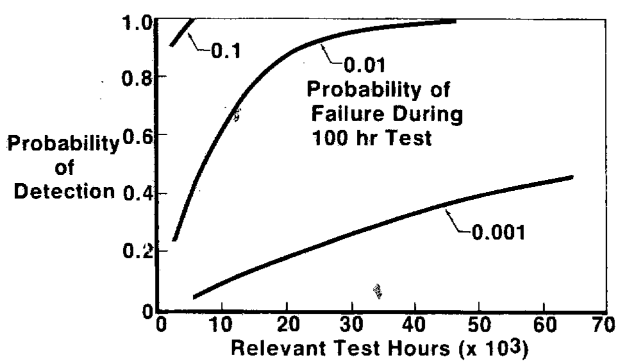

Fig. 1 Failure Mode Detection.

Another reason is that there will be interactions between random engine variables that in a few cases can produce extraordinary performance, stress, and functional suitability. The prediction of these rare events taxes the best engineering.

Monte Carlo simulations have been a valuable tool in the F100 engine development for dealing with these two classes of problems. It has provided insight and corrective action well in advance of the usual "surprises." Three of these are described in this paper.

The technique consists of programming a mathematical model of the physical system including the random variables. For each trial, a set of input data is generated by using random numbers to sample the input probability distributions. The math model or simulator is exercised with this input to produce the output variables. The process is repeated for hundreds or thousands of trials to accurately define the output probability distributions. The simulation accuracy is verified by comparisons with the existing system. Only after this validity is established, can the change, improvement, redesign, new mission, etc., be evaluated.

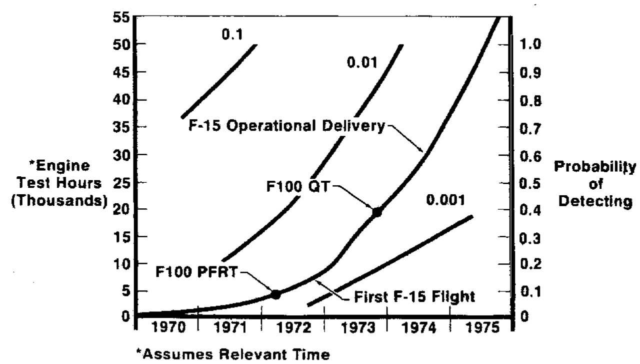

Fig. 2 F100 Development Testing.

The more random variables, the better the technique works. Accurate simulations can be programmed quickly and inexpensively. Sample sizes large enough to work well out in the tails of the distributions are available to detect the rare failure modes. The construction of the simulator often provides the engineers with new insight and understanding of their systems.

The application of this advance technology to the F100 engine is illustrated herein with three examples:

1. The selection of the best techniques for trimming the fuel control
2. An analysis of low cycle fatigue life in a turbine disk
3. The prediction of turbine blade failures from resonant vibratory modes

Trim Simulator

The objective of the trim simulator is to identify the best trim procedure, that is most accurate, simple, quick and repeatable procedure. The simulator is also used to re-evaluate best trim procedures for improvements in control logic, sensors, AGE equipment and engine components.

The F100 engine has several control trim adjustments available for idle, high power, augmentation fuel flow and variable geometry. The following sources of variation are programmed (Figure 3) in the simulation:

- Engine-to-engine variation. This is the main reason for having trim adjustments, i.e., trim adjustments allow an old deteriorated engine to produce the same performance as a new engine even after hundreds and thousands of hours of service.
- Control deadbands. These are null areas provided to keep the control from constant dither.
- Sensor and control errors. Both bias and prevision errors have to be accounted for.
- Test stand instrumentation errors.
- Engine run-to-run variation.
- Installed vs uninstalled. The aircraft environment is different from the test stand, i.e., bleed flow, power extraction, ram recovery, distortion, altitude, ambient temperature.

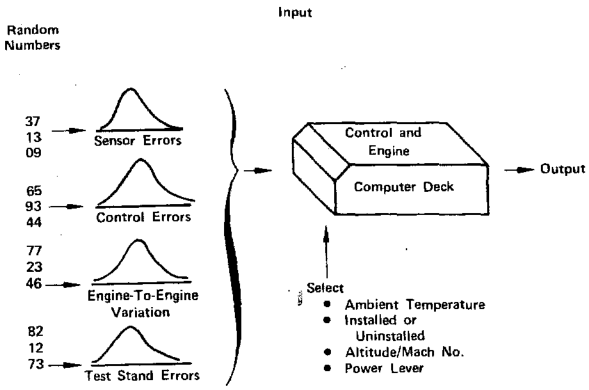

Fig. 3 Monte Carlo Trim Simulator.

