Air Force Life Cycle Management Center

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Analysis Spectrum != Load Sequence?

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Recently, it has come to light that there may be a *disconnect* in the way that some organizations implement a variable amplitude spectrum file in a fatigue crack growth (FCG) analysis and in any corresponding validation fatigue testing. The primary issue that seems to be driving the apparent discrepancy is the understanding of what the spectrum file represents and how it was generated.

This presentation is centered on this issue and will provide guidance information on how to go from flight recorded data, through some spectrum processing steps such as cycle counting, truncation, removing intermediate points, then resulting in a final spectrum file. The fundamental takeaway is to understand spectrum requirements for a crack growth analysis (cycle counted spectrum) vs fatigue testing (point-to-point reversal spectrum).

It is the intent of this presentation to clear up any possible *disconnect* in the way that crack growth analyses and corresponding validation fatigue tests are performed with variable amplitude loading.

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Acknowledgements

Dallen Andrew
Kaylon Anderson
A-10 ASIP
Everyone here

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Thanks to everyone that has helped me and all of us learn and get to where we are today.

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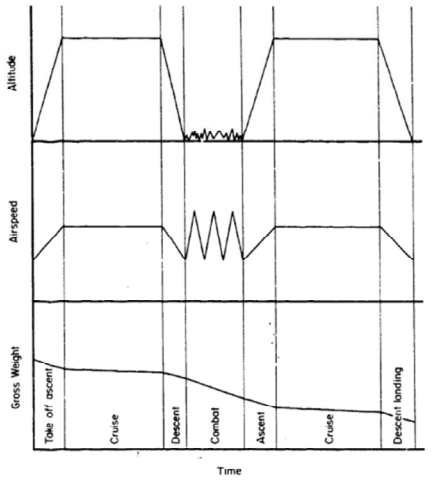
Spectrum Definition

Where do spectra come from?

- Recorded data from aircraft maneuvers
  - i.e. Take off ascent, Cruise, Descent, Combat, Ascent, Cruise, Descent landing)



USAF damage tolerant design handbook: Guidelines for the analysis and design of damage tolerant aircraft (AFFDL-TR-79-3021), 1979

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Very briefly, we're just going to start at the beginning, a spectrum is a representation of the loading the aircraft structure experiences.

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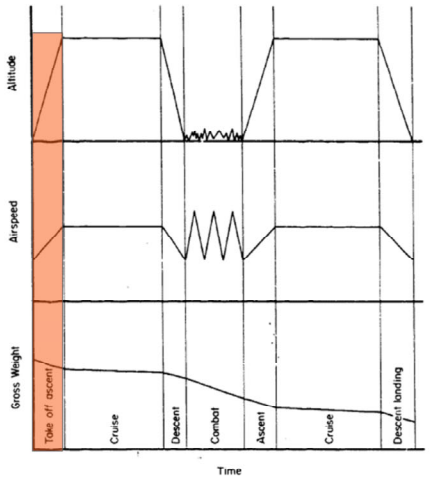

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Mission Profile

Flight recorder, records the fight parameters (Nz, Nx, Ny, V, alt, GW, etc.) throughout the mission profile and captures the loading as is seen by the aircraft.

The spectrum used in analysis comes from the recorded flight maneuvers associated with each mission profile.

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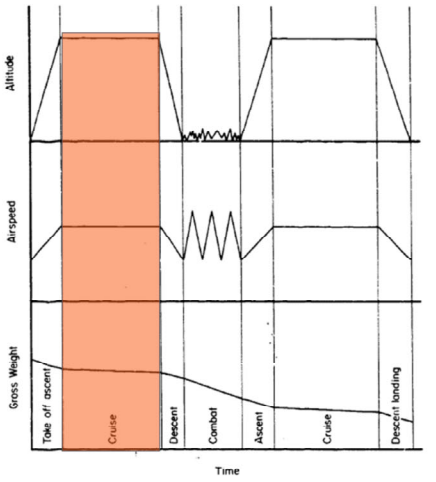

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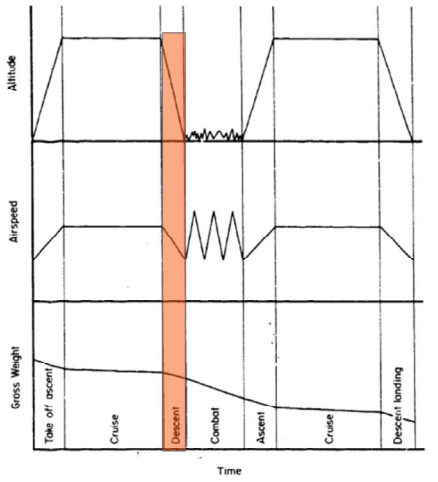

