APPLICATION OF STAR-CCM+ TO TURBOCHARGER MODELING AT BORGWARNER TURBO SYSTEMS

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This presentation will focus on how STAR-CCM+ has helped BorgWarner Turbo Systems in the design and development of turbochargers.

BorgWarner Turbo Systems have been benefiting from the capabilities of STAR-CCM+ since version 2.02 (2006). The first calculation undertaken was a Conjugate Heat Transfer (CHT) analysis of a full turbocharger turbine housing.

Numerous simulations have now been undertaken and for today’s presentation I will present some of these to give you a flavour of how STAR-CCM+ is applied in turbocharger design and development.
A turbocharger is coupled to the inlet and exhaust manifolds of a reciprocating engine.

At inlet a compressor, usually of radial inflow type, compresses the incoming air to raise its density allowing more fuel to be burnt in the cylinder for a given stoichiometric ratio.

In the exhaust manifold a turbine utilises the waste energy in the exhaust flow to drive the compressor.

Turbochargers are typically single shaft and single stage but some more modern versions have two stages to reduce ‘turbo lag’.

Almost all turbochargers in the automotive market are directly coupled to the exhaust manifold and hence are subjected to the pressure waves exiting the cylinders. This is a pulse turbocharging system.
Borgwarner Corporate Overview

- Borgwarner are a recognized world leader in advanced products and technologies for powertrain and system components.
- Borgwarner employs 16,000 worldwide with annual sales around $4 billion.
- Borgwarner Turbo Systems, a division of Borgwarner, is a leading supplier of innovative turbocharging systems and a component partner to the automotive industry worldwide.
- The supply turbochargers in the engine output range of 20-1000 kW.
A turbocharger has to operate across a wide range of engine operating conditions. This poses some unique challenges to the designer to ensure performance and reliability.

I will present some of the areas where CFD has helped address these challenges:

- A virtual compressor map and investigation of installation effects
- Simulating the aerodynamics of turbine guide vanes
- Thermal analysis of a turbine housing
- Transient conjugate heat transfer simulations of turbine housing
The turbocharger compressor has to deliver a boost pressure across a wide range of operating conditions.

The compressor map is a critical element to matching the turbocharger to an engine and is a key design parameter.

Accurate prediction of the compressor map is an important requirement when applying CFD to compressor blade design.

The work presented here was a validation exercise comparing multiple mass flow rates and pressure ratios at a single rotational speed against experimental data.
Compressor map
Geometry

- This is a single stage radial impeller with a splitter blade.
- The compressor is coupled to a nozzle-less volute.
- The diameter is 70mm and it operates at around 100,000 giving a tip speed of 360 m/s.
Computational Domain

- The domain consists of one passage for the impeller and the full 360 degree model of the volute.
- Periodic boundaries are used for the impeller and the impeller and volute are coupled using a mixing plane interface. This assumes circumferential averaging of the flow field between the planes.
- There is a small slot near the inlet at the blade tip which helps increase the surge and choke margin.
Volume Mesh: Volute

Polyhedral volume mesh generated for computational domain

3.6 M polyhedral cells with 6 body-fitted prism layers
Volume mesh: turbine

- Yellow surfaces represent interfaces of the rotating to static regions
- One blade passage modeled - View shows fully revolved region
- ~1.1 M polyhedral cells per blade passage
Physics and Boundary Conditions

- **Physics:**
  - Steady-State,
  - Ideal Gas
  - k-w SST Turbulence model w/ “All y+” wall treatment
  - Coupled solver
  - Moving Reference Frame (MRF)

- **Boundary conditions:**
  - Stagnation inlet and exit static pressure
  - Analysis procedure to evaluate the compressor map:
    - The exit static pressure is modified in stages and a new analysis is run to determine the mass flow rate
    - The exit pressure is adjusted (10) from the surge to the choke limit to give a constant speed compressor performance curve
Compressor Map (constant rotational speed)

Mass Flow Rate - Pressure Ratio Map (t-t)

Mass Flow Rate - Efficiency Map (t-t)

Total time from CAD import to results: ~4 hours man time
Typical Turbomachinery Post Processing

Blade to Blade
Meridional
Streamwise

Velocity
Entropy
Installation Effects on Compressor Performance

- Space restrictions in the under hood necessitate complex pipe work feeding the compressor.
- This can lead to non-uniform inflow conditions to the compressor thus degrading performance.
- An extension of a primary gas path analysis is inclusion of upstream duct work to investigate this degradation of performance.
- Example: connecting pipe work between a low and high pressure compressor in a dual sequential turbocharger.
Flow quantities at the inlet to the HP Compressor

Velocity

Sign convention

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Modern turbochargers include variable guide vanes on the turbine stage.

The guide vanes vary the inlet flow angle to the turbine for according to the engine operating condition in order to maintain a uniform inlet flow angle (and minimize incidence angle losses).

To determine the correct orientation of the guide vanes, STAR-CCM+ was employed to simulate the flow field through the vanes and into the turbine wheel at various guide vane angles.

Analysis of guide vane positions (i.e. clocking locations), vane angles and radial vane pivot positions.
Geometry

- The turbine housing geometry is shown on the right.
- The variable guide vanes sit in the volute just upstream of the turbine leading edge.
- The vanes each have their own pivot but are connected to a ring, which is in turn connected to a hydraulic actuator.
- This moves according to the operating condition of the engine to provide uniform flow guidance into the turbine.
The computational domain consisted of the volute inlet, all guide vanes and the complete turbine wheel.