Each engine simulation is trimmed according to the given trim procedure. The given trim procedure may be:

- Trim anywhere in the trim bands
- Trim to the center of the trim bands (perfect trim)
- Try a new, proposed trim procedure or trim band
- Use the "as-received" trims from the control vendor without readjustment.
- Combinations of the above for different trim parameters.

Then ten runs are made at each sea level ambient temperature considered and at high altitude, low and high Mach number to determine the effect of trim in flight.

Another engine is then created by random sampling the input distributions and the process repeated. Enough engines are trimmed and exercised to accurately determine the variation at each sea level and altitude conditions (Figure 4).

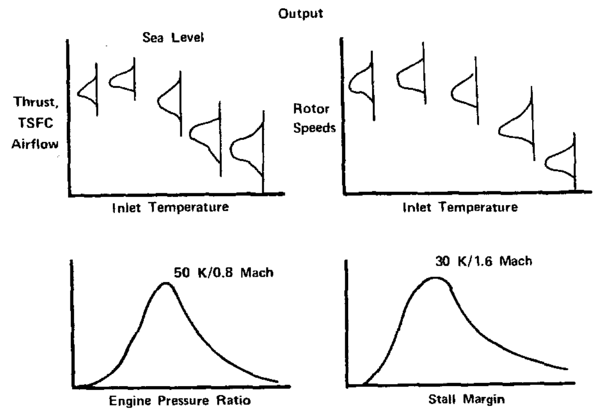

Fig. 4 Monte Carlo Trim Simulator.

The output may be displayed as frequency distributions on computer graphics devices or machine plotted. Any parameter available from the thermodynamic engine - control simulation may be considered as output: Airflow, stall margin, thrust, TSFC, augmentor stability, etc. With this output the best trim procedure may be selected and improvements evaluated.

Low Cycle Fatigue Life

Rotating machinery typically has low cycle fatigue limitations that require replacement of disks/spacers before they become life-limited by creep or stress rupture considerations. LCF life is influenced by:

- Dimensional control of stress concentration regions on the part
- The material property fatigue characteristics
- The rate of build up of high strain range cycles encountered in operation.

The variation from engine to engine from each of these three sources forms probability distributions. Each assembly in each engine is a random sample from these distributions. Although most engines may have many times the calculated minimum life, all parts must be replaced when the (calculated) minimum part's LCF life is used up.

For example, consider a Monte Carlo simulator of the LCF life of the F100 first turbine disk. The input probability distributions for each of the three sources of variation were obtained as follows:

- Actual measurements were obtained from production parts for each critical dimension. These data were used to form histograms or bar charts.
- The distribution of material properties came from fatigue tests of samples from production melts.

- The build up of high strain cycles was determined from the mission mix and engine usage of F-15 operational squadrons.

Each trial simulated a single engine turbine disk. Random numbers were used to sample each of the above distributions. The "data" was then transformed using equations that relate dimensions, material properties and engine usage to LCF life. (Figure 5)

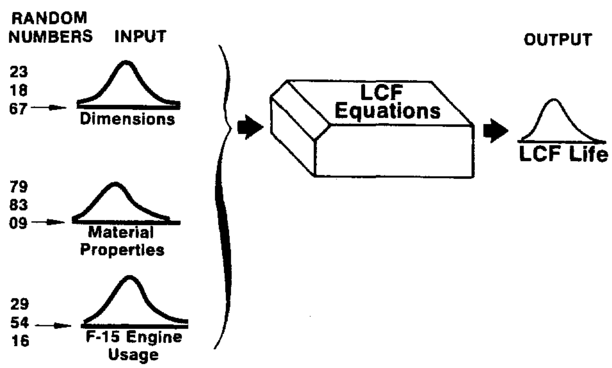

Fig. 5 Monte Carlo Simulation of First Turbine Disk.

In detail the hole through the rim of the disk - a passage to supply cooling air to the turbine blades - is the location of the stress concentration limiting cyclic life (Figure 6). This stress concentration factor (Kt) is a function of the dimensional control of the hole (Figure 7). The rim stress in turn is driven by rotor speed (Figure 8). Finally, the fatigue capability of the material has a log normal distribution from maximum to minimum properties.

