Analysis of Nonstationary Vibroacoustic Flight Data Using a Damage-Potential Basis

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  - Sheldon Rubin, Christian Lalanne
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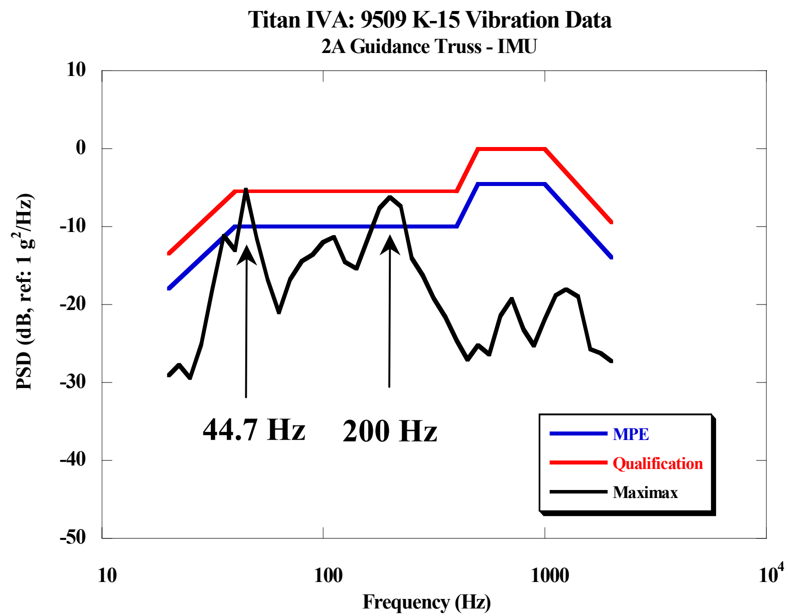
Background

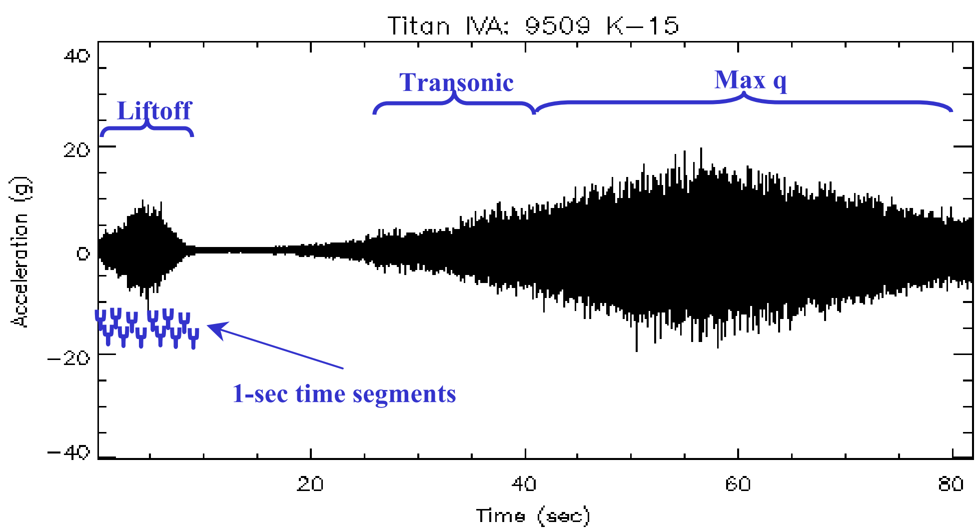
- Launch/space vehicle equipment subjected to complex, nonstationary (time-varying) flight environments
- Development, qualification, and acceptance test specifications developed from historical data and analytical/empirical techniques
- Testing performed using stationary (constant in time) random or sinusoidal excitation
- Qualification status reassessed after mission by comparing flight data with prior test