Polyhedral mesh with
- Local refinement,
- Focused, prismatic cells in the wall layer,

\(~2.7\) million cells
32.2-Degree Vane Opening, Nominal Position

Mach Number – Axial Section
Mach Number – Vane midspan -Relative frame
Vane Pressure –Pressure side
In-Plane Relative Velocity – Vane Midspan
Static Pressure-Vane Midspan
Vane Pressure – Suction side
Different Vane Angles

Mach Number – Vane midspan
-Relative frame (2 GV)

• In STAR-CCM+ the vanes can be rotated and the mesh reconstructed

• Previous solution is mapped onto the new grid

• Analysis is continued

Mach Number – Vane midspan
-Relative frame (10 GV)

Mach Number – Vane midspan
-Relative frame (63.3 GV)
Thermal Modeling of Turbochargers

- The turbocharger is typically connected directly to the engine and is thus subjected to high temperatures, both from the exhaust flow entering the turbine but also externally from engine mounting points.
- Thermal simulations at various operating conditions have been performed to investigate the temperature distribution through the turbine and bearing housing.
- In addition, thermal heat up and cool down transient calculations have been performed from part to full load conditions to investigate
  - Hot spots due to changing operating conditions, e.g. waste gate opening
  - Thermal soak back into bearing housing and (bearing) oil
  - Transient stress analysis for thermal cycles to failure
Example

- One of the first simulations performed using STAR-CCM+ for BorgWarner Turbo Systems was a thermal analysis of a sequential twin turbocharger.

- The turbocharger has two stages, a low pressure and a high pressure stage, connected in sequence with a valve diverting exhaust flow between the two.

- One stage is used exclusively at the low engine rpm’s of the engine and the other stage for the higher rpm’s.
  - This significantly reduces ‘turbocharger lag’.

- These operating conditions posed new and unknown thermal conditions.
Geometry: Sequential twin turbocharger

- Low Pressure (LP) stage
- High Pressure (HP) stage
- Diverter valve
Geometry

Diverter valve
Thermal Modeling: Simulations Performed

- Steady state thermal calculations were undertaken at part and full load conditions to determine the temperature distribution as well as serve as initial conditions for thermal transient calculations.

- Part load represented an engine coasting condition, full load is full engine rpm and full engine load.

- Thermal transient calculations simulating the thermal heat up and cool down of the turbine stage between part and full load.
Volume Mesh

- The computational mesh was constructed by merge/imprinting components and using split-by-surface topology to identify the different regions and automatically create interfaces
- Fully conformal mesh
- 4.5 million polyhedral cells
Volumes Mesh: Individual Parts

- HP Bearing Housing
- HP Bypass Valve
- HP Housing
- HP Turbine Wheel and Shaft
- IGV Back Plate and Guide Vanes
- IGV Front Plate
Steady State Conjugate Heat Transfer Analysis Full Load

- Steady state CHT analysis results of turbine stage at **full load** condition
- Steady, turbulent, compressible flow with temperature dependent viscosity and properties representative of an exhaust gas
- Solid components represented by their respective material type with temperature dependent properties
- The rotational effects on the fluid for the two turbine wheels was modeled using a moving reference frame (MRF) approach
- At full load, effect of bypass and wastegate valves, which control mass flow split between LP and HP stages was represented as a porous medium with coefficients adjusted to meet the boundary conditions
- The HP turbine receives only a small percentage of mass flow
Fluid Flow Results

- Pressure
- Choked
- Wastegate
- Impingement
- Velocity - near wastegate
Temperature Results

FULL LOAD
CONJUGATE HEAT TRANSFER ANALYSIS (STEADY STATE)
Cross section HP Stage

FULL LOAD
CONJUGATE HEAT TRANSFER ANALYSIS (STEADY STATE)
Temperature results: components

- HP Housing
- IGV Back Plate and Guide Vanes
- LP Housing
- LP Turbine Wheel and Shaft
- HP Bearing Housing
Following steady state CHT calculations, work was extended to transient heat up and cool down simulations

- Calculations from steady state part and full load analyses used as initial conditions for the thermal cycles
- Heating Cycle:
  - Fluid @ full load, Solid @ part load
- Cooling Cycle:
  - Fluid @ part load, Solid @ full load
- The analyses were run with a varying time step to capture the high temporal temperature gradients early in the analysis and for computational efficiency later in the analysis:
  - 0<time<15sec, time step = 0.5 sec
  - 15<time<80sec, time step = 1.0 sec,
  - 80<time<150sec, time step = 2.0 sec
  - 150<time<(end), time step = 4.0 sec
Heating Cycle

Time = 4 secs

Time = 18 secs

Time = 42 secs

Time = 105 secs

Time = 355 secs
Monitoring Temperature

Mon 4
Mon 24
Mon 45
Mon 39

Heating
Cooling

Temperature (K)

Time (sec)

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Cooling Cycle

Time = 4 secs

Time = 18 secs

Time = 42 secs

Time = 102 secs

Time = 352 secs
Borgwarner Turbo Systems have been successfully applying STAR-CCM+ to turbocharger design since v.2.02 in the following areas.

- Compressor performance maps
- Effects of on engine installation pipe work
- Turbine guide vane analysis
- Thermal conjugate heat transfer analysis
  » Steady state full and part load conditions
  » Transient heat up and cool down simulations
  » Thermal soak back into the bearing housing and oil
  » Thermal transient stress calculations through data mapping to an FEA grid