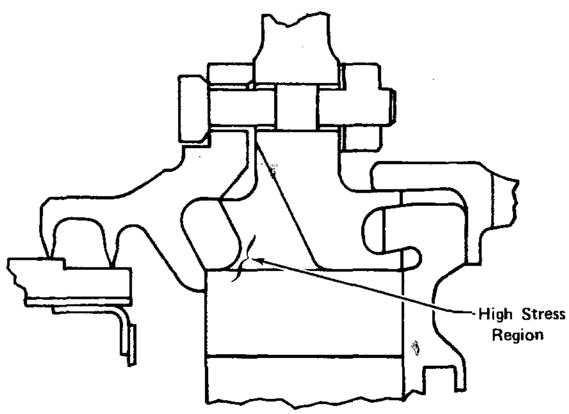

Fig. 6 The LCF Limiting Location Occurs in Cooling Passage Through Disk Rim.

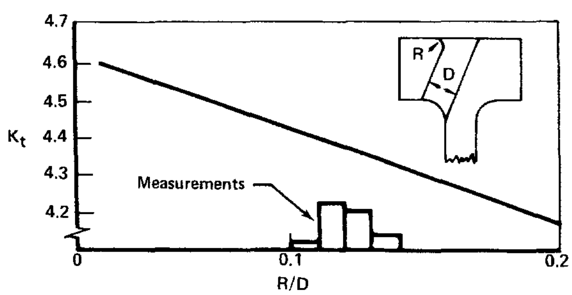

Fig. 7 Effect of Dimensional Control on Hole on the Stress Concentration Factor (Kt).

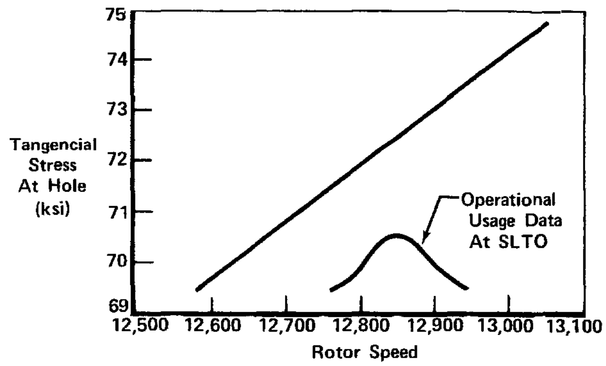

Fig. 8 Rim Stress as f (RPM).

Past practice has been to work with "worst case" life, the highest stress with the lowest material capability. But this masks (1) what drives the life, and also (2) how far out on the tail of the distribution curve you are in the "worst case."

The Monte Carlo simulation of thousands of F100 engines provided the expected distribution of disk life in the field (see Figure 9). There was an order of magnitude difference between the (2 σ) minimum and the maximum life disk.

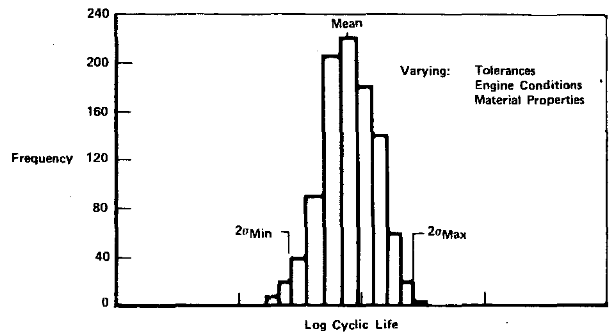

Fig. 9 1st Turbine Disk Cyclic Life Distribution of 1000 Engines.

To determine the effect of each variable on this large spread, we varied the dimension control on the hole, the typical design approach, in the Monte Carlo simulation, and recalculated the distribution of disk life in the field. A reasonable variation in the geometry only produced a 10% improvement in the life. Obviously something else was producing the large variance.

Holding the material properties constant at their mean value, resulted in the life distribution shown in Figure 10. This approach produced a 5:1 increase in the minimum life and drastically reduced the spread.

The driver on the LCF life on this disk, was the fatigue properties of the material, not the geometry of the rim hole or how the engines were being used.

So for a given amount of development time and cost, the potential payoff is greater working for better material properties (less spread or higher mean). That is where we concentrated our efforts, we found that the temperature levels and times at temperature during the process of making the "log" greatly effect the fatigue capability of the finished disk. Without the Monte Carlo simulation, the development effort would have been directed toward revising the geometry of the rim cooling hole.