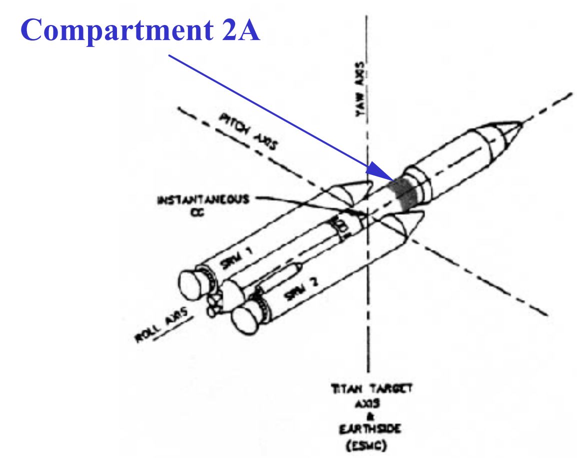
Need: Consistent, quantitative and accurate means for characterization and comparison of nonstationary flight and stationary test environments

Historical Maximax Approach

- Flight data treated as series of overlapping stationary time segments
- Determine power spectral density (PSD) during each time segment
- Retain maximum value of spectrum at each frequency independently and loop on number of time segments
- Compare maximax PSD with test specification







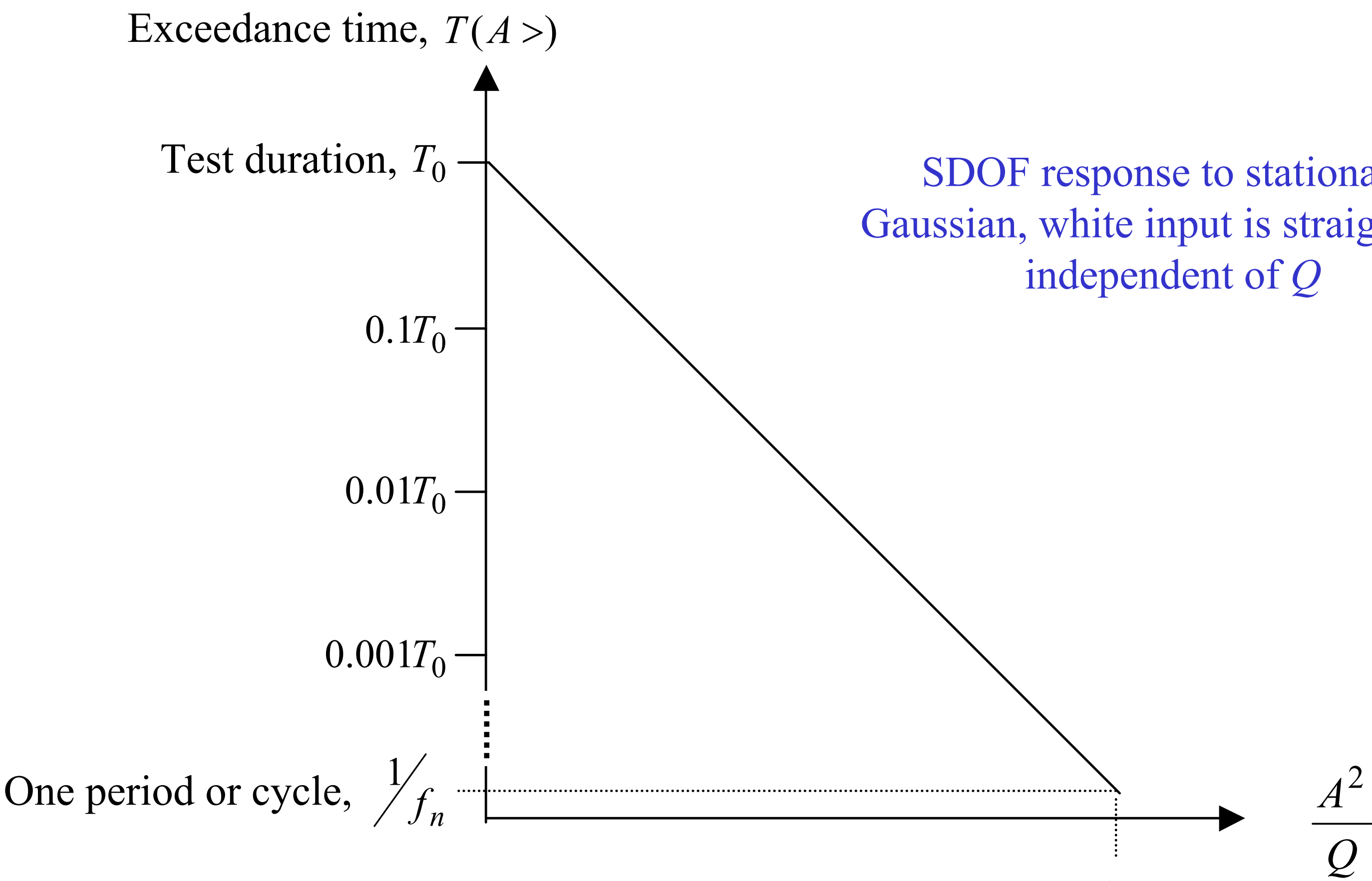
Maximax Limitations

- Fatigue failure mechanism not addressed
- Processing errors due to assumption of stationarity within each time segment
  - Peak responses in flight data can be considerably overestimated
    - Excessive conservatism in specification definition and consequent impact on testing techniques (more cost, less reliability)
    - After early missions, can cause inappropriate consideration/implementation of component re-qualification or other vibration reduction techniques (cost, schedule impact)
