Propulsion System Health Monitoring
An Insight into Wear Debris Analysis

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DTA Propulsion System Health Monitoring

• Provide advice to the RNZAF to:
  – Support continued airworthiness
  – Prevent flight safety events
  – Increase aircraft availability/reduce cost of ownership

• Propulsion systems:
  – Gas turbine engines/gearboxes/helicopter drivetrains
NZDF Context - Motivation

• Small fleets - U/S aircraft - high impact on capability
• Deployed A/C – minimal facilities and spares available
  – E.g. Antarctic Flights, helos embarked on ships, austere environments, in-theatre ops etc.
• Need for increased warning lead-time to required maintenance intervention
• Oil-wetted component defects significant driver for unscheduled maintenance

Wear debris analysis identified as one area requiring enhancement
Wear Debris Analysis - Definition

- Wear Debris Analysis infers the health of oil-wetted components from debris liberated from wear modes within the system.

- Provides data on:
  - Wear modes
    - Morphology
  - Origin of debris
    - Elemental composition
  - State of defect progression
    - Size/quantity
    - Debris rate
Wear Debris Analysis – Typical Aircraft Systems

- WDA employed by OEMs as a prime means of detecting oil-wetted component defects
  - In-line Magnetic chip detectors (MCDs) – indicating/passive
  - Filter debris analysis
  - In-line real-time particle detection (very limited application)
Wear Debris Analysis – Typical Aircraft Systems

Efficacy of MCDs vary between various designs

Upper MRGB Chip Detector

Lower MRGB Chip Detector
Wear Debris – Serviceability Assessment

- OEMs provide AMM inspection criteria for wear debris
- First Line assessment visual inspection process has changed little over time
- Inspection guidance can be ambiguous/open to interpretation
  - Often no detail on inspection method
  - Often no detail on filter debris inspection

- First Line assessment visual inspection:
  - Quantity and size
  - Morphology

- Within limits - no further review
  - Sample may not be retained

- Out of limits
  - Requires engineering review
  - Possibly laboratory analysis
## Wear Debris – Serviceability Assessment

Example of generic AMM serviceability criteria for wear debris

<table>
<thead>
<tr>
<th>Type</th>
<th>Qty/size</th>
<th>Prob Cause</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>Fuzz, fine hair-like particles or granular form</td>
<td>Normal wear</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Particles in splinter form</td>
<td>Usually indicates failure</td>
<td>Perform serviceability check</td>
</tr>
<tr>
<td></td>
<td>Thin flakes not exceeding 0.031 inch (0.78 mm) in diameter and 0.25 inch (6.35 mm) in length. Qty not to exceed 20 flakes</td>
<td>Small qty will not cause bearing failure</td>
<td>Perform serviceability check</td>
</tr>
<tr>
<td></td>
<td>More than 20 flakes not exceeding 0.031 inch (0.78 mm) in diameter or any Qty of flakes exceeding the above dims</td>
<td>Usually indicates failure</td>
<td>Perform serviceability check</td>
</tr>
</tbody>
</table>

How do you measure this in the field?
Wear Debris – Serviceability Check Example

Generic procedure for a helicopter main rotor gearbox

• Indications
  – MCD chip light – Assess iaw AMM criteria
  – Filter bypass
  – Other (high vib etc.)

• Perform serviceability check
  – Perform 30 min ground run at flight RPM – if OK
  – Perform 30 min hover check

  – Inspect MCDs
    • if QTY of particles increased – Reject gearbox OR
    • If QTY is less – assess debris and repeat serviceability check OR
    • If QTY is Nil – continue in service
Wear Debris – Engineering Review

- Inputs to serviceability assessment:
  - Lab analysis of wear debris sample – composition, morphology
  - Maintenance history
  - Known and predicted wear modes
  - Engineering data – e.g. metal map
  - Trend data – wear debris and other e.g. vibs
  - Engineering judgement

- Output:
  - Diagnosis: Go/No-go (based on AMM criteria)
  - Prognosis: time until required maintenance intervention
  - Mandated inspections/monitoring if remaining in service

- Issues
  - Data for engineering review may not be available
  - SMEs may be remote from samples – delay in analysis
  - Variable experience of personnel in WDA
Case Study – Iroquois T53 gearbox

- Multiple MCD indications over period of 100+ hours – all assessed as ‘S’
- Final in-service MCD indication – serviceability check
  - Further MCD indication 3 min into 20 min hover check
  - Teardown found 2 fractured gear teeth, abnormal wear on gear surfaces
  - Wear debris precursors not detected
Case Study – T56 Accessory Gearbox (AGB)

- Aircraft deployed on operation
- Mag plugs checked – Accessory Gearbox Mag plug had debris
- Debris assessed as ‘fuzz’ and within limits – sample sent to DTA slow time for review

Results:
  - ‘Fuzz’ shown to be fatigue spall flakes of bearing material
  - Particles <1/16\(^{th}\) inch limit

