Five Decades of Developing Aircraft Usage Technology

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Abstract

This paper presents a historic perspective of aircraft usage spectra development and structural usage monitoring. It overviews the evolution of aircraft usage analysis and monitoring technologies as applied to fixed-wing, rotary-wing, transport, tactical, military and civil aircraft. Example usage technologies are discussed by decade and usage technology formulation, development, application and results are included. In early decades, usage technology development is discussed in the context of simplifying assumptions that were made, and workable shortcuts that were devised to compensate for inadequate analysis tools and usage monitoring systems. The vignettes presented are the author's viewpoint, and it is left to the reader to ascertain any beneficial lessons-learned.

Keywords: Design Usage Spectra, Structural Usage Monitoring, Service Life Assessment.

Introduction

The requirements for conducting aircraft usage analysis to establish aircraft design fatigue lives, and monitoring usage to ascertain actual fatigue damage accumulation, have evolved over the past fifty years. This evolution has coincided with the availability of analytical and monitoring tools to facilitate aircraft usage technology development.

1960s

Engineering Tools

Structural analysis tools consisted of slide rules and electro-mechanical calculators as shown in Fig. 1. Slide rules were used for multiplication and division, and for roots, logarithms and trigonometry, but not for addition or subtraction. The analog results were typically three significant figures. Slide rules did not set the decimal, so the user had to know the magnitude of the answer. Electro-mechanical calculators could add, subtract, multiply and divide; provided many significant figures, and set the decimal.

Fig. 1: 1960s Usage Analysis Tools (Slide Rule and Electro-Mechanical Calculator)

C-141A and C-5A Design Usage Spectra

Developed C-141A design usage spectra. The C-141A was the first USAF aircraft to undergo fatigue analysis, which was performed while the first aircraft was in production.

Developed usage spectra for the CX-HLS proposal and C-5A initial design. Fatigue life was a contractual goal, not a requirement, whereas empty weight was a contractual requirement. As a result, fatigue was not allowed to influence design decisions.

The C-141A and C-5A are shown in Fig. 2. Design usage spectra for both focused on wing root bending moment (highest tensile stresses in wing lower skin). The usage spectra consisted of ground-air-ground cycles, flight maneuvers and gust modeled by von Karman Power Spectral Density (PSD) function. Fatigue analysis was based on Miner's Rule.

L-1011 Design Usage Spectra

Developed L-1011 design usage spectra. The L-1011 (Fig. 2) was the first FAA-certified aircraft to comply with a durability and damage tolerance (D/DT) requirement. Design usage spectra were developed for primary structure (wing, fuselage, empennage, propulsion system, landing gear, etc.), and secondary structure (flaps, ailerons, spoilers, elevator, rudder, etc.) based upon conservative usage assumptions. The usage spectra consisted of ground-air-ground cycles (with fuselage pressure cycles), PSD gust analysis and maneuver loads dominated by a Functional Check Flight profile. The L-1011 structural design was influenced by the resultant fatigue and damage tolerance analyses.

Fig. 2: USAF C-141A and C-5A Transport Aircraft and L-1011 Airliner

1970s

USAF A-7D Aircraft Structural Integrity Program (ASIP)

Created design usage spectra and usage monitoring methods for the USAF A-7D ASIP. The A-7D was the USAF version of the USN-designed A-7A. Both are shown in Fig. 3. The USAF performed the ASIP to evaluate the A-7D structural integrity and manage the operational life.

Fig. 3: USN A-7A and USAF A-7D Medium Attack Aircraft

The A-7D usage spectra were based primarily on data from counting accelerometers (CA) that were holdovers from the USN A-7A design. CAs mechanically recorded exceedances of 5g, 6g, 7g and 8g. There was a limited amount of velocity, altitude and normal acceleration (VGH) recorder data available, but no pitch, roll, yaw attitude, velocity, or acceleration. A-7D usage data was supplemented with statistical analysis of F-105D angular motion. Although the A-7D was a subsonic ground attack aircraft, and the F-105D was a Mach 2 interceptor, pilots who flew both stated that they had similar aileron-rudder interconnects, and responded similarly. Both are shown in Fig. 4.

