Dynamics based Maintenance
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Predictive Maintenance
Degradation models & Smart sensoring

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PERSONAL BACKGROUND
TIEDO TINGA

Education
- MSc Applied Physics / Materials Science at Groningen University
- PDEng in Materials Technology at Groningen / Delft University
- PhD Mechanics of Materials at Eindhoven University

Positions
- University of Twente → Professor Dynamics based Maintenance (3 d / w)
- Netherlands Defence Academy → Professor Life Cycle Management
- Past: Scientist at National Aerospace Laboratory NLR
TIME – MAINTENANCE CONSORTIUM

- Twente Is Maintenance Excellence – TIME
- 7 cooperating research groups:
  - Dynamics based Maintenance (prof. T. Tinga)
  - Tribology based Maintenance (prof. P. Lugt)
  - Maintenance Engineering (prof. L. van Dongen)
  - Construction Management & Engineering (prof. A. Doree)
  - Supply Chain Management (prof. H. Zijm) - BMS
  - Pervasive Systems (prof. P. Havinga) – EWI
  - Formal Methods & Tools (prof. J. v/d Pol) - EWI

- Together cover all relevant disciplines of maintenance
EDUCATION

Specialization Maintenance Engineering & Operations (MEO)

- Part of Master programs Mechanical Engineering and Industrial Engng
- MSc thesis on maintenance subject + core courses:
  - Maintenance Engineering and Management
  - Failure Mechanisms and Life Prediction
  - Structural Health and Condition Monitoring
  - Design for Maintenance
  - Reliability Engineering & Maintenance Management

PDEng program

- 2 year technical traineeship – 1 yr courses / 1 yr design assignment
- “technical MBA”

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Outline

• Background and introduction
• Load vs. Capacity
• Load types
• Failure mechanisms

• Applications
  – Preventive maintenance and prognostics
  – RAMS analysis → Relevant Failure Parameter
  – Maintenance optimization
  – Condition monitoring + sensors
  – Root cause analysis
Objective

• **Demonstrate benefit of understanding failures**
  - Enables quantification of maintenance
  - Provides structured way of problem solving

• **Give a flavour of loads & failure mechanisms**
  - Not complete overview
  - Simple examples
    › not representative for your practical problems
    › illustrate principles
    › demonstrate quantification – some equations!

• **Provide directions for application**
  - Not complete overview
  - Not in-depth treatment of one case
Background

Defence organization:
- Technologically sophisticated systems
- Largely variable and demanding operating conditions
- High requirements for availability and reliability
- Constant pressure to reduce costs

Maintenance important

*Predictability* of maintenance desired
Introduction

- Preventive maintenance → length of intervals
- Balance between
  - low costs → efficient
  - high availability → effective
- Two approaches to find optimum
  - Experience based approach
    › predict failures based on historic data
    › Reliability Engineering / RAMS analyses
    › requires large datasets / inaccurate for changing conditions
  - Model based approach
    › predict failures with physical failure models and monitored (or prescribed) variation in usage
    › quantitative relation between usage and degradation
    › enables *dynamic maintenance*
Failure

- **Requires understanding of failure behaviour**
  - How ? Why ? When ?

- **Failure**: “reaching such a state that the intended function can no longer be fulfilled”
  - depends on function
  - not always physical failure

- **Failure mode**
  - Manner in which a system functionally fails
  - Detected by decreased performance or inspection
  - Several hierarchical levels
  - Also non-physical causes: human errors / contamination

- **Failure mechanism**
  - Physical or chemical process yielding degradation and leading to failure
  - Limited number !
Balance

- Load versus load-carrying capacity
Load types and failure mechanisms

External system loads:
- Mechanical
- Thermal
- Chemical
- Electric
- Cosmic

Internal material loads:
- Stress / strain
- Temperature
- Concentration / pH
- Electric field / voltage / current
- Radiation intensity

Failure mechanisms:
- Deformation
- Fatigue
- Fracture / delamination
- Creep
- Wear
- Melting
- Burning
- Oxidation
- Corrosion
- Ageing
- Arc flash
- Partial discharge
- Dielectric losses
- Creep current / treeing
- Ageing