- Engine changed

AGB Lower mag plug: Visual
AGB Lower mag plug: Macro lens photo
Lower mag plug: SEM image
Case Study: Super Puma G-REDL 2009

• Eurocopter AS332L2 Super Puma G-REDL main gearbox failure 2009 [1], [2]
• Ruptured planet gear caused catastrophic failure of gearbox
• Main rotor separated – fatal accident 16 killed
• Wear debris precursors were present – incorrectly diagnosed
• Noted from report on the AMM WDA process: “No illustrations or photographs of representative particles, to aid the process of identification, are included in the procedure”

Summary Serviceability Assessment

- Primarily based on MCD findings
- Inspection criteria can be ambiguous
- In general, basic WDA systems and serviceability focus on confirmation of failures in late stages
- Refinement of process is operator dependent
DTA Development – Filter Debris Analysis

- Filters contain valuable wear debris data
- Potential to provide significant lead time to failure over MCDs alone \[3\]
- Advantage – applicable to all fleets without modification
- FDA under utilised
  - Time consuming
  - Limited guidance
  - Lack of capability to extract and analyse debris
  - Visual inspection of filter pleats inadequate to reliably detect bearing spall particles (200 µm)

FilterCHECK FC400

• RNZAF procured GasTOPS FC400 in 2009 on DTA advice
  – Automatic debris extraction
  – Quantifies debris (Inductive sensor)
  – Produces debris patch for further analysis (if needed)
  – XRF system can provide aggregate composition (NOT used)

• DTA developed analysis processes/limits [4]

• RNZAF routinely sample filters for trending
  – Reduced inspection interval trending if defects detected

FilterCHECK FC400 - Debris extraction

- Consistent extraction method - Only variables are:
  - Time on filter
  - Amount of debris

- MetalSCAN sensor output:
  - Particle count
  - Particle size / Type (Ferrous or Non Ferrous)

- Debris rate derived from hours on filter
  - Primary trend metric
FilterCHECK FC400 – Debris Patch

- All debris collected above 60 µm in size on filter patches

- Debris Patches reviewed by RNZAF
  - Morphology inspection via optical microscope

- DTA developed visual inspection guidance used
RNZAF/DTA Wear Debris Analysis Process

Filter samples

FilterCHECK

MCD Samples

Visual Inspection

Optical microscope

First Line Assessment

- Within AMM limits?

NO

NO

Engineering Review

- Further analysis required?

YES

Send to DTA

NO

No action required

Final Assessment

- Serviceability disposition
- Further monitoring requirements

DTA Analysis

Laboratory Analysis

Engineering Review

DTA Report
DTA Wear Debris Analysis Process

Sample received
- Filter patch
- MCD sample
- Sample details

Optical Microscope
Detailed assessment of Morphology (50 X)
Remarkable debris present?

NO
- DTA Report
  - Nil remarkable debris

YES
- Extract representative subsample for SEM/EDS analysis

SEM
Detailed assessment of Morphology

EDS
Composition of each particle assessed
Determine match to component Metal Maps

DTA Corp Knowledge
- Physics of failure
- System specific data
- Failure case studies
- Mechanical and materials engineering

DTA Report
- Detailed debris Summary
DTA Wear Debris Analysis Process

- Scanning Electron Microscope (SEM) - morphology analysis
- Energy dispersive x-ray spectroscopy (EDS) - elemental composition
Case Study – T56 Reduction Gearbox (RGB) Pinion Bearing

- Cruise FL280
- No. 1 engine Torque and RPM fluctuations
- Excessive red fluid streaming from engine
- Engine shutdown – return to origin
- Un-eventful landing after 4 hours on 3 engines
Case Study – T56 RGB pinion bearing

Magnetic Chip Detector Debris (Post Failure)
Case Study – T56 RGB pinion bearing

- SEM/EDS Analysis sample at failure:
  - M50 NiL bearing steel (AMS6278) – Match to pinion bearing
  - 9310 (AMS 6265) gear steel fragments

Magnetic Chip Detector Debris (Post Failure)
Case Study – T56 RGB pinion bearing

Rear Pinion Bearing Inner Race

Pinion Rear Bearing

Bearing Cage Heat Damage

Pinion Rear Bearing Rolling Element
Case Study – T56 RGB pinion bearing

- Inner Diaphragm Damage
- Torque-meter Housing
- Main Accessory Gear Damage
- Torque-meter Pickup Gouging
Case Study – T56 RGB pinion bearing

- SEM/EDS analysis 250 hours prior to failure
  - Mag plugs assessed as within limits

Report: Wear Debris Analysis: C-130 Hercules

Overall Assessment: ADVISORY

Comments: M50 NiL bearing debris was found indicating a surface contact fatigue defect. M50 NiL material is only known to be used for the RGB input pinion bearing.

Recommendations: Investigate source of debris.