Fig. 4: USAF A-7D and F-105D

Repeated loads were developed for critical airframe locations. Stresses were developed using NASTRAN finite element models and analysis (FEM/A) of each critical location. The stress spectra required tens of thousands “points in the sky” (combinations of gross weight (GW), normal acceleration (Nz), velocity (Ve), altitude, angular motion, etc). Since it was not affordable to run NASTRAN on the company’s IBM 360 mainframe computer, NASTRAN was run for selected “points in the sky” and the results were used to derive regression equations. Fig. 5 shows an example of NASTRAN-computed points (red symbols) and regression-interpolated points (green symbols). In addition to Ve and Nz, the analysis included variations in GW, stores, altitude, attitude, angular motion, etc.

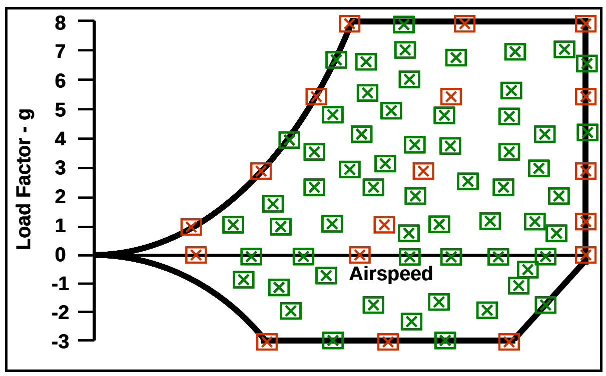

Fig. 5: Example of NASTRAN and Interpolated Analysis Points

Stress equations were derived using multivariate linear regression analysis. The equation terms were selected to ensure each variable had physical significance. The analysis identified the percent of error reduced by each term and thereby each term’s importance. An example regression equation, and the error reduced by each term, for stress in the wing root lower skin (wrls) took the form of Eqn 1. As illustrated, the regression analysis provided insight into which parameters are really important.

$$\sigma_{wrls} = C_0 + C_1(Nz \bullet GW) + C_2(Ve^2) + C_3(\ddot{p}) \ldots \qquad (1)$$

Percent error reduced: (82%) (12%) (4%) . . . $\Delta = 2\%$

As noted by Eqn 1, Nz • GW is the most important term in defining wing lower skin stress. As such, the A-7D CA could provide useful information in monitoring wing stress. Fig 6 shows examples of exceedances curves, or number of occurrences equal to or exceeding the ordinate values per 1000 flight hours, for Nz and fraction of vertical tail (VT) maximum stress. Since both Nz and fraction VT stress are plotted against the same ordinate, they can be cross-plotted at equal values of exceedances to establish an “iso-exceedance” relationship. With this relationship, the CA could be used to count exceedances of VT stress level.

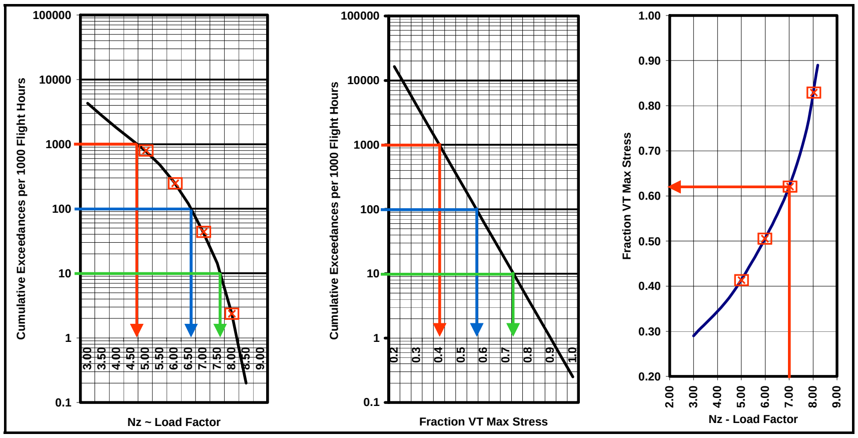

Fig. 6: Example Exceedance and Iso-Exceedance Curves

Using regression equations and iso-exceedance curves, relationships between Nz and critical location values of loads, stress, crack length and Damage Index (DI) were developed. For example, an equation for DI, which was derived from crack growth analysis and correlated with CA data, took the form of Eqn 2.

$$DI = C_1(N_{5g}) + C_2(N_{6g}) + C_3(N_{7g}) - C_4(N_{8g}) \qquad (2)$$

USAF Force Management Methods (FMM) R&D Program

A-7D ASIP usage technology development was followed by the USAF FMM effort to evaluate tactical aircraft structural usage monitoring technologies. FMM consisted of 1) conducting a state-of-the-art survey of existing approaches, 2) identifying, assessing and comparing emerging methodologies, and 3) recommending methods for tactical aircraft Individual Aircraft Tracking (IAT) and Load/Environment Spectra Survey (L/ESS).