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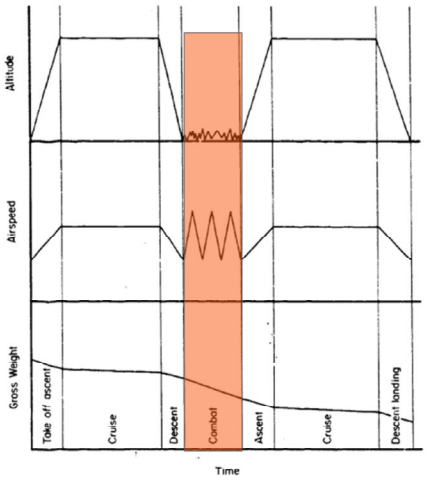

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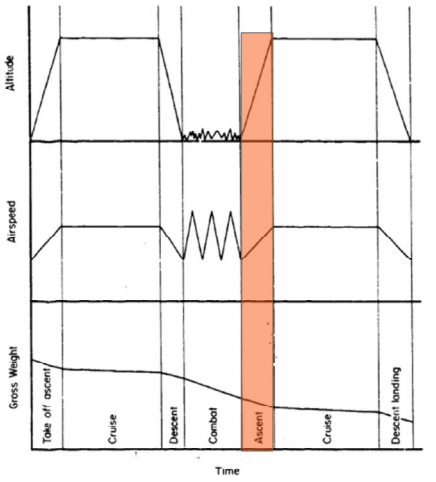

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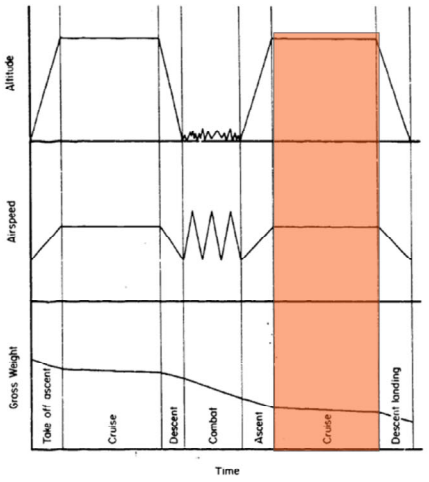

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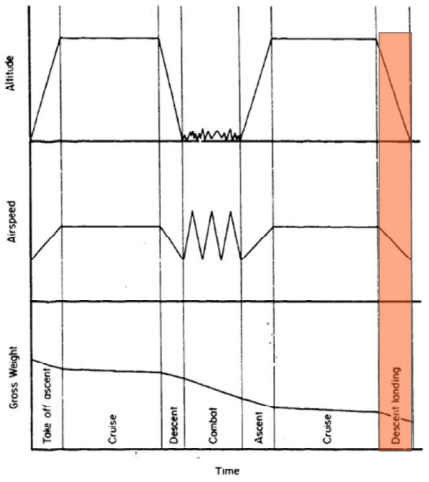

