OpenFOAM® Validation of the GAMM Francis Runner using SimpleSRFFOAM

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DoE Project Scope and Objectives

Project Scope:
• Develop an understanding of unsteadiness and resonance effects caused by wicket gate-runner interactions that will allow for efficient hydroturbine operation at off-design conditions

Motivation:
• In order to use hydro plants to improve the effectiveness of new wind and solar generation, the hydro turbines must operate efficiently at lower loads

Project Objectives:
→ 1. Gain proficiency in creating computational grids for turbomachinery applications.
→ 2. Investigate methods for analyzing steady and unsteady flows in turbomachinery and predicting the onset of unsteadiness.
3. Determine the relationship between unsteadiness and resonance effects caused by rotor-stator interactions at off-design conditions.
4. Develop recommendations for turbine design and operation to suppress unsteadiness and improve runner efficiency at off-design conditions.
Three-dimensional cut through the GAMM Francis turbine [2]

GAMM Francis Turbine
(Validation Case)
Background

• Designed and tested at IMHEF-EPFL, Lausanne, Switzerland

• Studied in:

• Comparison computational results:
  ▪ 1998 Gros et al. [3]
  ▪ 2002 Muntean at al. [5]

• Model Parameters
  ▪ Runner Diameter: 0.4 m
  ▪ Specific Speed: 0.5
  ▪ 13 Runner Blades
  ▪ 24 Stay Vanes
  ▪ 24 Guide Vanes
Model Test Data

- Best Efficiency Point (BEP)
  - Efficiency: 92%
  - Flow Rate: 0.372 m³/s
  - Torque: 369.1 Nm
  - Head Loss: 5.98 m
  - Rotation: 52.364 rad/sec

- 4 Off-Design Conditions were measured, but not analyzed in this study

Hill chart for the GAMM Francis turbine: Volume flow coefficient (Ψ), Energy coefficient (φ), Efficiency (η), and Gate angle (α) [2]
Model Test Data (cont.)

- **Time Averaged flow data**
  - B-B’: Inlet plane
  - C-C’: Middle plane
  - D-D’: Outlet plane

- **Problems:**
  - A-A’ and spiral case geometry not available
  - C-C’ available only at BEP

- **Time averaging** of transient data corresponds to circumferential averaging of steady state data

Meridional cross-section through the GAMM Francis turbine [2]
Computational Approach

• **Final Goal**: perform a fully coupled simulation including spiral case, distributor, runner, diffusor, and draft tube
  - Steady-State Calculations
    - Multiple rotating reference frames (MRF)
    - MixingPlane interfaces (under development)
  - Transient Calculations
    - Moving/Dynamic mesh
    - Sliding mesh interfaces

• Segregated Approach: analyze portions of turbine separately and loosely couple the steady-state results
  - Rotating reference frame only used in runner section (SRF)
  - Circumferential average flow profiles are passed to next down stream section
Computational Approach

- **Segregated Approach**: analyze portions of turbine separately and loosely couple the steady-state results
  - Rotating reference frame (SRF) used in runner section
  - Circumferential average flow profiles are passed from distributor to runner
GAMM Distributor
Distributor Analysis

• Mesh
  ▪ Coarse mesh: 350,000 Cells
  ▪ Fine mesh: 1,500,000 Cells

• Boundary Conditions
  ▪ Inlet: Uniform radial and circumferential velocity
    • Recommended in 1995 ERCOFTAC Seminar [2]
    →libCylindricalInletVelocity (A. Wouden)
    • Accurate Inlet profile or spiral case geometry not available
  ▪ Outlet: Fixed value pressure

• Post-processing
  ▪ Velocity profiles: SampleDict, Fortran, and Gnuplot
Geometry Overview

Comparison of actual geometry (red) to computational domain (green)

– Drawing not to scale

Computational Domain

Actual Geometry
Distributor Vanes – Coarse Mesh

- Mesh created using Gridpro
- 15 degree periodicity
- Cell Count: 347,000
- Target $y^+$: 50 (Wall Functions)

Isometric and detailed view of distributor vane passage with coarse mesh. Images generated using Pointwise®
Distributor Vanes – Coarse Mesh (cont.)

Velocity contour of distributor vanes at axial mid-plane

Note: Wake from guide vane is preserved by cyclic boundary condition

- Solver: simpleFoam
- Uniform inlet velocity (29 deg. swirl)
  - \( U_r = 1.2335 \, \text{m/s} \)
  - \( U_\theta = 2.2252 \, \text{m/s} \)
- Turbulence Model: K-\( \Omega \)
  - Turbulence intensity: 5%
  - Length scale: 1/3 inlet height
- \( y^+ \) average: 60
Distributor Vanes – Coarse Mesh (cont.)