IAT required 100% of aircraft be monitored to obtain basic operational usage data. L/ESS required up to 20% of the aircraft to be instrumented to obtain additional usage data which could be analyzed and statistically applied to supplement IAT. For the A-7D, the CA and mechanical strain recorder (MSR) were considered for IAT. The mechanical strain recorder was a device attached to the aircraft structure at a critical location. A sketch of the MSR is shown in Fig 7. Also know as a “scratch strain gage”, it consisted of two base plates, (1) and (2), with plate (1) containing the recording stylus (3), and plate (2) containing the brass recording disc (4). The CA was selected for the A-7D because 1) it was already installed in each aircraft, 2) it was simple to read and record Nz counts, and 3) many iso-exceedance and regression relationships had been developed. For L/ESS, the VGH recorder was selected.

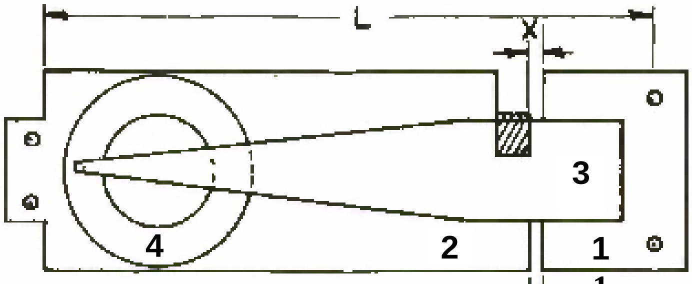

Fig. 7: Mechanical Strain Gage

USN Example: Benefits of Usage Monitoring

The USN pioneered usage monitoring in the 1960s by installing CAs in tactical aircraft. An example of monitoring benefits for the A-6 wing is shown in Fig. 8. Based on design usage assumptions and fatigue test results, the A-6 wing was replaced at 2200 hours. With the advent of the CA, the average life of the wing doubled to 4400 hours, because the average A-6 experienced one-half the Nz counts assumed for design and test. However, lacking information for point-in-the-sky (airspeed, altitude, etc) to associate with Nz, conservative assumptions were made. With the advent of multi-channel recorders, actual points-in-the-sky were monitored, and the flight hours almost doubled again.

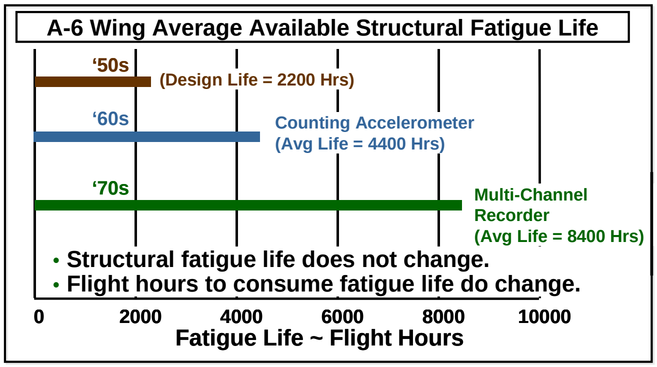

Fig. 8: A-6 Fatigue Life in Flight Hours

Fatigue and Fracture Evaluation of A-7E Arresting Gear Hookshank

The A-7E arresting gear hookshank, Fig. 9 was designed and tested to a conservative usage spectrum that resulted in a retirement life of 500 arrestments with a proof test after every 100 arrestments. The proof test interval posed a logistical challenge because a carrier cruise typically consisted of 150 launches and arrestments.