Loads → Capacity
Problem 1

Determine for the failures mentioned below
- the failure mechanism
- the governing load
- the load-carrying capacity
- a preventive solution

- Fractured window hit by football
- Broken bicycle chain
LOADS
 Loads

- **External loads vs internal loads**
- **Different load types**
  - Mechanical
  - Thermal
  - Electric
  - Chemical
  - Radiative
- **Relation with usage**
External and internal loads

- **Failure occurs on (microscopic) material level**
  - mechanical fracture = release of atom bonds
  - breakdown of electric insulator = release of electrons

- **Failure is governed by local *internal* load**
  - local stress, strain, electric field, temperature

- **Operator determines *external* loads**
  - Force, moment, charge distribution, heat input
Relating usage to service life

Usage monitoring

Usage → Platform / system

Zoom in to the level of the physical failure mechanism

1. Local Loads

2. Failure model

Remaining life

Prognostics

Service life / Damage accumul.

Load monitoring

Condition monitoring
Load types

- **Mechanical**: Forces/moments caused by various sources

  - **Specific sources**
    - rotation (centrifugal)
    - (air) pressure
    - weight / gravity
    - acceleration (dynamic)
    - propulsion (torsion)
    - boundary conditions
    - thermal expansion

  - **Generic loads**
    - Force
      - normal
      - shear
    - Moment
      - bending
      - torsion

  - **Material properties**
    - stiffness (E, ν)
    - yield stress

  - **Internal (material) loads**
    - stress
    - strain

- **Thermal**: Heat flow caused by several sources

  - **Specific sources**
    - gas compression
    - combustion
    - friction
    - electric resistance

  - **Heat input**
    - radiation
    - convection
    - conduction

  - **Material properties**
    - heat capacity (C<p>)
    - conduction (λ)

  - **Internal (material) loads**
    - temperature
Load types (2)

Chemical
- combustion
- electrolysis
- Concentration
  - acid
  - gas
- chemical resistance
- chemical potential

Electric
- solar cell
- generator
- Charge
- conductivity
- elektric field
- current density

Cosmic
- solar radiation
- Radiation intensity
- absorption coefficient
- energy density
Examples of sources mechanical loads

- **Pressure**
  - distributed load exerted by environment of body:
    - water pressure (hull of ship, submarine)
    - air / gas pressure (gas pressure vessel, aircraft wing)
  - total force determined by distributed load \( f \text{ in N/m}^2 \) and surface \( A \):
    \[
    F = \int_A f dA
    \]

- **Acceleration:**
  - acceleration \( a \) requires force (Newton’s law) proportional to mass \( m \) and \( a \): \( F = m a \)
  - Rotation is acceleration \( \rightarrow \) centrifugal force acts on rotating body (angular velocity \( \omega \) and radius \( r \)):
    \[
    F_{cf} = m\omega^2 r
    \]
Internal mechanical loads: stress

• Local load parameter
• Relating external load (force / moment) to the properties of cross section
• Normal force
  – uniform normal stress $\sigma$

$$\sigma = \frac{F}{A}$$
Thermal loads

- **Heat input per unit time and unit area:** \( q \ [\text{W/m}^2] \)
- **Internal heat generation**
  - friction \( Q = F_w v = \mu F_n v \)
  - electric resistance \( Q = \frac{V^2}{R} = I^2 R \)
- **External heat generation**
  - compression \( \frac{pV}{T} = \text{constant} \)
  - combustion
- **Causes increase or decrease of temperature:** \( T \ [\text{°C of K}] \) → internal load!
Summary

- **External loads**
  - Type and magnitude determined by usage of system

- **Internal loads**
  - Depend on magnitude external load + properties / dimensions
  - Directly responsible for failure

- **Usage + properties determine loads**

- **Compare with capacity → failure mechanisms**
FAILURE MECHANISMS
Failure mechanisms