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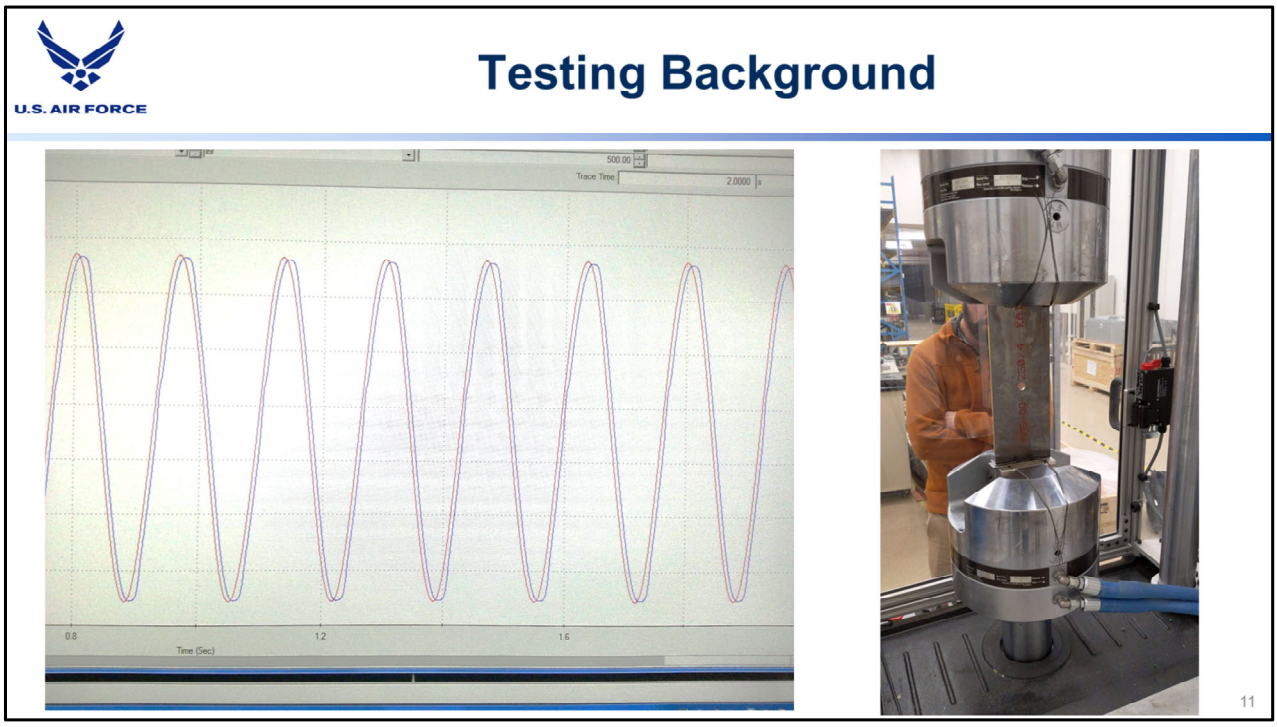
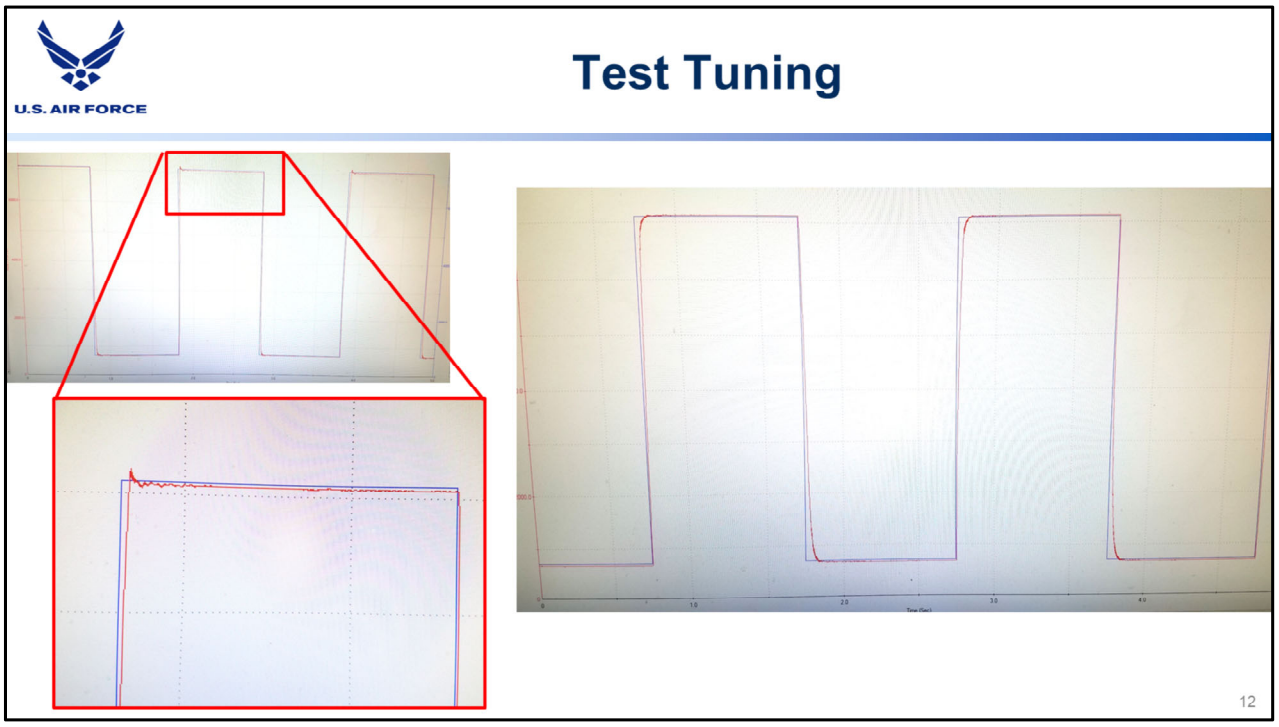


Once you have a load sequence defined from flight data you either run a tes with it or do an analysis. We'll discuss testing first.