Review all maintenance data including any other mag plug inspections/samples to isolate source of debris or determine if debris is residual from previous event etc.

System Details
- Aircraft: C-130 Hercules
- System Type: T56-A-15
- Serial No.: 
- Tail: 
- Work Order: TSO (Hrs): 1,478.8

Sample Details
<table>
<thead>
<tr>
<th>Sample</th>
<th>Sample Type</th>
<th>FilterCHECK No./Ref</th>
<th>DTA Sample No.</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Filtercheck</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>3</td>
<td></td>
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<tr>
<td>4</td>
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</tr>
</tbody>
</table>

Analysis Method:
- Optical microscopy (max 50X mag) used to identify and sub-sample any particles that have morphology indicative of a potential critical wear mode. Scanning Electron Microscopy/Energy dispersive x-ray spectroscopy (SEM/EDS) used to analyse individual particles in detail. Size listed in microns unless stated. 1000 micron = 1 mm.

Results: Sample 1

Debris Summary
<table>
<thead>
<tr>
<th>Quantity</th>
<th>Size Typmix</th>
<th>Morphology</th>
<th>Prob Alloy Match</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>100+</td>
<td>200/1000</td>
<td>Surface Contact Fatigue - Spalling</td>
<td>M50 NiL - Bearing steel</td>
<td></td>
</tr>
<tr>
<td>1-10</td>
<td>500</td>
<td>Surface Contact Fatigue - Spalling</td>
<td>SAC 3010 Grain/Steal</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1: SEM image of largest M50 NiL particle

Figure 2: SEM image of typical M50 NiL debris
Case Study – T56 RGB pinion bearing

Filtercheck ferrous debris rate

A - Monitoring since traces of M50 NiL first detected
B - Accelerated failure rate undetected due to overseas deployment (3 filter samples)

Debris Quantity (Counts/Hr) vs. Flight Time Prior to Failure (Hrs)

- Small Particles
- Med Particles
- Large Particles
- Total Particles

Fleet alert limit $\sigma + 3$ S.D
FDA Case Studies – Examples of catches

• RB211-535 – Detected power take off shaft steady bearing failure
  – Allowed repair on-wing

• RB211-535 – Pre first B757 Antarctic flight - detection of major bearing defect
  – Avoided flight safety risk/unscheduled engine change

• T56 – multiple reduction gearbox defects detected allowing scheduled intervention

• T56 – numerous cases detecting starter magnetic seal failures
  – Allowed on-wing repair
  – Avoided unnecessary engine removal
DTA Work: Advancing WDA

• Desire to standardise WDA to:
  – Allow more robust assessment of component health
  – Give guidance to operators
  – Provide standard means of analysis for laboratories
  – Provide a basis for OEMs to standardise AMM methods and inspection criteria

• DTA through TTCP nations produced FDA guidance document
  – None existed prior

• Covers:
  – Robust methods for debris extraction from filters
  – Analysis methods and requirements for detection of component defects
  – Interpretation guidance
DTA Work: Advancing WDA

- TTCP FDA document adapted and published by ASTM (2014)
  - Designation: D7898 – 14
  - “Standard Practice for Lubrication and Hydraulic Filter Debris Analysis (FDA) for Condition Monitoring of Machinery”
  - Covers debris extraction, analysis and reporting
  - Intended for aircraft systems (also applicable to wider machinery)
  - Includes simple manual methods and automated methods

- Future work planned to develop more comprehensive standard practice for all wear debris analysis
DTA Work: Advancing WDA

- Reviewing new analysis technology to enable deployed WDA
  - Strong need to have accurate serviceability assessment without delays

- Portable elemental analysis
  - X-ray fluorescence
  - Laser-induced breakdown spectroscopy (LIBS) based

- Portable microscope image capture systems
  - Compact microscopes
  - Digital imaging techniques
Summary

- **Legacy MCD based AMM inspection methods/criteria:**
  - Robustness of assessment heavily dependant on operator competency
  - WDA assessment process is variable between OEMs
  - Generally aimed at confirming late stages of a failure (Often insufficient warning to prevent unscheduled maintenance)
  - Inspection criteria is typically vague and can lead to incorrect assessment
  - Delay in accurate analysis can incur flight safety risk

- **RNZAF WDA programme**
  - Underpinned by DTA SEM/EDS capability and corporate knowledge
  - Augmented by filter debris analysis - has proven to detect significant proportion of defects with increased lead time
  - Future work to focus on enhancing deployed WDA capability

- **DTA WDA Advancement Recommendations**
  - Industry wide standards needed to improve and standardise WDA best practice amongst OEMs and operators
  - FDA ASTM standard D7898 – 14 is now in place
  - Civil aviation is encouraged to participate in future WDA standards development work!

- **Failure investigations**
  - Consider MCDs and filters and residual internal debris Fe and Nfe – very few failure modes produce no wear debris
  - Ask the question was robust WDA conducted?