Circumferentially averaged radial, tangential, and axial velocity profiles with comparison to experimental measurements using a coarse mesh at B-B’

- Relatively good agreement with experiment
- Discrepancies may result due to
  - Poorly resolved boundary layers
  - Non-uniform axial inlet
  - Upstream runner effects
Distributor Vanes – Fine Mesh

- Mesh created using **Gridpro** and modified using **Pointwise®**
- Increased axial resolution
- Cell Count: 1,560,000
- Target $y^+$: 1 (Resolved Sublayer)

Fine Mesh

Coarse Mesh
Distributor Vanes – Fine Mesh (cont.)

- Improvement over coarse mesh
- Poor agreement in radial velocity
  - Most probable cause of error is the non-uniform axial inlet

Circumferentially averaged radial, tangential, and axial velocity profiles with comparison to experimental measurements using a fine mesh at B-B’

![Graph showing velocity profiles](image_url)
GAMM Runner
Runner Analysis

• Mesh
  ▪ Structured mesh: 900,000 Cells
  ▪ Hybrid mesh: 800,000 Cells

• Boundary Condition
  ▪ Inlet: Axi-symmetric profile of experimental velocity values
    → profile1DfixedValue (Turbomachinery SIG)
  ▪ Outlet: Fixed value pressure

• Post-processing
  ▪ Velocity profiles: MapFields, SampleDict, Fortran, and Gnuplot
  ▪ Performance: TurbinePerformance library
    • modification to libturboPerformance (Turbomachinery SIG)
Post-processing Tools

- Map solution to cut-planes
  - mapFields
- Convert mapped solution to cylindrical coordinates
  - convertToCylindrical (B. Lewis)
- Extract cylindrical data
  - sample
- Circumferentially average the sampled data
  - averageCirc.f90 (Fortran Code)
- Compare averaged solution to experiment
  - gnuplot <scriptName>
Runner – Structured Mesh

Detailed view of structured mesh where runner meets the crown

- Mesh created using Pointwise®
- 27.69 degree periodicity
- Cell Count:
  - Runner: 600,000
  - Diffusor: 300,000
- Target y+: 50 (Wall Functions)
- Solver: simpleSRFFoam
- Turbulence Model: K-OmegaSST
Runner – Structured Mesh (cont.)

- Continuity is lost after 150 iterations
- Why?

Residuals for all solution variables with respect to iteration number

Iteration selected for post-processing

Residuals

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Variables:
- Ux
- Uy
- Uz
- Omega
- K
- P
Runner – Structured Mesh (cont.)

Circumferentially averaged meridional, tangential, and axial velocity profiles with comparison to experimental at C-C’ at iteration 100

At Iteration 100:
- Efficiency: 119% (92%)
- Torque: 1507.7 Nm (369.1 Nm)
- Head: 19.5 m (5.98 m)

Experimental values in green
Runner – Hybrid Mesh

- Mesh created using **Pointwise**®
- 27.69 degree periodicity
- Cell Count:
  - Runner: 700,000
  - Diffusor: 100,000
- Target y+: 50 (Wall Functions)
- No boundary layer on band and crown
  - Slip walls

Detailed view of hybrid mesh where runner meets the crown
Runner – Hybrid Mesh (cont.)

- Efficiency: 95.8% (92 %)
- Torque: 352.3 Nm (369.1 Nm)
- Head: 5.71 m (5.98 m)

Experimental values in green

Circumferentially averaged meridional, tangential, and axial velocity profiles with comparison to experimental at C-C’
Runner – Hybrid Mesh (cont.)

Circumferentially averaged radial, tangential, and axial velocity profiles with comparison to experimental at D-D’

- Efficiency: 95.8% (92 %)
- Torque: 352.3 Nm (369.1 Nm)
- Head: 5.71 m (5.98 m)

Experimental values in green

Outlet Profile

Circumferentially averaged radial, tangential, and axial velocity profiles with comparison to experimental at D-D’
Summary

• Uniform axial velocity at the distributor inlet is a reasonable approximation, but does not completely predict the correct velocity distribution at the runner inlet plane.

• Only minor improvement in distributor flow was observed with resolved viscous sub-layers.

• Runner analysis ... to be continued.

• Fully coupled runner and distributor simulations needed to accurately analyze rotor-stator interactions (maybe next year).
Questions?

Runner Inlet Profile

Middle Profile

Measured Ur
Measured Utheta
Measured Uz

Measured Um
Measured Utheta
Measured Uz