- Results dependent upon choice of processing parameters
  - i.e. record length, spectral bandwidth, number of averages
    - Not related to physical properties of system such as modal quality factor (damping)

Stationary Random Test Basics

- Test duration T_0 and magnitude G
- SDOF response has Rayleigh distribution of peaks
- Probability of cycles with amplitude > A: $P(A>) = e^{-A^2/2\sigma^2}$
- Time response cycles > A: $T(A>) = T_0 P(A>) = T_0 e^{-A^2/2\sigma^2}$
- SDOF mean-square response: $\sigma^2 \cong \frac{\pi}{2} G f_n Q$
- Yields: $\ln\left[T_0 / T(A>)\right] = \frac{1}{\pi G f_n} \frac{A^2}{Q}$
- Plot of $\log[T(A>)]$ vs. linear A^2/Q is a straight line

Plot for Stationary Test (for each f_n)



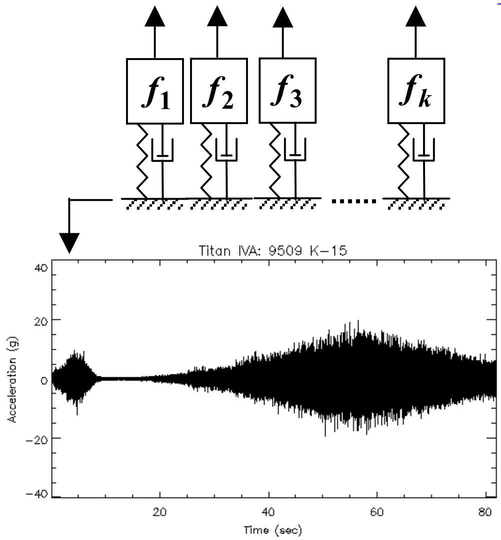
$$\frac{A_{\max}^2}{Q} = G\pi f_n \ln(f_n T_0)$$

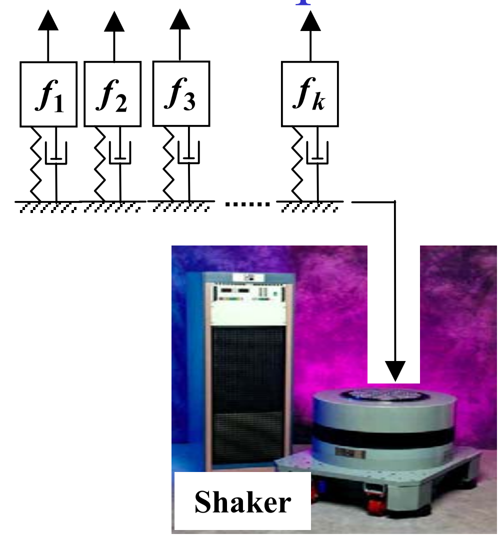
$$G = \frac{(A_{\max}^2 / Q)}{\pi f_n \ln(f_n T_0)}$$

