Analyses guided optimization of wide range and high efficiency turbocharger compressor

H. Sun, D. Hanna, Ford Motor Co.
L. Hu, J. Zhang, Ming-Chia Lai, Wayne State Univ.
E. Krivitzky, C. Osborne, ConceptsNREC

NETL Project Manager: Ralph Nine
DOE Contract: DE-FC26-07-NT43280
Single turbo?

The focus is to move high efficiency island on a compressor map to cover customer driving cycles.
Numerical simulation is the key to guide the design iterations!!
Validation of compressor model

- Compressor with arbitrary blades;
  - 6 main/splitter blades
- Low solidity vaned diffuser with different setting angle
  - Solidity=0.7 with 7 vanes

- Test at 108krpm, vaneless diffuser also tested.
Numerical model

- Mesh: Auto/Grid, Structure O-4H mesh, $Y^+ \approx 3$
- Solver: Fine/Turbo Euranus
- Turbulence Model: Spalart-Allmaras
- R/S interface: non reflecting BC
- Boundary Condition
  - Inlet: $T_t$, $P_t$, flow direction
  - Outlet: $P_s$/ target mass flow
Test of Compressor Performance

- Two setting angle of diffuser vane and vaneless diffuser

- Improved efficiency at low end;
- Surge extension with increase of setting angle;
- Penalty of choke flow rate: further reduction of setting angle would possibly improve the choke flow.
- Variable vaned diffuser is the best.
Numerical simulation of compressor performance

- Reduction of setting angle is included: 61° setting angle

- Increase of setting angle, compressor surge could be extended;
- Improved efficiency especially at low end;
- Reduction of setting angle could improve performance near choke;

Compared with test data, CFD prediction matches well with the test data except the near surge areas.
Transient simulation is needed for surge prediction

- Unsteady simulation: investigate how the vaned diffuser affects the compressor surge flow rate;
- Sliding mesh-diffuser vane was scaled to 6 vanes;
- Same BC, mesh applied @ 61°,67° vaned diffuser;
- Impeller+diffuser simulated.
Unsteady CFD analysis - pressure oscillation

- Fluctuation of Ps at leading edge of impeller:

- Both Ps oscillations are visible;
- With 61° vaned diffuser, more fluctuation in Ps
- The impeller with 61° vaned diffuser is less stable
Unsteady CFD analysis - pressure oscillation

- They differ in the frequency domain:

- Two frequencies: 10.8kHz (blade passing frequency)
- 450Hz - related to the stall phenomenon.
- 61° vaned diffuser: the magnitude at 450Hz is ~3 times that of 67° vaned diffuser, i.e. impeller matched with 61° vaned diffuser is less stable.
Unsteady CFD analysis - vorticity

- Flow field investigation at 5 time instants, 95% Spanwise:

- 61° vaned diffuser: the high vorticity gradually spills out of the impeller passage, unstable - indicating impeller stall;

- 67° vaned diffuser: the high vorticity stays inside the impeller passage, relatively stable.

- Compressor with 67° vaned diffuser is more stable.
Unsteady CFD analysis - entropy

- Flow field investigation@5 time instants, 95% Spanwise:

- Entropy distribution:
  - $61^\circ$ vaned diffuser: high entropy area gradually spills out of the impeller passage, entropy increased – impeller unstable;
  - $67^\circ$ vaned diffuser: more stable – increased diffuser vane angle is able to stabilize impeller flow.
CFD to guide optimization of compressor casing treatment

- No casing treatment
- Lean forward
- Lean backward
- Lean backward w/ wider slot
Optimization of casing treatment can extend flow range/surge margin without compromising efficiency.
Conclusions

- CFD simulation tool (Numeca) has been demonstrated to be very effective to guide the compressor optimization (the compressor went through 18 design iterations and only 4 designs went to hardware build/test);
- The accuracy of CFD tool has been validated in steady state and transient simulations for both vaned and vaneless compressors;
- Variable geometry compressor can extend the flow range dramatically but may have reduced peak efficiencies;
- Optimization of compressor casing treatment shows the potential of improvement in both surge margin and flow capacity without compromising of efficiency.