The image on the left is a command and feedback plot of load in the test frame. So the red line is what the machine is supposed to do and the blue line is what it actually does. This screenshot is of a constant amplitude test.

The image on the right shows a close up of a test in a load frame. The specimen is relatively small in the middle of the picture on the right and the grips are the large cylindrical parts holding the test piece. The top grip remains fixed during testing, and the lower grip moves up and down to apply the desired load. These grips weigh quite a bit, 170 lbs. So even though you might be running a test on a small piece, the machine is moving quite a bit of mass in addition to the stress it is applying. Also, there's a lot to these test frames that isn't shown in these pictures. Powered by hydraulics you have a large pump, and a chiller to cool the hydraulic fluid, an accumulator to maintain hydraulic pressure on difficult load excursions, etc. This machine shown here is a 50 kip machine, capable of applying 50,000 pounds in tension or compression in a fraction of a second. Point being, it's a large, powerful system that merits a lot of respect by the operator, otherwise the equipment can be damaged and you could severely injure yourself.



As we showed before, while the constant amplitude waveform shown on the previous slide is convenient, it doesn't match reality for aircraft structure. To get closer to reality you must apply a spectrum load sequence. To prepare the test system for accurate execution of a spectrum load sequence the system is tuned. Tuning involves adjusting a number of feedback and gain options to accurately achieve load without overshooting. The images here show the command and feedback signals for a square waveform. A square waveform is often used to tune a system because it is the most difficult, requiring max load immediately and then holding that load without deviation. The images on the left show the feedback from a system prior to tuning. The red signal overshoots the blue command and oscillates trying, to settle on the command load. This system is not well tuned. The image on the right shows a better tuned system. The load does not overshoot or oscillate after reaching the command load.

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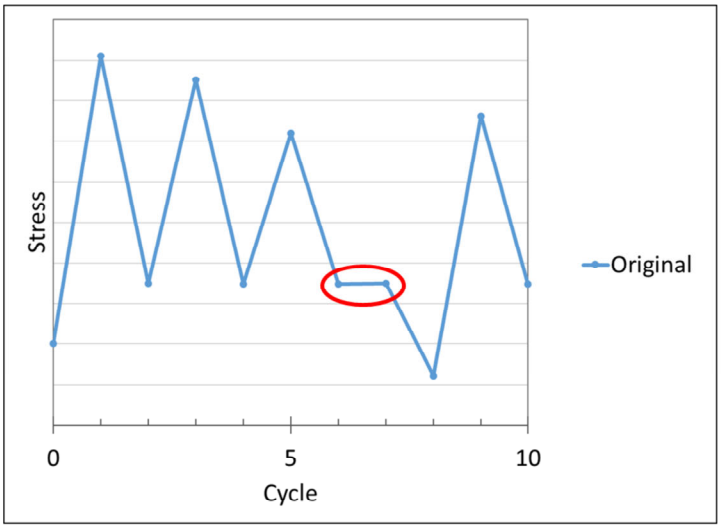
Load Sequence Pre Processing



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With the system tuned you can begin preparing the load sequence for application to the load frame. Your original load sequence may look something like this. The load frame will likely produce a lot of error on cycle turning points 6 and 7 so the user will typically run the sequence through a pre processing algorithm to remove intermediate points and truncate small load excursions.

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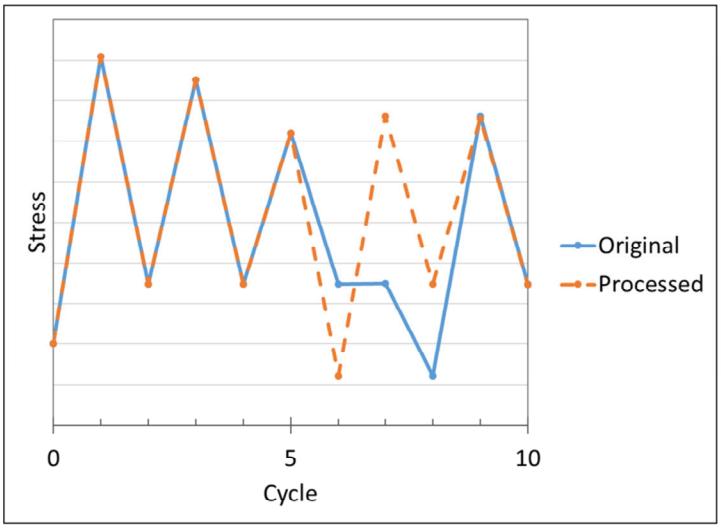
Load Sequence Pre Processing