Damage Potential Comparison

SDOF oscillator response is basis for comparison

Flight





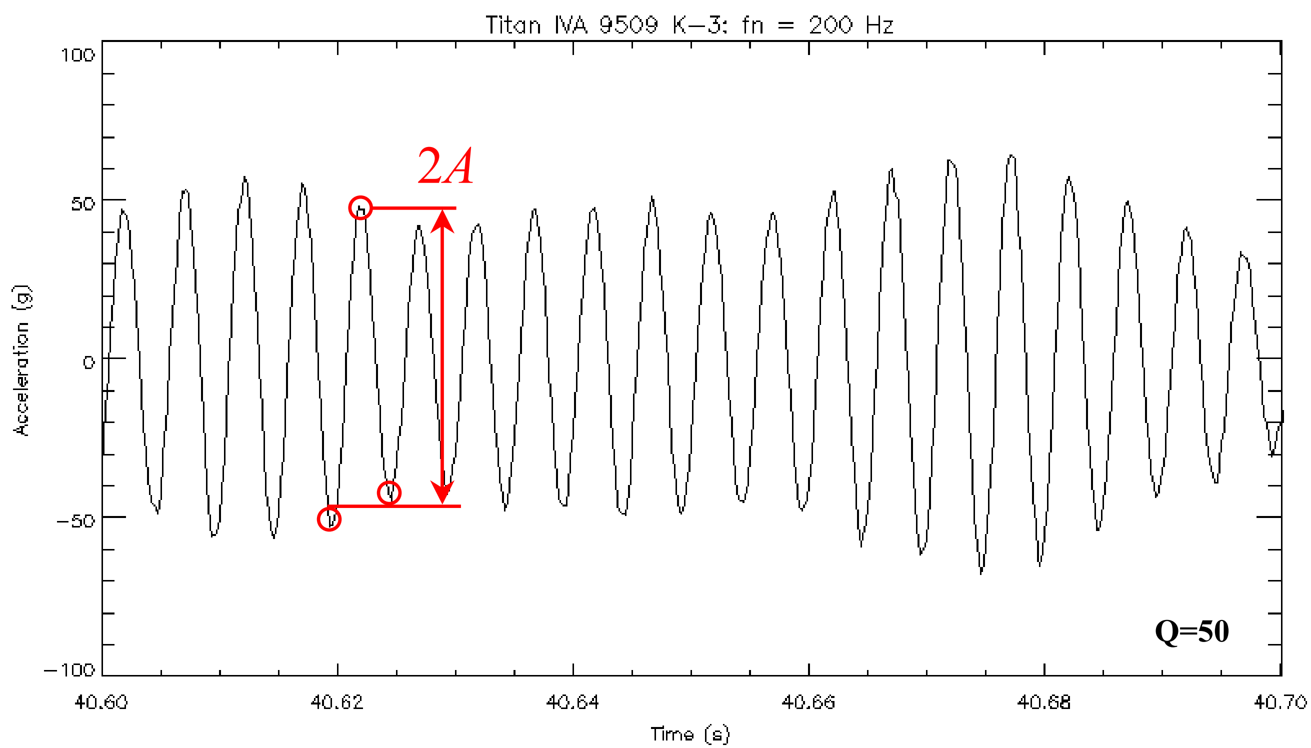
Test

- Apply flight data as input to series of SDOF oscillators
  - 1/12th-octave spacing, range of Q (10,25,50)
- For each f_n and Q, determine SDOF response and count cycles $N(A>)$ for which amplitude A is exceeded
- For SDOF narrowband response, $T(A>) = \dfrac{N(A>)}{f_n}$
- Plot $\log[T(A>)]$ vs. linear A^2/Q

