Two-way fluid structure interaction of medium-sized heliostats using system coupling on 2D and 3D models

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• Introduction
• Getting the wind right
• Solving for mean flow
• How to do Fluid-Structure Interaction (FSI)
• Modal analysis
• 2D and 3D URANS
• 2D 2-way FSI
• Scale Resolving Simulations
• 1-way FSI with 3D SRS
Introduction

- Trends show shift to renewable energy sector, especially solar energy
- CSP technology has advantage of storing heat during times of no sun.
- Central Receivers consist of an array of heliostats that reflect solar radiation to a central receiver.
- Designs may differ significantly
- Heliostats make up large portion of capital cost
- Optimal design can reduce overall cost of electricity produced
- Need to analyse conditions experienced by heliostat accurately
Atmospheric Boundary Layer (ABL) inlet boundary condition

- Characterize the ABL
- Inlet profiles and how to sustain them (Homogeneous-inlet, approach, incident profiles)
- Dense mesh near surface
- roughness length < roughness height
- log law type not a power law
- Equations used to match wind tunnel (Peterka (1986)) velocity or turbulence intensity profile using least-squares approach

\[ k = \frac{U_{ABL}^*}{\sqrt{C_\mu}}, \quad \varepsilon(Z) = \frac{U_{ABL}^*}{\kappa Z}, \quad I_u(Z) = \frac{\sqrt{2}k}{U(Z)} \]

\[ \frac{u(Z)}{u_{Ref}} = \ln \left( \frac{Z}{Z_0} \right) \quad \ln \left( \frac{Z_{Ref}}{Z_0} \right) \]
CFD model of LH-2

- Block structured mesh of domain before adaption with roughly 4.7mil cells for RANS
RANS flow patterns for LH-2 heliostat

- Maximum torque tube moment case (60° elevation)
Validation of mean loads on LH-2 heliostat

- The LH-2 heliostat from the Brightsource Ivanpah project
- 173 500 heliostats in three power plants
- RWDI performed wind tunnel tests and RANS CFD (Huss, S. (2011))
- CFD validation comparing Realizable k-ε (RKE)
- Better comparison with experiment than RDWI CFD
- Identify two cases: Maximum drag and Maximum torque tube moment

• WT=wind tunnel
• CFD=present CFD
How to do FSI?

• Choose validation case to sort out System coupling
• Sort out CFD modelling
  – RANS mean flow to find cases to be evaluated
  – Unsteady RANS (URANS) for transient (sufficient?)
  – Scale Resolving Simulation (SRS) for capturing upstream turbulence as well as vortex shedding
• Understand structural response
  – Modal analysis to identify modes and frequencies at risk of excitation
  – Transient structural model with external data (from CFD)
• System coupling
  – 1-way FSI
  – 2-way FSI
FSI Validation using test case from literature*

- 2-way FSI validation ANSYS workbench system coupling
- 2D fixed sphere, slightly off centre, flexible beam attached to the rear as seen below
- FSI on 3D geometry so 1 cell thick domain was used
- Beam displacement at point A as well as the FFT

FSI Validation (cont.)

Displacement (laminar case)

- benchmark is given as 1.953Hz - exactly the same as attained in ANSYS Mechanical
- lift coefficient benchmark is given as 4.99Hz and the FFT gives 4.4Hz
- Successful validation

FFT of displacement

Velocity magnitude contours
FSI Validation (cont.)

- Turbulent LES FSI validation was carried using Breuer, M (2010) results for comparison
- Using a Fluid density 1000 times smaller, the FFT gives a Strouhal number of 0.175 compared to 0.172 for a rigid body case (Breuer)
- Turbulent FSI validation is successful
LH-2 Modal analysis

- A modal analysis was performed of the LH-2
- Possible resonance failure of the heliostat given input loads
- Matty (1979) (flat plate experiments): vortex-shedding frequency could be roughly 1.4Hz to 2Hz for a velocity of 10m/s
- Vortex shedding may excite the natural frequencies
- Case for 2-way fluid structure interaction
LH2 2-way FSI