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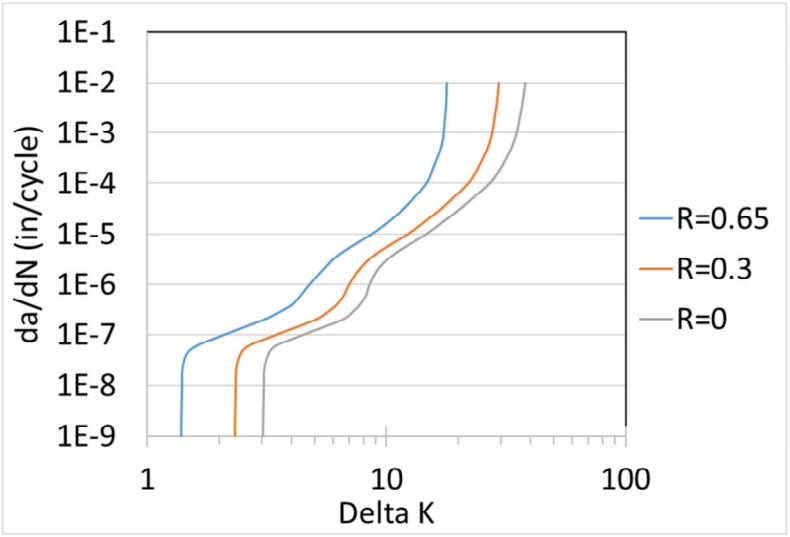
For our example sequence, the pre processing algorithm would result in the sequence shown here by the orange dashed lines. Essentially, the turning points 6 and 7 have been removed to make one large cycle in place of two small ones. The orange dashed sequence is ready to be run in the load frame.

How Does Analysis Process a Spectrum?

- **Rate data from ASTM E 647**
  - Constant amplitude loading
    - Equivalent load and unload in load event
  - Prediction looks up dK for each cycle to define crack growth



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Okay, that's how test uses a flight spectrum. Now, the other application, analysis/prediction.

Predictions start with the material file, or the rate data, depicted by the graph on the right. This rate data is developed by ASTM E647 tests conducted under constant amplitude loading. The crack growth measured between cycles is plotted against the delta K from the loading.

Why does that matter? Rate data is developed from constant amplitude tests. So to perform predictions, the spectrum file must be processed to represent a series of equivalent constant amplitude cycles. This pre processing is typically called counting. The next few slides will briefly explain this pre processing step.

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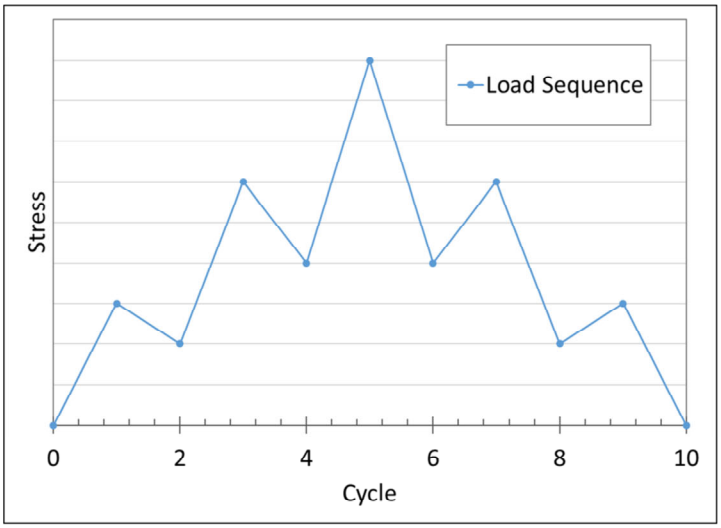
Analysis Spectrum Counting



16

This example load sequence will represent what the actual loading applied to the aircraft structure.

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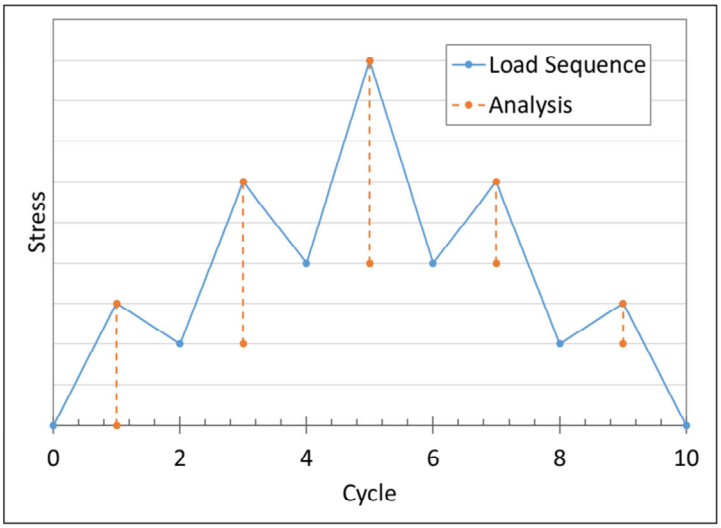
Analysis Spectrum Counting