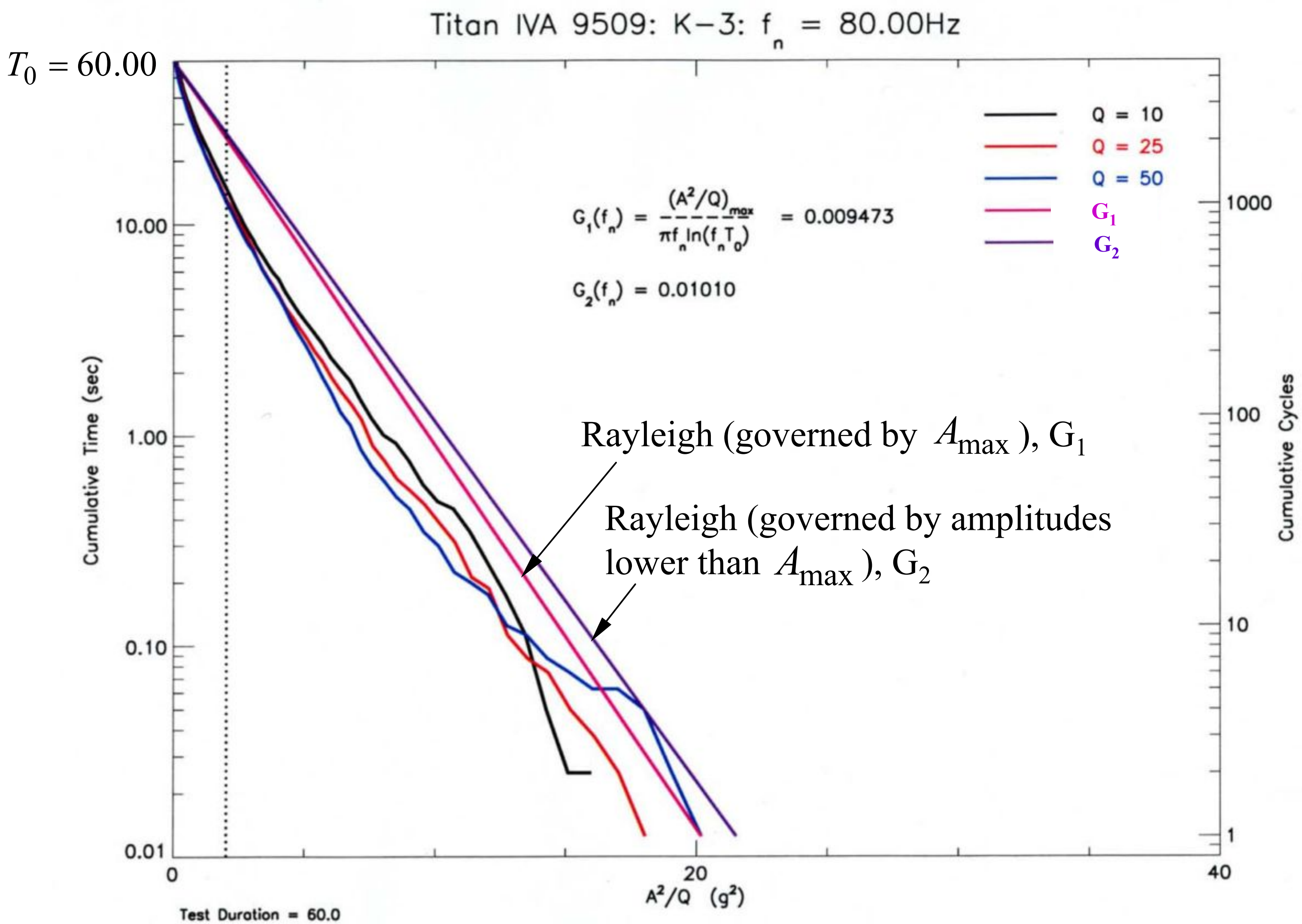
- For a test duration T_0, if results for test envelop all flight data, damage potential of test exceeds that of flight
  - Number of cycles in test exceeds number of cycles in flight for all amplitudes
  - Both maximum response and fatigue aspects covered

