Computational modelling of leading edge erosion

Overview and next steps

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Problem

- Due to leading edge erosion, up to 25% annual energy loss can be expected.
- LEE can be seen 2...3 years after installation of WT.
Main steps of LEE modelling

1. **Estimation of loading**: Rain density, droplet size distribution, dust, flow velocity

2. **Impact contact** between droplet/particle and surface: pressure on the surface, time

3. **Deformation and damage initiation**: Wave distribution, Rayleigh waves, coating cracking, debonding, cracks in composite

4. **Fatigue and materials degradation over time**: fatigue, material loss, roughening of surface, estimation of lifetime

5. **Solutions**: New coatings
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## 5. Solutions:
- New coatings
Estimation of loading

Amirzadeh, et al JWind Engineering and Industrial Aerodynamics 2017:

- Stochastic model of rain texture
- Used rainfall data for the city of New Bedford 1992-2000
- Raindrop size distribution by Best

\[ F = 1 - \exp \left[ - \left( \frac{d}{1.3 I^{0.52}} \right)^{2.23} \right] \]

- \(d\) is the drop diameter in mm, \(I\) is the rain intensity in mm/h and \(F\) is the fraction of liquid water in air comprised of drops with a diameter smaller than \(d\)

- Rain as homogeneous spatial Poisson process. Number of drops in volume \(V\) follows a Poisson distribution

\[ P(N(V) = k) = \frac{e^{-\lambda V} \lambda^k}{k!} \]

- \(\lambda\) is the expected number of raindrops in volume \(V\) and \(P(N(V) = k)\) is the probability of finding \(k\) raindrops in volume \(V\).

- Rain scenario (3D field of raindrops) is created
Estimation of loading

Castorrini et al, Computers and Fluids, 2016:
- FE particle tracking cloud method.
- Turbulent flow modelled.

Fiore, Selig, Wind Engineering, 2015
- Simulation of airborne particle collisions with a 38 m, 1.5 MW horizontal axis wind turbine blade

Amirzadeh, et al J Wind Engnrng Industrial Aerodynamics 2017:
- Taking into account time dependency of water pressure during the contact
- CFD simulations. Equations of conservation of mass and momentum. Impact velocity 100 m/s. Impacts are normal to a rigid smooth surface.

Eisenberg, Laustsen, LEP Protection lifetime prediction model et al, windeurope.org/summit2016

My opinion: due to rough input data, exact numerical solution of complex fluid equations is not justified.
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Impact contact and transient stresses

How it looks like

Bulk waves decay with $1/r$ into the solid and with $1/r^2$ at the surface. Raleigh waves decay at $1/\sqrt{r}$. 
Impact contact and transient stresses

Water hammer equation and modified version

\[ P = \frac{Vp_1 c_1 \rho_1 c_s}{\rho_1 c_1 + \rho_s c_s} \]

P - pressure created during impact, \( \rho_0 \) is the density of the fluid, \( c_0 \) is the speed of sound in the undisturbed liquid and \( V_0 \) is the impact velocity, and \( l \) and \( s \) as subscript refers to liquid and solid bodies, Dear JP, Field JE. J Applied Physics. 1988;63:1015


thin hard elastic coating. Reflection at the coating–substrate interface is taken into account
Impact contact and transient stresses

- FEA of a water droplet impacting thick compliant coatings.
- Deep craters develop in impacted polyurethane coatings which probably alters the evolving water drop shape, substantially.
- Impact by a single water droplet cannot initiate failure for polyurethane coatings.

Amirzadeh, et al J Wind Engnrng Industrial Aerodynamics 2017:
- FE transient stress analysis for various raindrop sizes
- Modelling entire layup structure and only Gelcoat layer with rigid bottom (difference in stresses only 5%)
- Raindrop load defined using VLOAD subroutine
Impact contact and transient stresses


- combined Eulerian/Lagrangian approach
- Explicit Dynamics tool in ANSYS
- Stresses in composite and deformation of droplet modelled


- Lagrangian approach
- Water hammer pressure for initial loading (first stage, the water drop behaves as a compressible body) and Bernoulli’s stagnation pressure (second stage, incompressible fluid behavior)
- thermodynamic states of the water is described by the Mie-Gruneisen equation of state
FE simulations of stress waves in LE

- Ball impact simulations in hyperelastic/elastic laminate. Explicit method.
- FEM/Abaqus of impact onto the coated laminate was developed to study internal transient stresses. The target laminate was modelled using the commonly used Eulerian domain. Water droplet specified in the Lagrangian domain, where the material was not fixed to the mesh but flew through it.
- At the beginning (transient stage of the impact), the highest stress is localised under the contact surface, at the quasi-static stage the high-stress region forms in the depth under the surface. Similarly, rather high shear stresses form at the angle 30° to 45° under the contact surface.
Coupled Eulerian Lagrange simulation of raindrop/surface interaction
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Damage

How it looks like
**Damage: Simple Models**

**Erosion damage at arbitrary angles $E(\alpha)$**

\[
E(\alpha) = g(\alpha)E_{90}
\]

\[
g(\alpha) = (\sin \alpha)^{n_1}(1 + H_v(1 - \sin \alpha))^{n_2}
\]

$g(\alpha)$ - impact angle dependence of normalized erosion at 90°, $H_v$ denotes the material hardness given in GPa, and $n_1$ and $n_2$ are exponents.

Oka YI, Mihara S, Yoshida T. 17th Int Conf Wear of Materials. 2009;267

**Different erosion mechanisms**

- Reactive:
  - (a) direct deformation
  - (b) stress wave propagation
  - (c) lateral outflow jetting
  - (d) hydraulic penetration (Adler, 1979).

