LAT-PR-xxxxx:

TKR-Grid I/F Anomaly
Structural Assessment

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3 Dec 2003
Agenda: TKR-Grid I/F Anomaly Structural Assessment

• Loads Assessment
  – Current Loads Assumptions – a look at Grid analysis, TKR analysis and test loads
  – True Loads Experienced at Test – a study in probability density

• Grid Analysis Reprised
  – Margins of Safety Summary for bearing of shoulder bolt on Grid, with expected design dimensions (shoulder/thread engagement)
  – Adjusted margins of safety for as-tested design

• Shoulder Bolt Bending Loads
  – Bolt strength
  – Bolt margins under instantaneous load
  – Bolt margins under cyclic load
  – Unique loading due to 2-thread engagements / Helicoil pullout strength

• System Behavior due to dead band, slippage and impacting
  – Dead band, i.e. TKR alignment and positional uncertainty
  – Slippage, i.e. relative motion between the two mating surfaces after the frictional capacity is exceeded
  – Impacting, i.e. two initially separated surfaces come into contact and exchange momentum

• Conclusions, recommendations and Further Work
Loads Assessment

- Current Loads Assumptions – a look at Grid analysis, TKR analysis and test loads
  - New CLA derived loads are most realistic loads available
    - The maximum TKR corner flexure loads from September 2003 CLA
      - $S_{max} = 691 \text{ N}$
      - $Fz_{max} = 945 \text{ N}$
      - $1171 \text{ N (1303 N NTE mass)}$
    - With 1.1133 factor applied to achieve max launch mass, $F_{max} = 1303 \text{ N}$
  - Flight loads are significantly more benign than the random vibration test loads.
    - The maximum TKR attachment load due to 68 flight load cases
      - $F_x_{max} = 1642 \text{ N}$
      - $F_y_{max} = 1615 \text{ N}$
      - $F_z_{max} = 2280 \text{ N}$
      - $3241 \text{ N (3608 N NTE mass)}$
    - With 1.1133 factor applied to achieve max launch mass, $F_{max} = 3608 \text{ N}$
  - Loads induced at a random test are notoriously high due to high amplification above spec levels.
    - Hytec design loads were governed by static equivalent loads due to random vibration testing
      - 3-$\sigma$ design load of 27g lateral, plus shear component added
      - 4235 N (952 lb) shear load on fastener
      - During test, “notching” was allowed, 3-$\sigma$ load was 24g
      - $3764 \text{ N}$
  - True Loads Experienced at Test – a study in probability density
    - For any instantaneous response, 3-$\sigma$ load covers 99.87% of peaks
    - As total time of exposure increases, 3-$\sigma$ no longer covers 99.87% of peaks
    - From Clough, Dynamics of Structures, the probability wrt number of standard deviations can be observed as
      $$F_c(n_\sigma) = \exp \left[ -N \cdot \exp \left( -\frac{n_\sigma^2}{2} \right) \right]$$
The cumulative distribution function depends on:
- $f_1 =$ frequency of primary mode
- $t =$ duration
- $N =$ number of positive maxima $= f_1 \times t$
- $n_s =$ number of standard deviations

This function is plotted at right based on our observed test parameters:
- $f_1 =$ 130 Hz
- $t =$ 120 s
- $N =$ $f_1 \times t =$ 15600 cycles
- $n_s =$ range from 3.0 to 6.0 shown

The probability of choosing an enveloping load for:
- $3-$σ is 0.000%, i.e. 100% chance to hit $3-$σ
- $4-$σ is 0.534%, i.e. 99.466% chance to hit $4-$σ
- $5.8-$σ is 99.923%, which meets our goal to envelop 99.87% of all peaks over duration

If we apply $5.8-$σ to the Hytec 1-σ load (1412 N),
- Peak design load = 8190 N

7.00x higher than CLA!
Shoulder Bolt Bearing Calculation Assumptions

Load distributions considered

Distribution 1 – Uniform through depth – UNCONSERVATIVE.
This distribution idealizes the bearing load of the pin on the hole, but is valid for short pins (L/D is a small number). In this case, L/D is 0.89, which is not small.

Distribution 2 – Trapezoidal; Linear varying through depth – REALISTIC.
This distribution is probably the most realistic case. However, there is not a clear method of calculating w1 and w2.

Distribution 3 – Triangular; Linear varying through depth – CONSERVATIVE.
This distribution represents the critical pin depth where less engagement would result in a trapezoidal distribution and more engagement would result in pin bending, i.e. “Distribution 4.” This distribution is conservative and easy to calculate.

Distribution 4 – Bending; Linear varying through depth – MOST CONSERVATIVE.
This distribution is well suited for longer pins where pin bending may become a factor. In this case, it is not necessary to be overly conservative.
Grid Analysis Reprised

- **Margins of Safety Summary for bearing of shoulder bolt on Grid, with expected design dimensions (shoulder/thread engagement)**

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<tr>
<th></th>
<th>Peak Load [N]</th>
<th>Diameter [mm]</th>
<th>Engagement [mm]</th>
<th>Bearing Stress [MPa]</th>
<th>MS y</th>
<th>MS u</th>
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- **Margins are positive, except for probability extreme loads**

- **Adjusted margins of safety for as-tested design (pin engagement ~0.125” as opposed to expected 0.197”)**

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<th></th>
<th>Peak Load [N]</th>
<th>Diameter [mm]</th>
<th>Engagement [mm]</th>
<th>Bearing Stress [MPa]</th>
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<td>-0.58</td>
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- **Margins are negative, implying some onset of failure during the test**
Shoulder Bolt Bending

- **Bolt strength**
  - Catalog item: McMaster-Carr, 18-8 Stainless (70 ksi /482 MPa strength)
- **What load is required to deflect the shoulder 0.004”**?
  - Based on linear beam theory, the tip load required is 12656 N. This corresponds to a linear stress of 6333 MPa, which has no physical meaning
- **What is the max bending stress at the root of the shoulder?**

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- This shows the bolt cannot carry the bending stress associated with the loads
- Conclusion: the should must not deform so as to put the threaded portion into bending

- **Unique loading due to 2-thread engagements**
  - Two thread engagement corresponds roughly to 1 DIA engagement. According to the helicoil strength document, the helicoil can withstand 2300 lbf of pullout.
  - The 70 ksi bolt is good for less than 1500 lbf
System Behavior due to dead band, slippage and impacting

- How does 4 mil diametral clearance affect overall system dynamic behavior?
  - Dead band, i.e. TKR alignment and positional uncertainty – possibility for classic spring stiffening effect
  - Based on test observations, this is not a significant effect
  - Slippage, i.e. relative motion between the two mating surfaces after the frictional capacity is exceeded
    - Clamping energy is released in the form of heat – this increases damping in the joint
  - Impacting, i.e. two initially separated surfaces come into contact and exchange momentum
Conclusions, Recommendations and Further Work

• Conclusions

• Recommendations
  – Change bolt design so shoulder bottoms out on Grid instead of through the Flexure. This will
  – Random vibration environment commonly induces loads 2X or more higher than flight loads. Is a TKR acoustic test feasible?

• Further Work