Cycle Counting Process

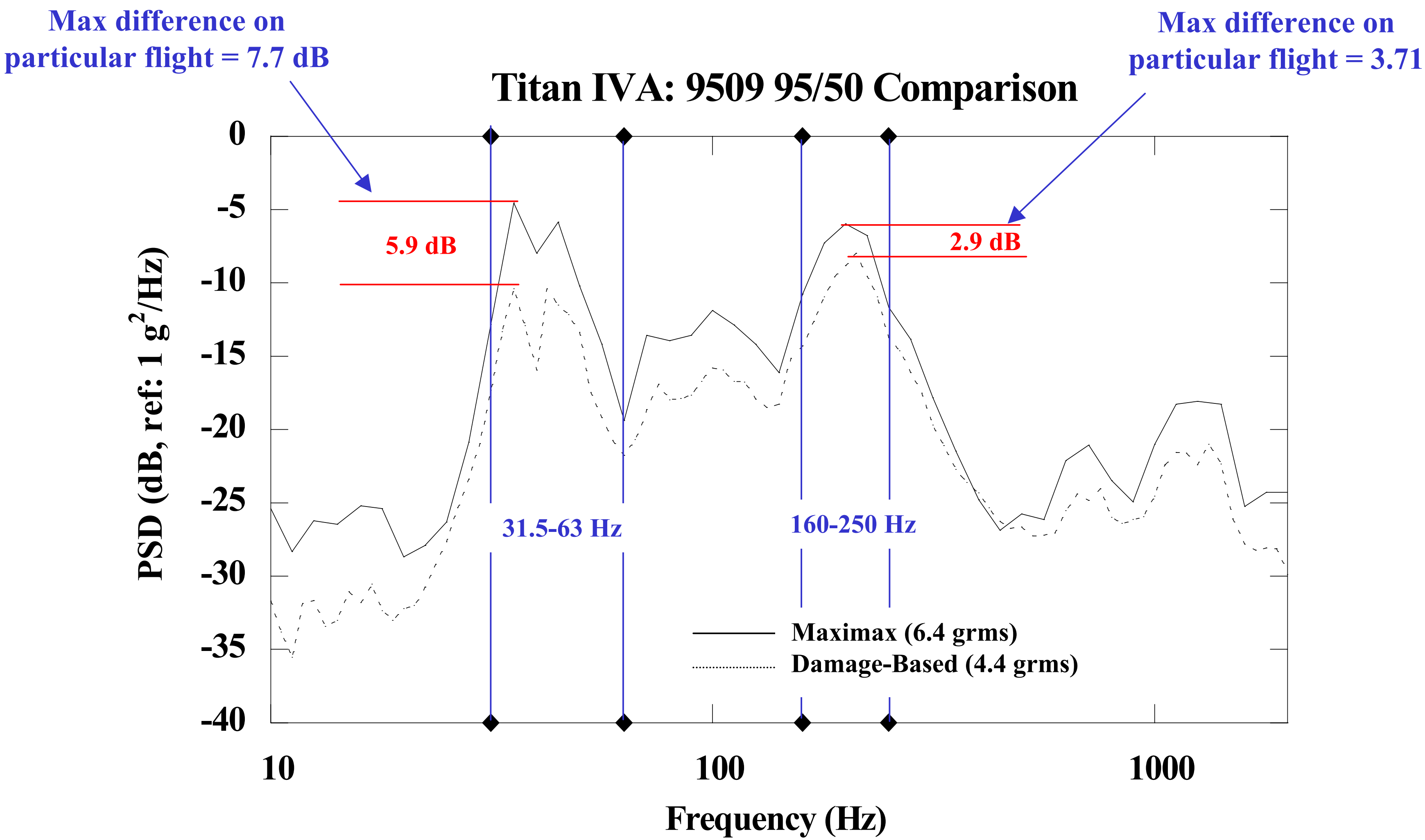
- Cycle of oscillation defined to occur between pair of minima
- Double amplitude equal to value of intermediate maximum minus average of minima
- For narrowband response with zero mean, this is meaningful for evaluating fatigue accumulation