- *Static overload*
- Deformation
- *Fatigue*
- Creep
- *Wear*
- Melting
- Thermal degradation
- Electric failures
- Corrosion
- Radiative failures

**Complete overview:**

*Principles of Loads and Failure Mechanisms*

T. Tinga

*Springer Series in Reliability Engineering*
Static overload

• **when stress > strength**
  - $load = stress$
  - $capacity = material strength$

• **tensile strength determined by tensile test**

• **tensile strength temperature dependent**
  - $T \uparrow \sigma_t \downarrow$

• **design: expected load < strength**
  - effect temperature
  - safety factors

• **Failure analysis**
  - fracture surface $\rightarrow$ ‘dimples’
Fracture surface static overload
Fatigue

- caused by cyclic load
- stress level below tensile strength
- failure occurs after large number of cycles ($10^4 - 10^7$)
- load = strain or stress cycle ($\Delta \varepsilon$ of $\Delta \sigma$)

![Graph showing cyclic load and stress](image_url)
Fatigue (2)

- **Capacity = fatigue resistance**
  - *S-N* diagram or Wöhler-curve
Failure analysis
Life assessment

- **Constant amplitude: from S-N or Smith diagram**
- **Variable amplitude: Miner damage rule**
  - $n$ cycles at load with life $N$ yields damage $D$
  
  \[ D = \frac{n}{N} \]
  
  - $0 < D < 1$: percentage of life consumed
  - $p$ blocks of $n_i$ cycles with life $N_i$ yields damage

  \[ D = \sum_{i=1}^{p} D_i = \sum_{i=1}^{p} \frac{n_i}{N_i} \]
  
  - no sequence effects
Problem 2

For a gas turbine blade it has been derived:
- \( \sigma = 3.95 \ N^2 \)

A start/stop cycle is defined as:
- start/stop: N from 0 to 14,000 rpm and back to 0

• Calculate the number of start/stops before the blade fails due to fatigue
Solution - 1

Calculate stress amplitude:

- **Min**: $\sigma = 0$ MPa
- **Max**: $\sigma = 774$ MPa

Read the number of cycles to failure from S-N diagram

- **$N = 3000$ cycles**
Problem 2

For a gas turbine blade it has been derived:

- \( \sigma = 3.95 \, N^2 \)

A start/stop cycle is defined as:

- start/stop: N from 0 to 14.000 rpm and back to 0

• **Calculate the number of start/stops before the blade fails due to fatigue**

In addition to the start/stop cycle two more cycles exist:

- manoeuvre: N from 8.000 to 14.000 rpm and back to 8.000 rpm
- correction: N from 10.000 to 12.000 and back to 10.000 rpm

The usage profile of the engine is: per flight 1 start/stop, 3 manoeuvres and 10 corrections.

• **Calculate the number of flights to failure**
Solution - 2

Calculate stress amplitudes:
- $N = 0 - 14000$: $\Delta \sigma = 774$ MPa $\rightarrow N_f = 3000$ cycles
- $N = 8k - 14000$: $\Delta \sigma = 521$ MPa $\rightarrow N_f = 22000$ cycles
- $N = 10k - 12000$: $\Delta \sigma = 174$ MPa $\rightarrow N_f = 10^8$ cycles

Calculate damage $D$
- $D = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3}$
  \[= \frac{1}{3000} + \frac{3}{22000} + \frac{10}{10^8} = 4.69 \times 10^{-4}\]

Calculate number of flights to failure
- $N = \frac{1}{D} = 2132$ flights
Wear

- **occurs when parts move relative to each other or along liquid / gas**
- **two types**
  - two-body wear mechanisms
    » on contact between two parts
  - single-body wear mechanisms
    » on surface due to flowing medium
- **resulting in**
  - bad fitting
  - vibrations (e.g. bearings)
  - cracks – fracture
Wear mechanisms

Two-body wear

• abrasive wear
• corrosive wear
• surface wear
• adhesive wear
  – strong bonding between peaks of surface roughness
  – high friction → high temperature
  – improve by lowering friction:
    » materials
    » lubrication

Single body wear

• Erosion
Wear mechanisms (2)