**Damage Threshold Velocity (DVT)**

= lowest velocity which could cause damage in the target material.

\[
V_{DT} \approx 1.41 \left( \frac{K_{IC}^2 c_R}{\rho_w^2 c_w^2 d_w} \right)^{1/3}
\]

$V_{DT}$ = DVT, $K_{IC}$ fracture toughness of the target material, $c_R$ the Rayleigh wave velocity on the target material, $\rho_w$ the density of water, $c_w$ the compressional wave speed in water, and $d_w$ is the diameter of the water droplets, Evans AG, ET AL. Impact Damage in Brittle Materials in the Elastic-Plastic Response Regime. Rockwell 1978;361:122-136.

**Nader, Eisenberg, Siemens, LEP Lifetime estimation:**

\[
S = \frac{4\sigma_u(b - 1)}{1 - 2\nu} = \text{erosion strength}
\]

- $\nu$: Poisson’s ratio
- $\sigma_u$: Ultimate tensile strength
- $b$: Wöhler slope
Springer, Yang A model for rain erosion, 1972:

\[ N_i = \frac{8.9}{d^2} \left( \frac{S}{P} \right)^{5.7} \]

= number of impacts until failure

Larger drops cause more damage per impact

- \( d \): Diameter of droplet
- \( S \): Coating Strength
- \( P \): Water Hammer Pressure

Eisenberg, Laustsen, **LEP Protection lifetime prediction model et al, windeurope.org/summit2016**

- non-dimensional number of impacts required until erosion begins

\[ N_i^* = 7 \times 10^{-6} \left( \frac{S}{P} \right)^{5.7} \]

\( S \) is the erosive strength of the material that has been determined through rain erosion testing and \( P \) is the pressure of the water droplet impact.

- rate of damage

\[ \dot{N}_i = \frac{q \cdot V_s \cdot \beta(d)}{8.9 \left( \frac{S}{P} \right)^{5.7}} \]

\( q \) is the number of droplets per cubic meter of air, \( V_s \) is velocity of the material in m/s, \( \beta(d) \) is the impingement frequency as a function of droplet diameter, and \( d \) is the droplet diameter in mm.
Damage

Amirzadeh, et al J Wind Engnrng Industrial Aerodynamics 2017:

- Equivalent stress condition
- Fatigue damage at given point=superposition of damages from individual raindrops

Cortés et al, Manufacturing issues which affect coating erosion performance in wind turbine blades:

- Two wave fronts – into liquid and into coating
- Interface delamination: Cohesive zone modelling of coating-substrate interface

Castorrini et al, Computers and Fluids, 2016:

- Use DVT equation
- Assume that the damage is proportional to the impact force and the number of droplets impacting

\[ \Delta D = \Delta n_w \frac{F_i}{F_D} H \left( \frac{F_i}{F_D} - 1 \right) , \]

Where \( \Delta D \)-damage during the time step \( \Delta t \), \( \Delta n_w \) is the number of droplets impacting during \( \Delta t \), per unit surface area, and \( H(\cdot) \) is the Heaviside step function, \( F_D \) minimum impact force that causes damage to the blade, \( F_i = m_i v_i^2 / d_w \) - impact force of a droplet, \( m_w \) representing the mass of a water droplet, and \( v_i \) its impact velocity.
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Fatigue

H.M. Slot et al, Renewable Energy 80, 2015, Surface fatigue model = removal of particles detached by fatigue arising from cyclic stress variations

Main points:
- Palmgren–Miner rule
- Damage evolution as a function of stress
- Cumulative fatigue damage equation

Amirzadeh, et al J Wind Engnrng Industrial Aerodynamics 2017:
- Miner-Palmer fatigue rule
- Damage accumulation linear (proportional to time)
- Rainflow counting

My opinion: too simple fatigue models (typically, Miner rule) makes it senseless to use very complex rain models as input
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Solutions

Industrial solutions:

- Repair: epoxy putty and a gel coat
- ProBlade Collision Barrier by LM Wind Power
- Arkema KYNAR PVDF-acrylic hybrid emulsion coating
- 3M Polyurethane Coatings, W4600
- Polyurethane Tape (Bergolin, Duromar)
- Enercon two component polyurethane coating system
- Blaid Protective Sheet, by IER Fujikura
- Belzona 1331 and Belzona 1381, erosion resistant coatings based on immiscible blend of a tough ductile phase within a hard epoxy matrix

M. Legault, Wind blades: Progress and challenges, CW, 10/1/2013
Observation

- There is a very simple “default” analytical solution of the problem:

  Water hummer equation for contact pressure
  +
  Hertzian contact problem with cone crack
  +
  Damage model
  +
  Miner rule

- Elements of this simple model chain are often embedded in complex models
Why these models are not enough

- Oversimplified model of fatigue:
  - Miner damage accumulation rule, instead of mechanism based models

\[ \sum_{i=1}^{k} \frac{n_i}{N_i} = C \]
Next steps

- Application to coating development:
  - Models of LEE should lead to new coatings
Conclusions

- There exist a number of good models, from good analytical approximations to complex multistep “all aspects of real life” models.

- Many multistep models allow very complex simulations (turbulent flow, real rain statistics), but use very rough assumptions of other steps.
  - Does it make sense to use very exact models at step 3 if we use rough model at step 7? Errors accumulate.

- The expected output of these models – to design new, better coatings is still far away.
  - Many models have no output to coating development.
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