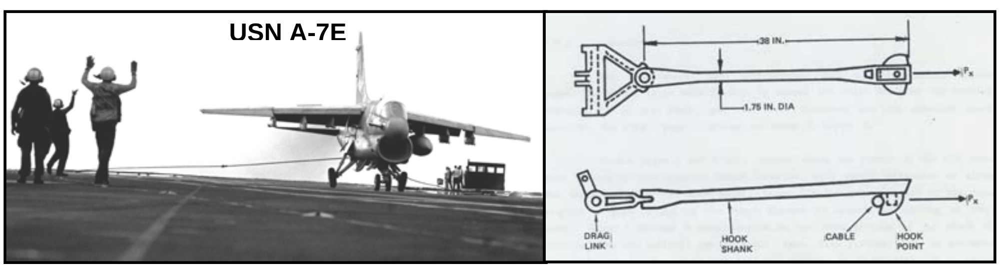

Fig. 9: USN A-7 Arresting Gear Hookshank

Hookshank design and test results identified the critical location to be the base of the hook point attachment boss as shown in Fig. 10. The figure also shows the bending moment produced by applying the design test loads (red curve) as compared to that produced by operational loads (black curve). At Station 20.5, there was a transition in the internal diameter that produced a stress riser. The conservative test loads deformed the hookshank and thus straightened the load path, and produced a bending moment of 1470 kN.m (13 in-kips) at Station 20.5, whereas realistic operational loads applied in the evaluation produced a bending moment of 3730 kN.m (33 in-kips) and identified the actual critical location. The program, based upon analysis and test using realistic operational loads, not only identified the actual critical location, but also increased the operational life to 2200 arrestments, and extended the proof test interval to 550 arrestments.

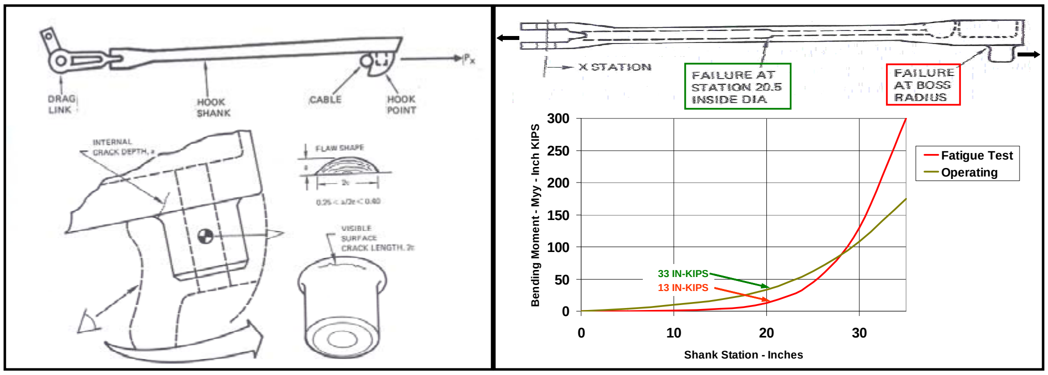

Fig. 10: A-7 Hookshank Failure Location and Bending Moment

1980s

USN Structural Life Extension

The A-7E arresting gear hookshank test and evaluation was the first USN program based upon D/DT and fatigue crack growth. Follow-on life extension programs continued into the mid 1980s, and included A-7E drag link and launch bar, and F-14 and F-4 hookshanks. The success of all the programs resulted from applying realistic operational loads, and led to full-scale test and evaluation of the A-3D and A-6E, which are shown in Fig. 11.

Fig. 11: USN A-3D and A-6E

1990s

K-MAX Aerial Truck

The K-MAX prototype #1 was basically a proof-of-principal flight test article that used the drivetrain and rotor system taken from a retired USAF HH-43B. See Fig. 12. Prototype #2 incorporated an upgraded engine and transmission, and newly designed rotor blades and dynamic components. All components were designed for infinite life. Since the K-MAX was purposely designed for external lift, repeated fatigue loads are produced by external load lift-and-release cycles. The K-MAX was designed primarily for the logging industry, and the design spectrum consisted of 60 “turns” per hour with ~2700kg (6000lb) loads. A load cell incorporated in the external long line is employed to monitor operational usage.

Fig. 12: HH-43B and K-MAX Helicopters

MaxLife Structural Usage Monitoring System (SUMS)

The MaxLife SUMS was designed to provide data required for regime recognition and damage accumulation calculations. A block diagram of the MaxLife SUMS, including sensors and parameters, and a system photograph, are shown in Fig. 13. The configuration shown was designed for installation beneath the H-60 copilot's seat.