- 2-way FSI using URANS in ANSYS system coupling has been performed on various fluid mesh sizes ranging from 1 to 10 mil
- The ANSYS workbench setup is seen below for full 2-way FSI of the LH-2 heliostat.
LH2 2-way FSI using 3D URANS

- URANS is incapable of correct transient flow behaviour (vortex shedding) for this 3D geometry (3D FSI not successful using URANS)
- Smaller cases run on 8 cores for 5 days.
- 10 million cell case run on 16 cores for 25 days
- System coupling seemed to be buggy (version 16)
- At the time, not available on the CHPC to do interactive system coupling of Fluent + Mechanical on multiple processors
- What about 2D models?
2D URANS Flat plate (Matty)

• 2-D URANS validation of the Matty (1979) vortex shedding wind tunnel experiments was conducted
• The Matty Strouhal number is $St=0.15$: this equates to 14.763Hz.
• An FFT of the URANS produces 14.53Hz, a 1.5% error.
• The resulting Strouhal number is $St=0.147$. 
2D URANS – LH-2 heliostat

- 2-D URANS performed on the LH-2 heliostat
- Expected vortex shedding frequency from Matty (1979) is 0.467Hz from the St=0.15
- FFT of the drag coefficient signal, frequency of 0.505Hz
- This is a 7% error, 2D URANS is successful in modelling vortex shedding for this geometry.

TKE only in wake due to RANS assumption
2D URANS 2-way FSI

- 2-D 2-way FSI performed with System Coupling
- Drag coefficient frequency of 0.53Hz and 1.06Hz found with FFT

Cd FFT
2D URANS 2-way FSI

- Mechanical results show a 0.53Hz signal, followed by a 1.07Hz signal and a 1.5Hz signal.
- Graph showing the displacement of the top mirror vertex
- 2D results not necessarily comparable to 3D but do illustrate the potential increase in structural model frequency response.

Displacement of top mirror vertex FFT

3rd peak not seen in drag coefficient
Scale-Resolving Simulation (SRS) CFD

- SBES CFD simulation conducted on LH-2 (one of hybrid LES-RANS models in Fluent incorporating SST k-ω)
- Same domain as RANS validation with increase of mesh from 4.8mil to 28mil cells
- Peterka (1986) ABL profiles implemented with Vortex method (1825 vortices) at inlet
- SST k-ω RANS model with the WALE sub-grid scale model
- Time-step of 0.0003 seconds run at CHPC
- Approx 48 hours for 1 second on 240 cores
- Total 20 seconds run for both 0° (maximum drag) and 60° (maximum torque tube moment) cases
SRS CFD

turbulent structures

Iso-Surfaces of Q-criterion coloured by velocity magnitude of SBES, a) Q=100 s$^{-2}$ b) Q=1000 s$^{-2}$
SRS CFD: 0° compared to 60°

Iso-Surfaces of Q-criterion coloured by velocity magnitude of SBES, Q=500 s⁻²
Checking the inertial sub-range energy cascade...

- SBES turbulent energy spectrum of point just upstream of heliostat comparable to Kolmogorov theory
- LES able to model turbulence down to SGS in the inertial sub-range
SRS CFD Results: 0° Drag coefficient and velocity

- Average value compared to wind tunnel results (RWDI)
- Possibly further run time required

Spikes due to Vortex method at inlet (physical?)

Main vortex shedding frequency
SRS CFD Results: 60° Drag, lift and moment coefficients

- Average values compared to wind tunnel results (RWDI)
SRS 1-way FSI

- Pressure files were written from the SBES CFD simulation on the LH-2 faces
- Using External data the pressure is mapped to an ANSYS Mechanical Transient Structural component
External data (imported pressure – one file each 0.0003 sec)

Front (2.97sec)  Back (2.97sec)
Total deformation and equivalent stress traces for 3sec
Main component of FFT at 2.69Hz
Corresponds to 3\textsuperscript{rd} mode being excited
Reaction force at pylon base
Conclusions

• FSI easy implement in ANSYS Workbench using System Coupling
• CFD of flow over heliostats is not easy:
  – RANS only useful for mean loads
  – 3D URANS does not capture correct wake behaviour
  – 3D SRS very costly but valuable
• 2-way coupling only feasible for 2D
• 1-way coupling results need further investigation
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