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To perform an analysis, the sequence is converted into discrete, unconnected, constant amplitude load cycles depicted by the orange dashed line.
I used a vertical dashed line to represent the constant amplitude cycle because there is no way to differentiate the loading portion from the unloading portion of a constant amplitude test. The intent, then, of the vertical line is to simply show the delta sigma that will be referenced in the crack growth calculation.
Take note, that if the analysis were to be conducted with just the discrete orange line loading events, it would miss the bigger picture load excursion going from 0 up to the global max, back down to 0.

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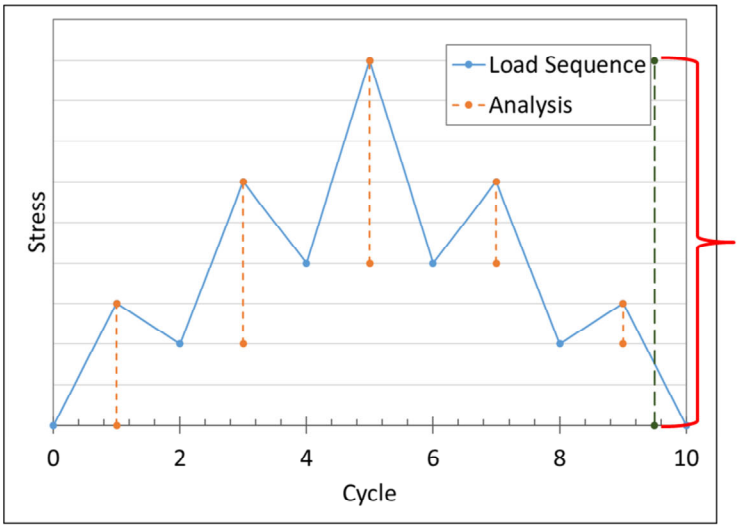
Analysis Spectrum Counting



Additional Cycle added by counting algorithm to account for load excursion beyond immediate local max/min

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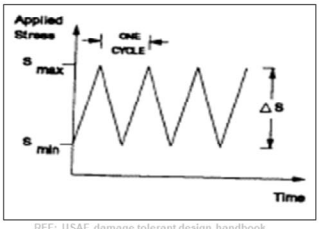
To account for that bigger picture, global point of view, the counting process adds another discrete cycle represented here by the green dashed line. So the analysis pre processing step, counting, adds additional discrete loading events to represent equivalent damage of the load sequence.

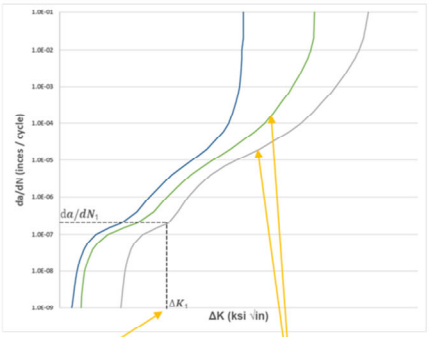
Analysis Summary

Fundamental: Crack growth life predictions are based on constant amplitude rate data

- ASTM E647
- Predictions reference a ΔK value for growth rate
- Analysis prediction cannot be done on the load sequence directly, the sequence must be processed into discrete constant amplitude events
- ***ANALYSIS REQUIRES A FULL CONSTANT AMPLITUDE CYCLE TO PERFORM A ΔK CALCULATION***