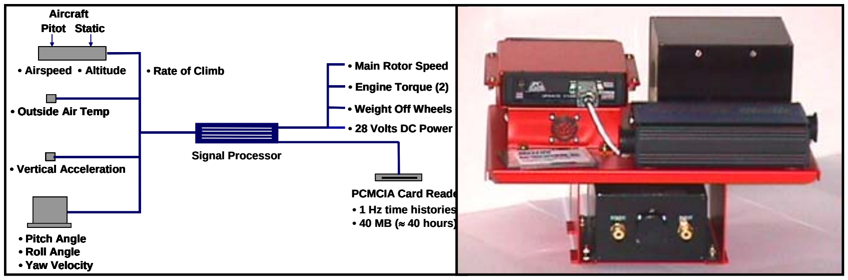

Fig. 13: MaxLife Diagram and Photograph

MaxLife was demonstrated in USCG HH-60J and USN HH-60H, SH-60B, SH-60F. The USCG HH-60J and USN HH-60H, shown in Fig. 14, are essentially the same platform, being fabricated on the same production line. MaxLife provided snapshots of operational data that was used to compare USCG with USN usage.

Fig. 14: USCG HH-60J and USN HH-60H

Fig. 15 shows a comparison of time in damaging regimes, and the resultant fatigue damage accumulation in eight selected components. The results indicate that the USCG HH-60J was flown slightly more robustly than the USN HH-60H.

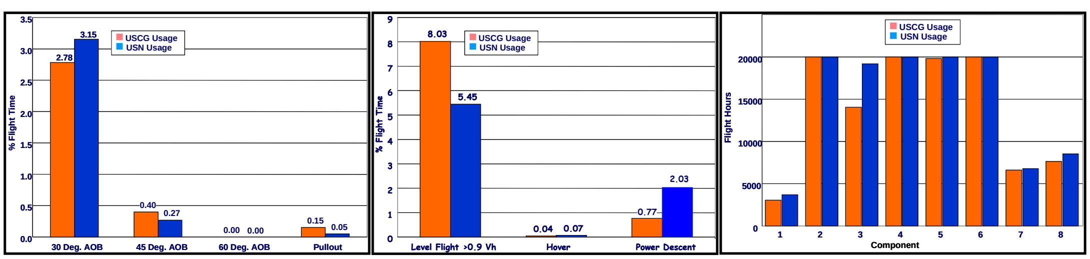

Fig. 15: Comparison of USCG HH-60J and USN HH-60H Usage and Damage

2000s

Structural Usage Monitoring with a GPS Recorder

An R&D project was undertaken to determine the minimum number of usage parameters required for regime recognition. The investigation verified that time histories of 3-D GPS latitude, longitude and elevation provides information from which aircraft ground speed, altitude, direction, roll angle and normal acceleration could be derived. A schematic of the

3-D GPS approach, along with an actual time history trace of latitude and longitude are shown in Fig. 16. The rate of change of latitude and longitude provided aircraft heading.

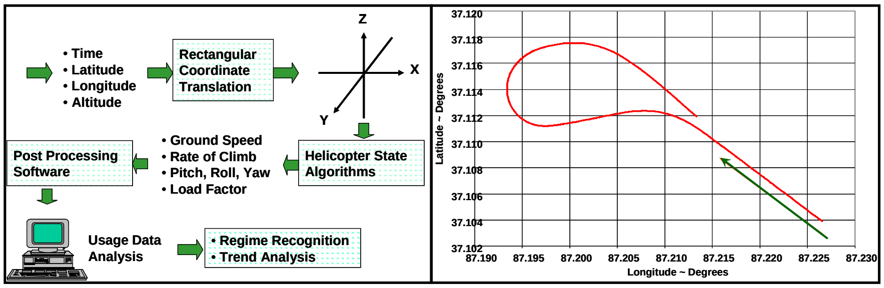

Fig. 16: GPS SUMS and Recorded GPS Latitude vs. Longitude

Fig. 17 shows comparisons of GPS-derived roll angle and normal acceleration with independently recorded angular and acceleration values. Roll angles were calculated from the rate of change of direction (which was determined form the rate of change of GPS latitude-longitude). Normal acceleration was calculated from the Eqn 3.

