HELICOPTER PLANETARY GEARBOX
FAULT DETECTION

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Helicopter Planetary Gearbox Fault Detection

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Background – 2009 accident of the Super Puma Helicopter

- **AS-332L2** crash off Scottish coast (16 lives lost)
  - Caused by 2\(^{nd}\) stage (upper) planet gear fatigue failure (spall-induced)
  - One metal particle found (36 hours prior)

From Aviafora.com website
Background – 2016 accident of the Super Puma Helicopter

- **H-225** crash off Norwegian coast (13 lives lost)
  - Again caused by 2\(^{\text{nd}}\) stage (upper) planet gear fatigue failure (spall-induced)
  - metal particles trapped by oil cooler
- In both cases, on-board Vibration Health Monitoring (VHM) didn’t detect the fatigue cracks
- Extremely challenging to detect such fault & its progression – a worldwide challenge
Detection Method

• Planetary rotation make detection very hard using fixed sensor
• Best candidate technique:
  ✓ Licensed to Honeywell (implementation ??) – certainly not in VHM system of Super Puma
  ✓ Not mandatory for VHM

• Need to calculate Planet Gear Synchronous Signal Averaging

Web download: gear_fa_by_mcsoftware-d8bcjck.gif
Detection Method

• SSA with planet carrier is commonly employed in VHM
• SSA with planet gear is less commonly employed (if at all ??)
• Composite Planet-Gear Synchronous Signal Averaging (CP-SSA) is employed here
• ‘Composite’ means SSA is the combined vibration from every planet gear, and there is no separation of the vibration from the individual planet gears

Reasoning:
• Planet gear deformation caused by a bore crack would distort its mesh with the ring and sun gears, and thus distort the planet gear mesh signature in the CP-SSA
• The distortion would produce extra modulations to the normal gear mesh signature, which should appear as modulation sidebands in the CP-SSA spectra
Detection Method

Raw Vibration Signal → Composite Planet-SSA (CP-SSA)

remove the planet gear mesh harmonics → residual signal for the planet gear

RMS energy of the planet gear residual signal can be trended against time

To further enhance the diagnosis, we can obtain the CP-SSA over multiple revolutions of the planet gear.

In the envelope signal, we expect to observe double peaks when the defective section in the planet gear is in mesh with either the ring gear or the sun gear.

a squared envelope is then applied to the residual signal
Test Data

- A simple planetary gear test rig at University of New South Wales (UNSW) in Australia

- Torques on output shaft: 45 Nm, 65 Nm and 85 Nm
- Speed of input shaft: 293 rpm fixed
- 3 planet gears

- Two accelerometers and one tachometer
- Sampling rate of 131072 Hz, 100 sec of data length
Results — Carrier-SSA & its spectrum

• dominant spectral components are the planetary gear mesh harmonics indicated by multiples of 81 (ring gear tooth number)
• drive gear mesh harmonics by multiples of 55 (tooth number of the spur gear which meshes with the drive gear with 42 teeth)
Results – CP-SSA

• Could remove the two sets of dominant gear mesh harmonics at $\times 81$ and $\times 55$
• However, the removal of $\times 81$ and $\times 55$ harmonics from the carrier-SSA spectrum will still not be able to obtain the bore crack induced characteristics
• because the spectral content synchronous to planet gear rotation is averaged out in the Carrier-SSA
• This is why it is crucial to employ the SSA of the planet gears

Obviously, there are 23 spikes in the CP-SSA.
Results – residual signal from CP-SSA, healthy-state condition

- removed the planet gear mesh harmonics at $\times 23$
- a flat pattern (no peaks) with the planet gear residual signal across the whole revolution of the planet gear.
- However, the RMS under heavy load was increased slightly (from 0.0319 to 0.0353)
Results – residual signal from CP-SSA, 1-mm slot faulty-state

- some obvious spikes in the residual signals at certain rotation angles of the planet gear,
- there is a monotonic increase of RMS values with the increasing load.