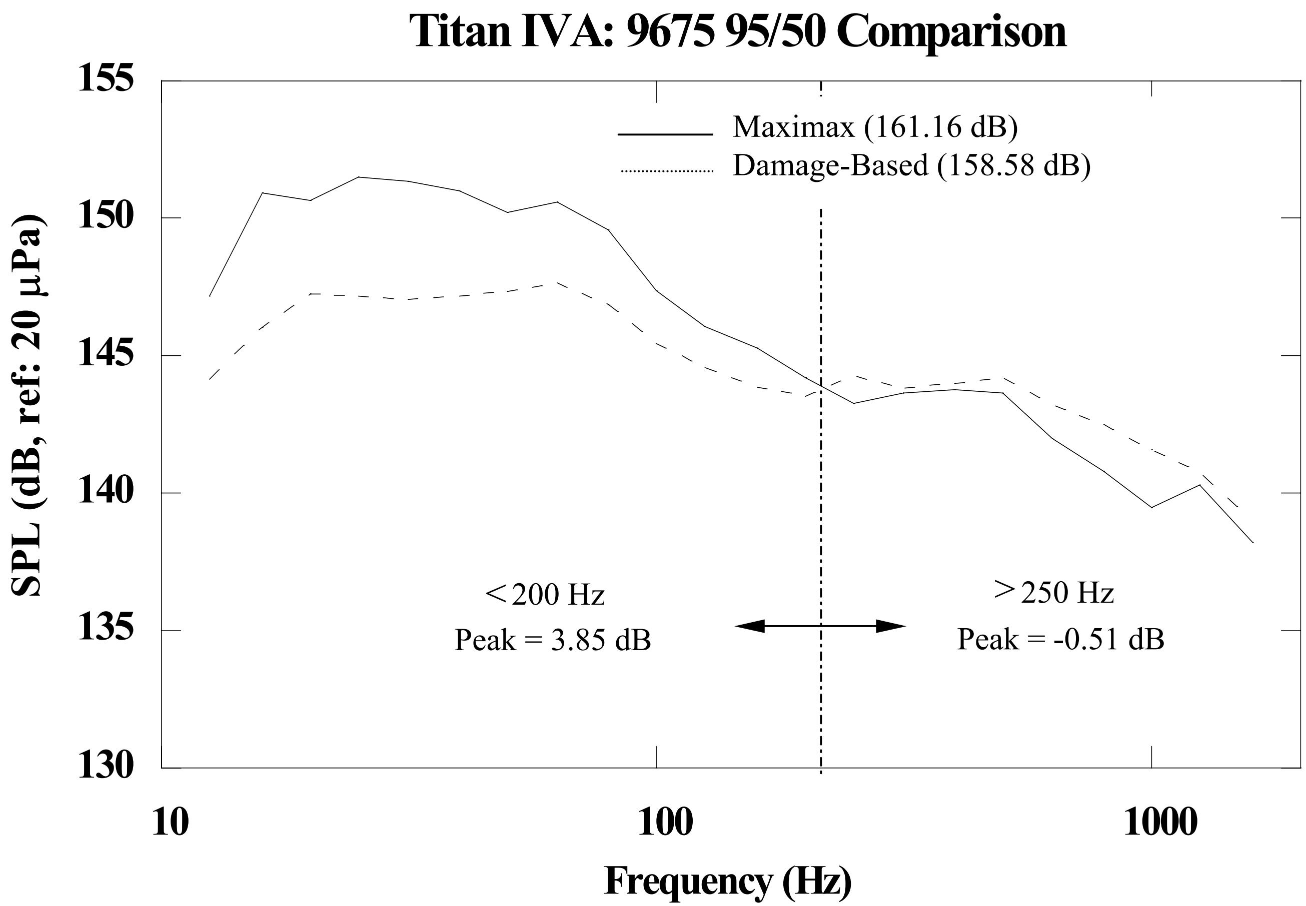
Example Cycle Count Plot



Comparison of Vibration Results (12 flights)