REF: USAF damage tolerant design handbook



$$\Delta K = \Delta\sigma\beta\sqrt{\pi a}$$

$$R = \frac{\sigma_{min}}{\sigma_{max}}$$

$$\Delta\sigma = \sigma_{max} - \sigma_{min}$$

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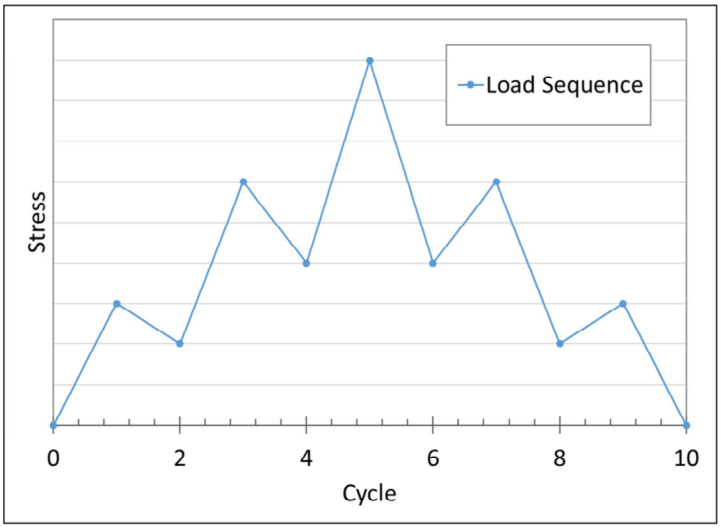
So, for analysis the load sequence must be pre processed into a series of independent, constant amplitude load segments to calculate a delta K to ultimately calculate growth rates.
Similarly, a load sequence must be pre processed. However, these pre processing steps are completely different and shouldn't be applied to the other application.

What if We Test a Counted Sequence? Original Load Sequence



20

What if we do fatigue tests on a sequence that has already been counted?
Let's reference this same example sequence.

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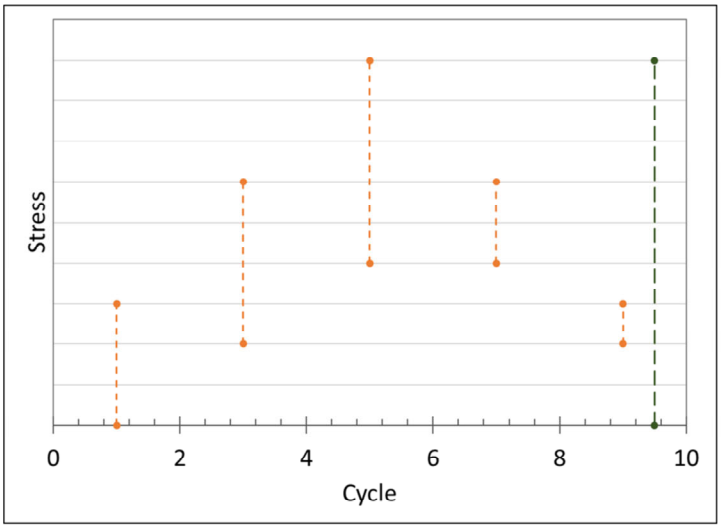
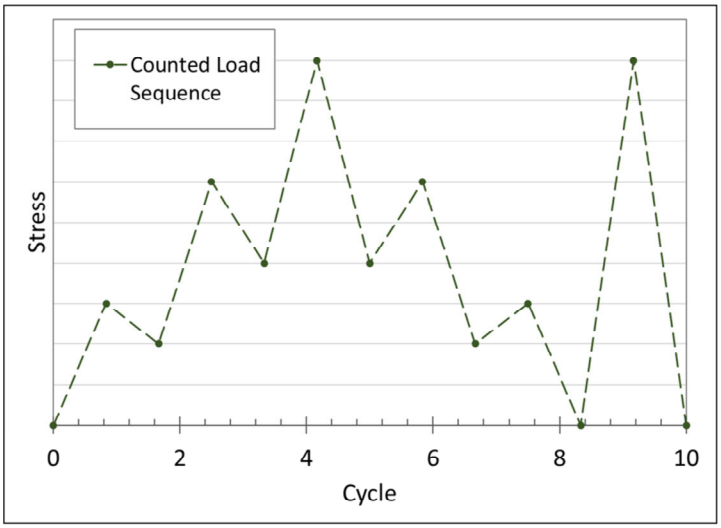
What if We Test a Counted Sequence?
Counted Sequence



21

Here are the equivalent independent constant amplitude load cycles defined by the counting process. Turning those independent load cycles back into a load sequence of turning points for a test frame results in…

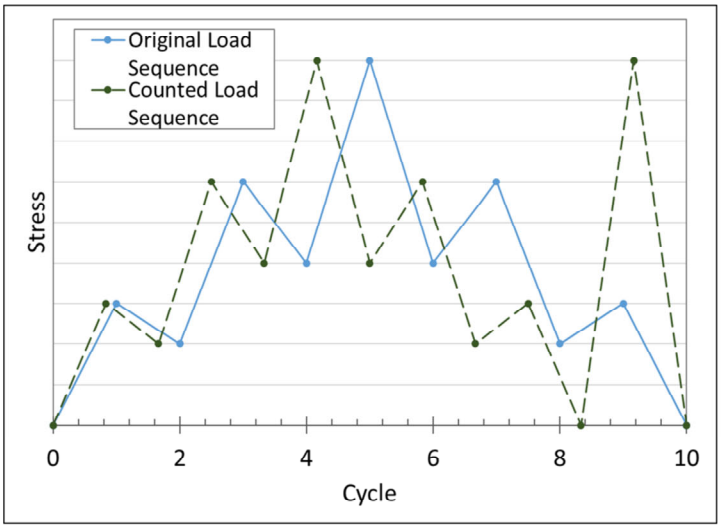
What if We Test a Counted Sequence? Counted Sequence Turning Points