- **abrasive wear**
  - when considerable differences in hardness (> 20%)
  - presence of hard particles
    » as additional body (three-body): sand
    » fractured particles (debris)
Wear rate

- **Archard’s law**

\[ V_i = k_i F s \]

- \( k [\text{mm}^3/\text{Nm}] \) is specific wear rate (different for two bodies)

- \( k \) depends on
  - material combination
  - surface roughness
  - contact temperature
  - hardness
  - lubrication
More advanced methods

- Calculate loads with FE / CFD models
- Complex (multi-scale) damage models

- Find balance between effort and benefits!
Summary

• Loads – capacity balance
• Load types
• Failure mechanisms

• Application in maintenance
  – Preventive maintenance and prognostics
  – RAMS analysis → Relevant Failure Parameter
  – Condition monitoring
  – Root cause analysis
Application in maintenance

Knowledge on failure (mechanisms) can be used ...

• before failures occur
  – Identify critical components \(\rightarrow\) FMECA
  – Predict time to failure \(\rightarrow\) determine optimal maintenance intervals
  – Develop efficient condition monitoring \(\rightarrow\) smart sensing

• after failure has occurred
  – Why did component fail ?
  – How can future failures be prevented ?
  – Root Cause Analysis

• when a fraction of a (larger) population has failed
  – Quantify failure behaviour
  – Find Relevant Failure Parameter (RFP)

\(\rightarrow\) Any experience ?
1. Preventive maintenance & prognostics

- **Procedure**
  - Monitor actual usage of the system
  - Derive internal loads from the usage
  - Develop physical models for critical failure mechanism(s)
  - Calculate service life consumption and remaining life
  - See Tinga, Reliability Engineering and System Safety 2010

- **Applied to several military systems**
  - Chinook helicopter
  - NH-90 helicopter
  - CV-90 combat vehicle
  - LC frigate
NH-90 helicopter prognostics

- **Identified critical components**
  - Cost drivers
  - Availability killers

- **Determined failure mechanism + governing loads**

- **HUMS system available for monitoring**
  - Usage \(\rightarrow\) flight hours, landings, conditions, etc.
  - Health \(\rightarrow\) mainly vibrations

- **Maintenance primarily related to flight hours**
NH-90 helicopter prognostics

- Landing gear shock absorber is critical
- Time to failure not correlating to FH
- Develop prognostic method

![Graph showing MLG MTBF (in FH)]
NH-90 helicopter prognostics (2)

- Mechanism: wear of seal (oil leakage)

- Relevant Failure Parameter: travelled distance → # landings + weight

\[ V_i = k_i F_S \]
ELECTRICAL SYSTEMS / COMPONENTS

- Method life prediction Printed Circuit Boards (PCB)
- Assessment of loads
  - Vibrations
  - Temperature (changes)
- Indication service life for various usage patterns
2. Relevant Failure Parameter

- **RAMS / data analyses → typical approach**
  - Collect failure data - *ttf* in calendar / operating time
  - Analyze data
    - Mean Time Between Failures (MTBF)
    - Parameters of distribution function (Weibull, exponential)
  - Adapt maintenance policy to obtained values

- **Problem: uncertainty / variation**
  - Variation in usage / conditions causes variation in MTBF
  - Ineffective or inefficient maintenance

- **Solution**
  - Determine more relevant failure parameter
    - Operating hours, starts, cycles, ... in stead of hours / days
Relevant Failure Parameter - example

- **Airliner with fleet of aircraft**
- **Part fails due to fatigue (~ 10,000 cycles)**
Problem 3 - RFP

• A car is maintained every 15,000 km / 1 year
  – Many parts replaced or inspected
  – Usage parameter: km or calendar time

• What would be the most relevant failure parameter for:
  1. brake discs
  2. tires
  3. structure
  4. engine lubrication oil
  5. hydraulic oil in the brake system

• Is usage based maintenance the most appropriate policy?
3. Optimization ship-level maintenance

- **Complex system**
  - Many subsystems with different failure behaviour

- **Maintenance needs determined by usage profile**
  - Large variation in time / across fleet / between subsystems

- **Maintenance should be more dynamic**
  - Dynamic intervals for all subsystems most efficient, but not feasible
  - How to cluster maintenance activities in small number of periods?