45Nm torque where
RMS = 0.0576

65Nm torque where
RMS = 0.0614

85Nm torque where
RMS = 0.067
Results – residual signal from CP-SSA, 1.5-mm slot faulty-state

- Again, there is a monotonic increase of RMS values with the increasing load
- the monotonic increase of the RMS values with the slot size
- Under 65 & 85NM load, two abnormalities (double-peak) or fault features (separated by roughly 180 degrees of shaft angle) are identifiable

45Nm torque where
RMS = 0.0676

65Nm torque where
RMS = 0.0767

85Nm torque where
RMS = 0.0809
Results – Trending of RMS values of residual signals derived from CP-SSA

• The EDM notch lengths of 1.0 mm and 1.5 mm into the rim of planet gear are equivalent to 28.57% (i.e. 1 / 3.5) and 42.86% (i.e. 1.5 / 3.5) of the gear rim being cracked from the bore

• The RMS value of the residual signal seems to be a good index for trending the crack length (severity) development

• Monotonic trend with both load the slot size

• planet gear bore cracking can be detectable using the residual signal of the CP-SSA
Results – for diagnosis (1 mm slot) CP-SSA over 3 revs

- 45Nm torque – weak planet-sun mesh
- 65Nm torque – stronger planet-sun mesh
- 85Nm torque – stronger planet-sun mesh

With the 1.0 mm notch, the features with planet-sun mesh appear to be quite weak and the in-between feature is stronger, for which we do not have an explanation.
Results – for diagnosis (1.5 mm slot) CP-SSA over 3 revs

- With the 1.5 mm notch, there are two main features associated with the planet-ring mesh and planet-sun mesh (roughly 180 degrees apart), and other smaller features can be seen in between the two main features

45Nm torque – strong planet-ring mesh

65Nm torque – stronger planet-ring mesh

85Nm torque – obvious planet-sun mesh
Results – explained

• A diagram showing the opening on tensile stress (red) and the closing on compressive stress (blue) of the bore crack of a planet gear in mesh with the ring and sun gears, respectively
• spikes due to the planet-ring and planet-sun gear meshes.
• This is because the planet gear with a bore crack is more deformed when the crack is aligned with radial load from gear mesh, i.e. the crack opens up in the tensile stress zone, than the planet gear without a bore crack.
• When the crack is not aligned with radial load of gear mesh, i.e. the crack closes down in the compressive stress zone, the deformation of the cracked gear is similar to the un-cracked gear
Summary

• a technique to detect and diagnose a very challenging type of fault – planet gear bore cracking.
• The fault detection can be achieved by trending the RMS values of the residual signal derived from the composite planet-gear SSA (CP-SSA) signal.
• When the RMS value exceeds a certain threshold, an anomaly of the planet gears is claimed to be detected.
• The diagnostic capability may be achievable using the squared envelope of the CP-SSA residual signal over multiple revolutions of planet gear.
• The meshing of the defective section in the planet gear with the ring and sun gears are individually identifiable by the local spikes in the envelope of the residual signal, especially under high-load conditions.

• The technique has been validated using test data acquired from a small industrial planet gearbox test rig.
• Will be further validated by test data from a real helicopter gearbox
Summary – planned testing using Bell-208B main gearbox

- A full-scale Bell-206B helicopter main rotor gearbox will be tested with a very fine EDM notch defect inserted into the rim of the planetary gear
- Try to initiate a real fatigue crack from the EDM notch and propagate it for a certain length with sufficient margin of safety to avoid catastrophic failure
- Multiple types of sensors used during this test, such as an in-line oil wear debris sensor, a wireless vibration sensor placed on the planet carrier inside the planetary gearbox, and traditional accelerometers externally placed on the gearbox housing
- The data from the various sensors will be fused to produce more convincing results
Question: Is this a unique problem for Super Puma?
Answer: Not necessarily (but the solution can be unique for Super Puma)

- If it would happen to any of the ADF Helicopters
- we would be unable to detect it — safety & availability issue