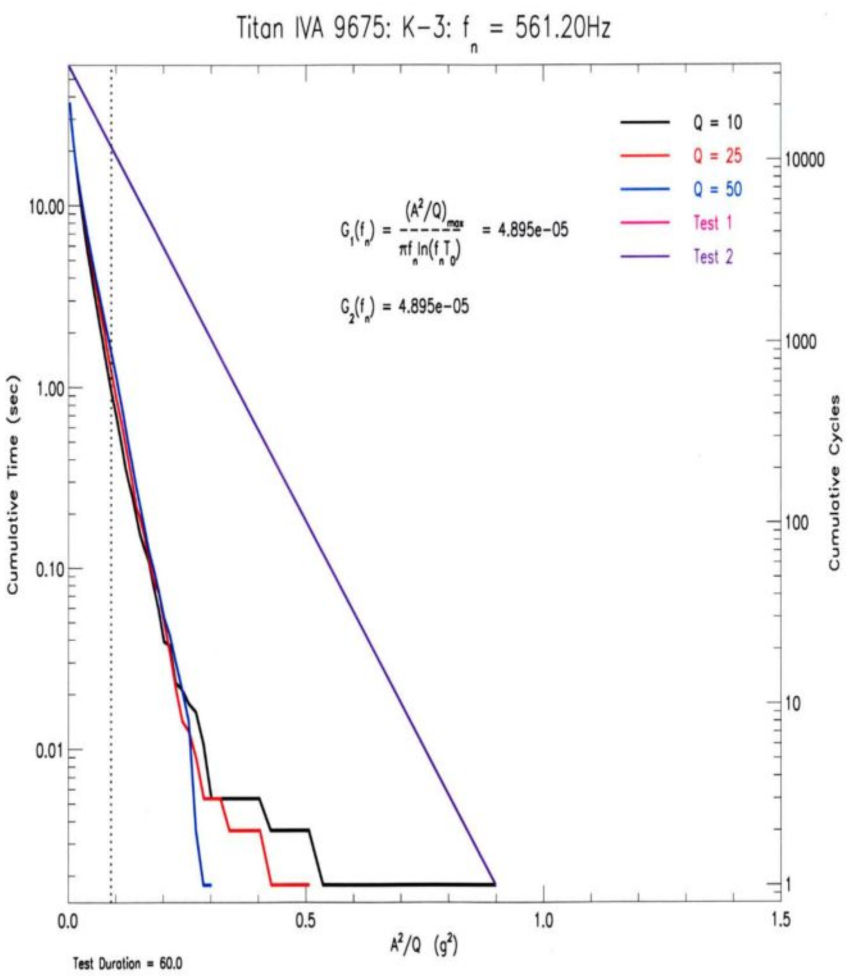


Comparison of Acoustic Results (15 flights)



Conservatism of Damage-Based Acoustics Results

- Conservative nature of damage-based acoustic results at higher frequency result of two factors
  - Maximax results contain more frequency smoothing due to third octave band SPL averaging within each overlapping time segment
    - Damage-based results computed at each oscillator frequency and converted to third octave SPL at end of processing
    - Present in all measurements
  - Higher frequency damage-based results controlled at some frequencies by transient characteristics (see plot)
    - Possibly due to data editing approach and treatment of dropouts
    - May be unique to this measurement



Summary

- Damage potential to hardware should be basis for flight and test equivalence
  - Not addressed by maximax approach
- SDOF oscillator response is a meaningful basis for comparison
  - Proportional to a modal response of test item
  - Damage potential due to fatigue accumulation, in addition to peak response, considered
- Large degree of over-conservatism in spectral peak values avoided
  - Avoid band-splitting during qualification testing as a result of excessively high overall grms
  - Avoid unnecessary re-qualification or vibration reduction measures resulting from results on early missions

Summary (cont.)

- Comparison of results available for statistically meaningful sets of Titan IVA vibration and acoustic measurements
- Applications
  - Assess adequacy of past qualification given new environmental data
  - Develop new test requirements
- Method to be available in VISPERS

Backup

Why Results Not Always Dominated by Largest Q

- Proportionality between Q and SDOF oscillator response differs depending on type of flight input
  - Random: $A_{\max} \propto \sqrt{Q}$
  - Sinusoidal: $A_{\max} \propto Q$
  - Transient: Relatively insensitive to Q
- Stationary random test always inversely proportional to Q

$$G = \frac{(A_{\max}^2 / Q)}{\pi f_n \ln(f_n T_0)}$$

  - Random flight data: Relatively insensitive to Q
  - Sinusoidal flight data: $G \propto Q$
  - Transient flight data: $G \propto 1/Q$