$$\Delta Nz = 1/\cos(\text{roll angle}) \tag{3}$$

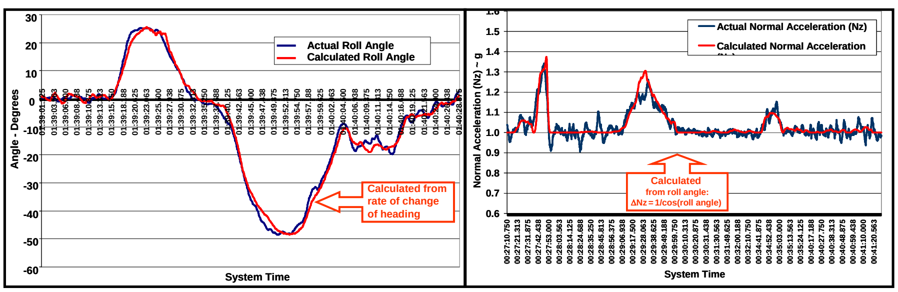

Fig. 17: Roll Angle and Normal Acceleration

Ground speed was derived from GPS latitude-longitude time histories by using spherical geometry that accounts for longitude convergence as a function of latitude. Fig. 18 shows that the difference in GPS ground speed and independently recorded airspeed was explained by relative wind changes with aircraft direction due to ambient wind speed.

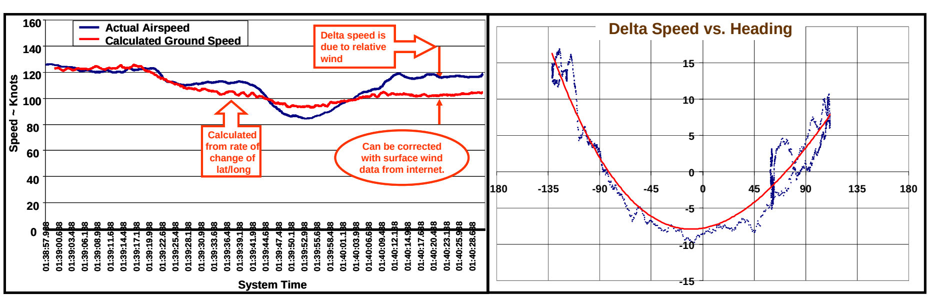

Fig. 18: GPS Ground Speed and Delta Speed vs. Heading

Fig. 19 shows that GPS SUMS could recognize most of the regimes that produce damage in 35 fatigue-life-limited part numbers. In fact, GPS SUM could recognize regimes that produce ~90% of the aggregate damage in the 35 part numbers, and the regimes that produce >95% of the damage produced by regimes recognized by sophisticated HUMS. This is because none of the systems currently recognize droop stop pounding events.

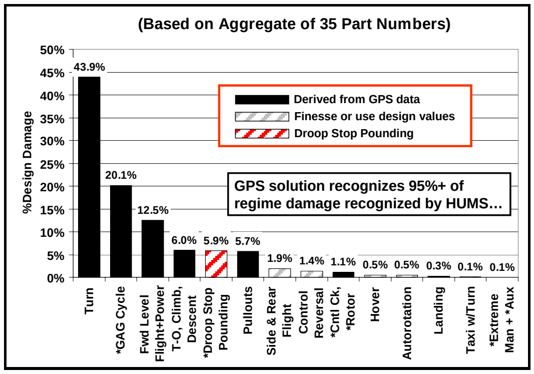

Fig. 19: Regimes Recognized by GPS SUMS

US Army Lead the Fleet (LTF) Program

The purpose of LTF was to fly selected helicopters at a tempo twice that of average fleet aircraft as shown in Fig. 20. The figure also shows the damaging effects to a pitch change link (PCL) that resulted from severe usage. The LTF data analysis and investigation into the PCL damaging events are briefly discussed.

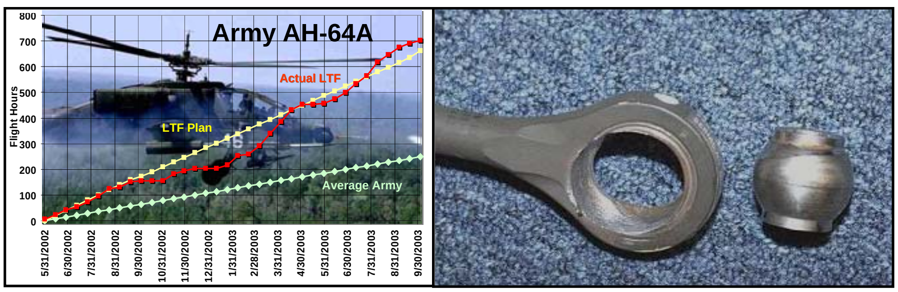

Fig. 20: AH-64A LTF Tempo and "Failed" PCL

LTF regime usage and resultant damage of 30 part numbers are compared to design usage and damage in Fig. 21. LTF banked turn usage was greater than design, but design damage was greater. Reason: design assumed more time would be spent in high bank angles.