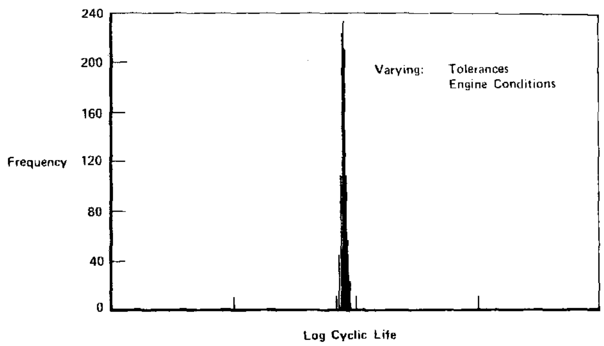

Fig. 10 1st Turbine Disk Life Distribution Holding Material Properties at Mean.

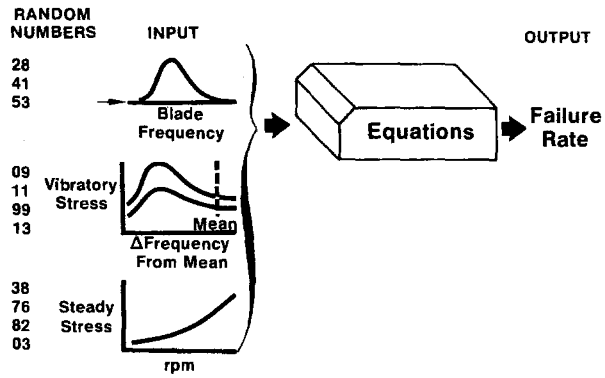

Fig. 11 Monte Carlo Simulation of 2nd Turbine Blade Failure.

Turbine Blade Resonance

Early F100 production engines encountered cracks in the 2nd turbine blade on initial teardown in production after run-in. It was found that the cracked blades characteristically had low (natural) frequencies.

The cause of the problem was analyzed to be a resonance occurring at high rotor speeds possibly amplified by the tip rubs that characteristically occur during run-in. Only the low frequency blades would be in resonance at these speeds and therefore only these blades were cracked.

The fix was to cull all blades in this low frequency region before they got into engines. A Monte Carlo simulation was constructed to confirm the analysis.

Some 3700 blades were frequency checked to provide the population of 1st mode frequencies expected to occur in production. A core engine was strain-gaged to provide the distribution of vibratory stress vs rotor speed, and laboratory testing provided the vibratory allowable for this material at the steady stresses present at high speeds.

The Monte Carlo predicted a failure rate of 7/1000 engines with these distributions whereas we were encountering more like 7/100 failures in early production. The simulation was carefully checked for both engineering and programming errors. (Meanwhile a production engine that had been culled for low frequencies came up with a cracked blade!) Upon reanalyzing the strain gage data, a second stress region was found in the mid rotor speed region that only occurred on those blades that were close to the disk harmonic but whose natural frequencies were significantly lower than the average frequency for that wheel, the "tuned absorber" phenomena.

This was a completely different failure mode that also matched the fact that only low frequency blades were found cracked. The distributions for the vibratory stresses and material allowables for this failure mode were added to the input to the Monte Carlo. (Figure 11) It now calculated the observed failure rate.

An experimental engine was built with the blade frequency distribution contained in the last production engine. It cracked the low frequency blade without running high rotor speeds.

With an operating Monte Carlo that contained all the experimental data, analytical functions linking this data to the tuned absorber and matching the observed failure rate, we could then use the Monte Carlo to evaluate candidate fixes.

The short term approach was to match the frequencies in the wheel such that there were no "strangers" lower than a certain frequency level below the average of the wheel. The Monte Carlo was used to select this frequency level.

The long term approach was to redesign the blade with a revised wall thickness distribution. Again the Monte Carlo model was used to select the configuration and tolerance control that gave the best balance of failure rate for the blade and LCF life for the disk.

Conclusion

The Monte Carlo simulator can be built from engineering data collected during the development program ... to define the rare failure modes that could otherwise only be identified well into the statistical base of full production.

The F100 engine program has used the Monte Carlo technique extensively during CIP to attack a variety of engineering problems. In each case it has contributed to quantifying the "drivers" on the problem, and defining the payoff of the solution.