Simulation model

Mission type (incl. environment)
1. in harbour 27%
2. training 17%
9. mission in polar conditions 4%

Mission phase
1. transit 10%
2. surveillance 15%

Subsystem usage
Gas turbine 0%
2 (out of 4) diesel generators active 70%
1 water chiller active 0%
2 water chillers active 0%
3 water chillers active 70%
SMART-L 30%

Mission type selection + mission duration ($T_m$)
Specialization

- **Specialization within fleet (3 ships)**
  - 1 ship: all severe missions in hot circumstances
  - 1 ship: all missions in cold regions / close to base
  - Remaining missions → 3rd ship

- **Resultaat**
  - Ship 1 requires large amount of maintenance / high costs
  - Ship 2 / 3 require less maintenance

- **On fleet level → total costs are lower!**

<table>
<thead>
<tr>
<th>Role</th>
<th>Number of intervals</th>
<th>Total costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship 1 hot missions</td>
<td>5* 9</td>
<td>426.4</td>
</tr>
<tr>
<td>Ship 2 cold missions</td>
<td>5 9*</td>
<td>207.9</td>
</tr>
<tr>
<td>Ship 3 remaining</td>
<td>5 9*</td>
<td>250.0</td>
</tr>
<tr>
<td>Equal division over 3 ships</td>
<td>5* 9</td>
<td>395.8</td>
</tr>
</tbody>
</table>
4. Condition monitoring

- Sensoring and data acquisition now well developed

- Remaining challenges
  1. Translation of data into maintenance information → only when condition is not directly monitored
     - performance
     - usage
  2. Add prognosis to diagnosis
  3. Selection of proper measurements and location

Condition Monitoring → Condition Based Maintenance
Diagnosis vs. Prognosis

• **Condition monitoring** → assess the present condition

• **Need for prediction of future maintenance**
  › less risk / better planning

• **Two options:**
  – wait for indication of failure / degradation (**diagnostic**)  
    » often based on certain threshold value with safety factor
  – predict remaining life (**prognostic**)  
    » from every state prediction of expected maintenance
    » prediction improves when reaching end of life
    » based on assumed usage

• **Prognostic approaches**
  – raw data / statistics → trending
  – physical processes
Development of new CM / CBM systems

• **Selecting appropriate quantities for CM**
  – which parameters should be measured?
  – at what location?
  – how can measured quantities be translated into condition information?

• **Criteria**
  – representative (knowledge on failure mechanisms)
  – measurable (sensors, accessibility)

Condition Monitoring ➔ Condition Based Maintenance
A1) possible to identify critical components, failure mechanism & associated condition parameters?

A2) can these parameters be measured?

A3) can measured quantities be translated into maintenance intervals / failures?

A4) does application of CBM yield financial or safety benefit?

A5) possible to implement CBM in organization?

NO

YES

YES

YES

NO

Asset NOT SUITABLE for CBM

Information (section)

FMECA (5.1.1)

RCM (5.1.2)

Sensors available (5.6)?

Location accessible?

Data collection possible?

Prognostic or predictive tools available? (5.3)

Cost Optimization (5.4)
SENSORS AND SENSING STRATEGIES
**SENSORS**

- Monitoring requires sensors
  - Vibration → acceleration
  - Oil analysis → mostly in lab, now also online (moisture, particles)
  - Corrosion → Impedance or Electro-chemical Noise (EN)
  - Deformation → Fibre Bragg Grating (FBG)
    - Optical fibres
    - Sensitive for strain
      - also temp., moisture
    - Can be integrated in composite structures
SHM SENSORS

