Automated Scan-to-CFD Pipeline for Damaged Turbine Blades

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01 Motivation & Objectives

- Turbine blades are inspected and analyzed regularly.
- 3D scanning to detect defects is common in aero-engine maintenance, but the path from scan to simulation is not automated.
- Erosion and impact damage reduce aerodynamic performance. Figure 1 and 2 show common damages on blades.
- We propose an end-to-end automated workflow from 3D scanning to the simulation.

PROPOSED WORKFLOW
3D Scan → Geometry Def. → Mesh Def. → Simulation

Objective 1 — Automatic mesh deformation in the AMR library t8code
Objective 2 — Simulation and crack propagation
Objective 3 — End-to-end automation

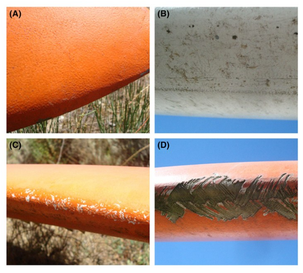


Fig 1 — Rain erosion on the leading edge of wind-turbine blades [1]

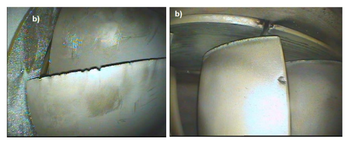


Fig 2 — Damage on an RD-33 engine gas turbine [2]

02 Use Case

The example use case is a damaged aero-engine turbine blade with the corresponding design CAD and a manually reconstructed CAD model, shown in Figure 3.

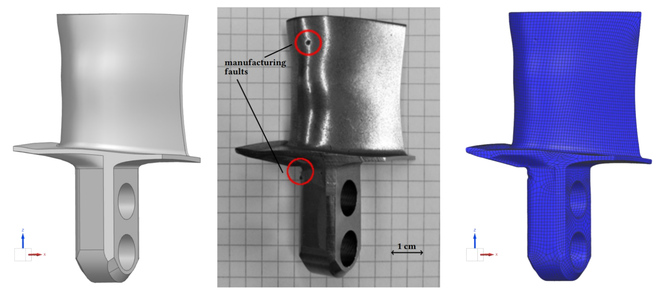


Fig 3 — Left to right: design CAD of an aero-engine turbine blade; damage on a real blade; CAD of the scanned blade [3]

03 3D-Scan



Fig 4 — Registration (alignment) of a 2D design and scan point cloud: RANSAC coarse alignment followed by ICP refinement

Steps for a successful 3D scan

- Calibration
- Orientation
- Multiple scans from different viewpoints
- Scan alignment / registration (Figure 4)
- Cleanup (Figure 5)

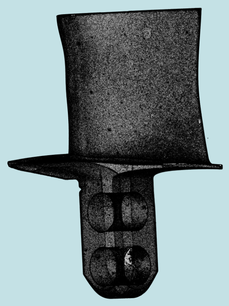
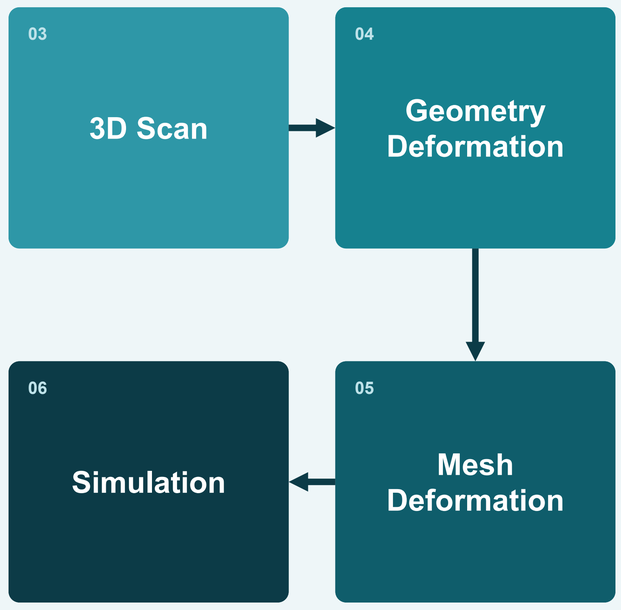


Fig 5 — Registered scan point cloud

SCAN QUALITY
The registration error propagates directly into the deformed mesh, i.e., the quality of the cleanup and alignment processes limit achieving a high accuracy using the whole pipeline.

Workflow

End-to-end automated pipeline



PIPELINE

03 3D-Scan
Registration and alignment of the measured point cloud

04 Geometry Deformation
Morph the design CAD onto the measured shape

05 Mesh Deformation
Deform the CFD mesh directly including the boundary layer

06 Simulation
CFD and crack propagation on the damaged blade

04 Geometry Deformation

Traditional reconstruction [4]

- Point-cloud cleanup
- STL reconstruction incl. optimization and repair
- Interpolation of the STL surface to NURBS surfaces
- Manual and time-consuming process
- The whole process is shown in Figure 6

NURBS deformation [4]

- Deform the NURBS geometry by moving control points
- Calculate new control point position with the least squares method
- Quick geometry-reconstruction solution
  - Enables further analysis of the CAD
  - Acts as baseline for geometry-coupled mesh deformation
- Fast, automatic alternative to manual reconstruction