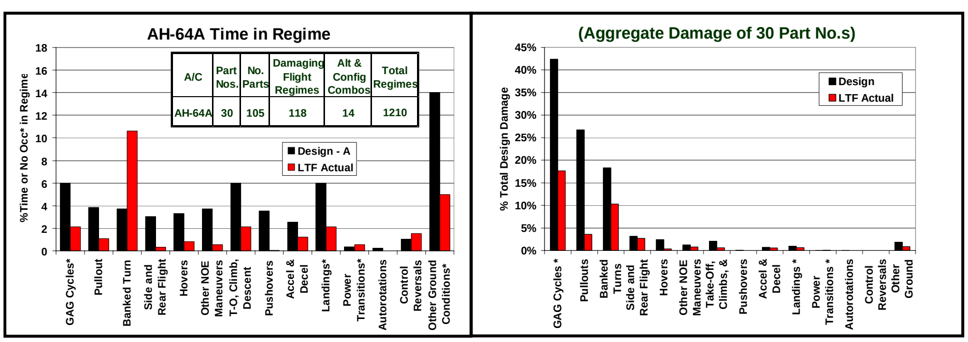

Fig. 21: LTF Design vs. Actual Usage and Resultant Damage

A LTF AH-64A crew noted excessive rotor system vibration and landed. Inspection revealed a damaged PCL, shown in Fig. 20, which was replaced prior to another flight. LTF usage data was analyzed with results shown in Fig. 22. The PCL "failure" flight occurred at high elevation where max power was required. Further study revealed PCL damage was produced by 1.5g turns and rolling pullouts (RPOs) at 1.0Vh (max airspeed).

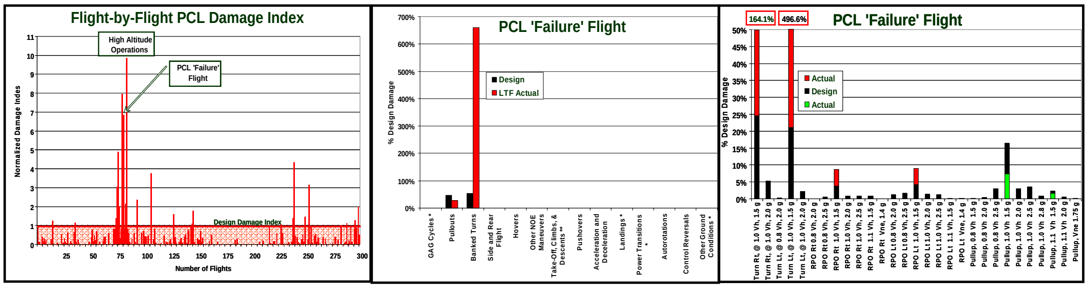

Fig. 22: LTF "Failure" Flight and Corresponding Regime Damage

2010s

OH-58D Structural Health Monitoring

The OH-58D (Fig. 23) transmission sidebeam experiences high vibratory stress during autorotation. To account for the resultant damage, worst case stress levels are assumed to occur during each autorotation and significantly reduce fatigue life. Sidebeam replacement is labor intensive and increases aircraft downtime and maintenance cost. A solution being pursued is to monitor autorotation strain and decrement life based upon strain level. The goal is to extend the sidebeam replacement interval to increase readiness and reduce cost.

Fig. 23: Army OH-58D

C-12 Service Life Assessment (SLA)

Many Army C-12s (Fig. 24) are approaching a major wing structural rework action. For planning purposes, it is necessary to predict, by tail number, when the rework is to be performed. This requires knowledge of the actual mission profiles flown at various locations. A pilot program is being planned to record ~1000 flight hours of usage at operational locations to supplement and verify pilot surveys. Mission profiles will be developed and fatigue damage accrual will be monitored to project the rework schedule.

Fig. 24: Army C-12

Conclusions

As stated in the Abstract, the vignettes presented are from the author's viewpoint and it is left to the reader to ascertain any beneficial lessons-learned.