- Smart layer
  - 9 piezo actuators / sensors

- Optical fibres
  - Fiber Bragg gratings
  - Strain, Temp., Humidity

- Comparative Vacuum Monitoring (CVM)
CORROSION MONITORING WITH ENM

- Project with Navy / TNO / TU Delft

- Monitoring corrosion process – electro chemical noise
  - Passive method – no disturbance / low power
  - Interpretation of data is challenging
  - Signal analysis with wavelets / Hilbert-Huang / EMD
  - Detection of mechanisms

- Aim: corrosion sensor for CBM

Homborg et al., 2012 / 2013, Electrochimica Acta
Homborg et al., 2013, Corrosion Science
EXAMPLE: SINE WAVES

1 sine wave

1000 Hz

3 sine waves

100 Hz
500 Hz
1000 Hz
SINE WAVES: FAST FOURIER TRANSFORM

- Determine the power spectral density

No localization in time
SINE WAVES: HILBERT SPECTRUM
HILBERT SPECTRUM (ALUMINIUM AA2024-T3)
HILBERT SPECTRUM

Stainless steel AISI304, HCl pH 3.0
SENSING STRATEGIES
DEVELOPMENTS

- **Wireless**
  - For badly accessible locations (rotor blades)
  - Wires are not a weak link (railway)
  - Limitations for processing / communication

- **Autonomous**
  - Self-supporting $\rightarrow$ own power supply
  - Energy harvesting $\rightarrow$ piezo's

- **Smart**
  - Sensor node decides which role it has
    - Sensor or actuator
    - Structural vibrations or propagating waves
WIRELESS SENSOR NETWORKS

- Smart Autonomous Wireless Sensor Networks

- Applications
  - Rotor blades
  - Production machines
  - Train (bearings) / track

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5. Root Cause Analysis (RCA)

- **Structured method to find the cause of a failure in a system**
- **Solving problems is often only solving the symptoms**
  - Failures keep returning
  - Low availability / high costs
- **RCA should be executed to a sufficiently deep level → failure mechanism + loads !**
- **Solution is often rather simple**
  - Reduce loads on the system
  - Increase capacity of the system
Case studies in WCM-IP

- **Bosch Rexroth**
  - hydraulic cylinder for off-shore

- **Wärtsilä**
  - Bearing in thruster
Case studies in WCM-IP

• Gasunie → valves in gas network

• Koninklijke Marine → fire extinguishing pump
Mechanism based Failure Analysis

- **Procedure**

![Diagram showing the procedure for Mechanism based Failure Analysis]

1. **Load**
2. **Failure Mechanisms**
3. **Solution**
   - reduce Load
   - increase Capacity

**RCA**

**FMECA**

**Fault Tree Analysis (FTA)**

**Pareto**

**Top 5 Failure Modes**

- **Effects**
- **Criticality**
- **Risk Priority Numbers**

**CMMS Data**

**Data**
4 types of causes

1. Capacity too low → quality control
   • e.g. wrong impeller material → corrosion

2. Human error → (obeying) regulations
   • e.g. wrong rotation direction

3. Load avoidably too high (misuse)
   • e.g. shaft fracture due to misalignment, operating with closed valve

4. Load unavoidably too high
   • e.g. failure of non-rotating bearing due to vibrations
Mechanisms & Solutions

• **Seal leakage**
  - Mechanisms
    › wear (no water in pump during operation)
    › thermal shock (cooling of heated seals causes fracture)
    › damage due to vibration overload (cavitation, misalignment)
  - Solution
    › mainly caused by operating the pump incorrectly
    › prevented by better instruction and training of the operators

• **Insufficient yield**
  - Mechanisms: damaged impeller due to
    › Corrosion, erosion by sand (shallow water), fatigue (cavit.)
  - Solution
    › most impeller failures unavoidable \(\rightarrow\) due to regular usage
    › Prediction may be possible \(\rightarrow\) monitor operating hours in shallow water
Conclusion

- Understanding the failure behaviour enables more efficient maintenance strategies
- (in)balance between load and capacity is key to failures
- Effect of variations in usage is often neglected

- Model-based approach good addition to traditional experience-based approach
Further reading

• Check our publications on
  – https://research.utwente.nl/en/persons/tiedo-tinga