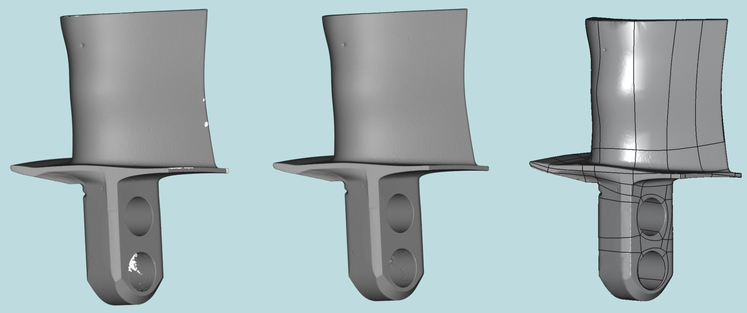


Fig 6 — Geometry of the scanned blade: STL construction, STL optimization and the deformed NURBS model

05 Mesh Deformation

Interpolation-based methods

Radial Basis Function (RBF) [5]

- Preserves mesh quality near the boundary
- Interpolates the movement of the nodes
- Compact (radius-defined) or global variant
- High computational cost

Delaunay Graph Mapping (DGM) [6]

- Mesh is divided into Delaunay elements
- Nodes are assigned to an element
- Graph is moved according to the deformation
- Interpolation is carried out per element
- Not suitable for large deformations or rotations

Delaunay-Graph RBF (DG-RBF) [7]

- Combines the advantages of both methods
- Interpolation carried out with RBF
- Computationally lightweight
- Performs well near the boundary → preserves boundary layers

REQUIREMENT FOR CFD
The deformation has to preserve the boundary layer resolution. The mesh quality near the wall decides whether the CFD result is usable. DG-RBF is, therefore, the current candidate for the t8code implementation.

06 Simulation

CFD and crack propagation

- Preliminary CFD Euler Simulation
- Flow over design CAD in comparison to damaged blade
- Figure 7 shows a comparison of the pressure coefficients and highlights the damaged area

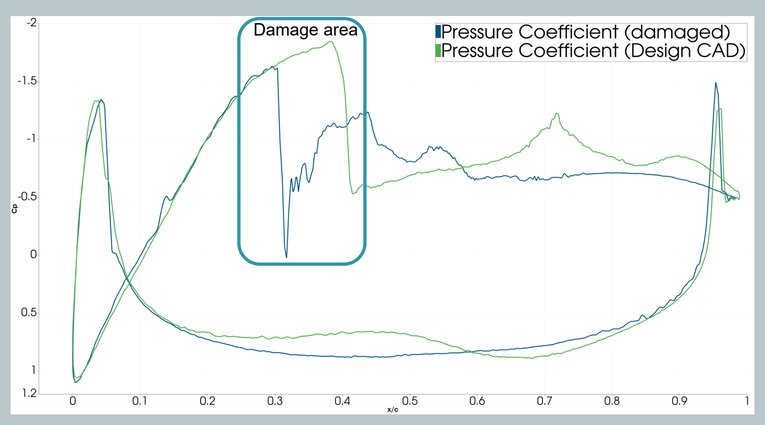


Fig 7 — Results of Euler flow over design cad (green) and damaged blade (blue)

IMPLEMENTED IN

t8code

Parallel adaptive-mesh-refinement library (forest of trees). Mesh Deformation via radial basis functions is currently under development.

- No manual CAD reconstruction and remeshing required
- Scales to large meshes through parallel AMR
- The boundary layer is deformed together with the surface

07 Early Experiments

- Current state in t8code
  - RBF-based mesh deformation for moving components in dynamic AMR
  - Deformation based on coarse input mesh, coupled pressure-defined refinement (Figure 8)

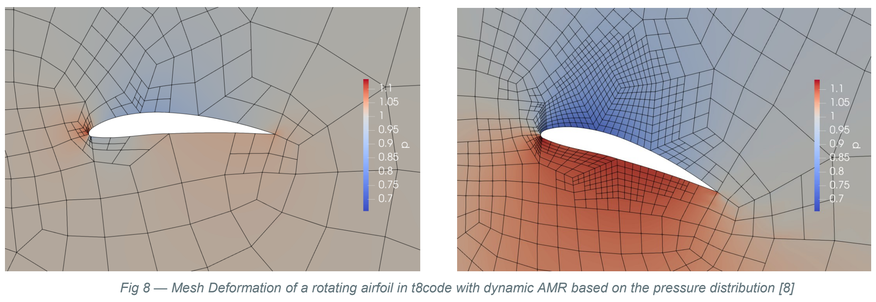


Fig 8 — Mesh Deformation of a rotating airfoil in t8code with dynamic AMR based on the pressure distribution [8]

08 Conclusion & Future Work

→ No complete end-to-end workflow exists yet. Many partial solutions are available, but none has been applied to damaged wind turbine or aero engine blades.

→ Next steps:

→ Compare the mesh-deformation methods in t8code and evaluate the most suitable method for the automated workflow.

→ Boundary-layer-aware deformation is feasible; crack propagation still has to be integrated.

→ Validation of the whole pipeline against a reference CFD simulation on a remeshed geometry.

GOAL **From a 3D scan of a damaged blade to a quantified aerodynamic performance loss, without a single manual CAD or meshing step.**

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