22

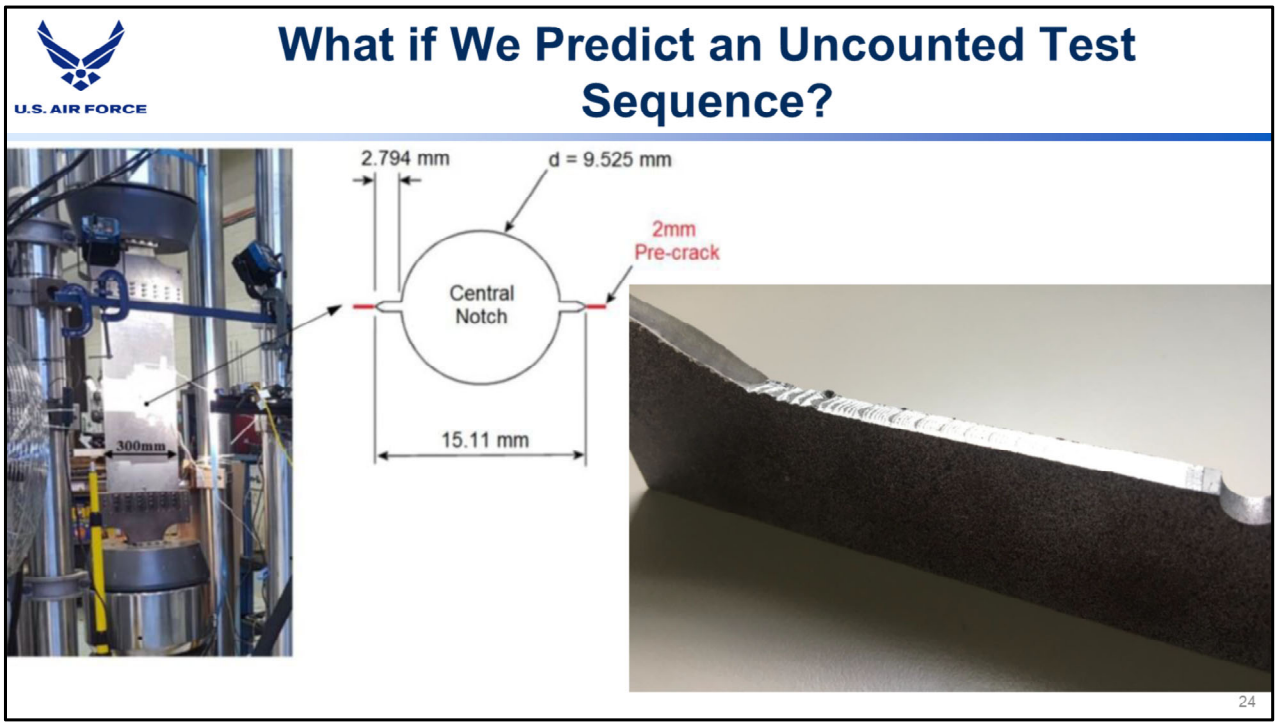
This, where there is now an additional cycle at the end of the load sequence.

What if We Test a Counted Sequence? What's the Difference?



23

The counted load sequence is clearly different than the original sequence.



Conversely, you should not run predictions by simply taking the load sequence turning points and applying that directly as a list of constant amplitude cycles for a prediction.

Last year the DSTG ASSIST group hosted a prediction challenge of a wide panel under a transport aircraft wing root bending spectrum. The spectrum they provided was the sequence as it was applied to a load frame. One analyst that participated in this prediction challenge (me), submitted a prediction without counting the provided sequence, assuming the sequence to have already been counted. Upon realizing my error the predictions were re-run with a counted representation of the spectrum and the difference in predicted life was about 40%.

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Conclusions

- Testing typically requires pre processing of spectrum to truncate small excursions and remove intermediate points
- Analysis requires pre processing to count spectrum to represent continual load application into discrete independent delta K events
- Using a counted spectrum in a load frame results in duplicative pre processing, inherently changing the spectrum
- Conversely, predicting using an uncounted spectrum can have dramatic impacts
- Be sure to understand the source of the spectrum you are using and whether or not the spectrum has been counted, truncated, etc.

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Questions?