Thermal Analysis of HD Diesel Engine Exhaust Manifold using CFD Coupling

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Outline

- Introduction
- CAE Coupling Methodologies (3 methods)
- Thermal Camera Results
- Conclusion
- Q&A
Company Overview

- Ford Otosan is the leading company of Turkish Automotive Industry, equally owned by Ford Motor Company and Koc Holding.
- The company operates at 5 facilities in Turkey.
  - Kocaeli Plant
  - Inonu Plant
  - Yenikoy Plant,
  - Kartal Parts and Distribution Center,
  - Sancaktepe Engineering Center

Transit

Transit/Tourneo Courier

Ford Cargo Trucks

Sancaktepe Engineering Center

Ecotorq 13L/9L
EU3-EU5-EU6
Introduction

Aim:
• to obtain the accurate temperature distribution of exhaust manifold
• to model the transient warm up period of Heavy Duty (HD) EU6 exhaust manifold

Objective & Method:
• to develop more accurate and robust CAE methodology (CFD-FE Coupling)
• Exhaust manifold system is a typical multiphysics problem where there is a strong interaction between the fluid and solid domains

The Challenge:
• CFD analysis is run as transient. Since the gas flow inside the exhaust manifold has pulsating behaviour, very small time steps must be used to get the fluid solver converged (about 1e-5 sec.), however with this time step, modelling the entire warmup period (600 sec.) using conjugate approach is not feasible, which takes several months to run. So, an alternative approach cosimulation method is tried.

Conjugate approach solves the temperature field of the structure simultaneously with the fluid flow, and hence, eliminates the need to define thermal boundary conditions on structure-fluid interface (i.e. iterative data exchange process between CFD & FE is avoided)
1st Method

STAR-CCM+® & Abaqus Sequential Coupling
To assess the durability of the manifold structure:
- thermal analyses were carried out to predict the temperature distribution of manifold which is required by the subsequent structural analysis

CFD and FE analyses are effectively used to drive the exhaust manifold design.

Data exchange which is a tedious process is handled automatically by the Java scripts developed in house.
Modelling

- The analyses were conducted @ rated power condition
- The CA resolved boundary conditions at the inlets and outlet were supplied by 1D CFD engine performance analyses
- 1 engine cycle is 720°CA
- Each CFD run is conducted for 3 engine cycles (2160 ° CA), and the 3rd engine cycle thermal load data is time averaged and mapped onto the interface of FE model.
- Each FE model is run for 600sec., which is the warm up period.

Mass Flow Rates obtained from 1D Engine Performance Analysis (Inlets&outlets)
Modelling:
• Trimmed elements are used (about 300k)
• STAR-CCM+ 9.06 is used as mesher and solver

Assumptions:
• Transient analysis (pulsating flow)
• Mass Flow Inlet was defined at the inlet boundaries
• Pressure was defined at the outlet boundary
• The flow was assumed as compressible
• High k-e turb.model with high y+ wall function
• Time dependant boundary conditions were provided by 1D CFD
• Time step size is 1.0e-5 sec.
The solid model contains:

• Exhaust Manifold
• Gasket
• Bolts
• Studs
• Head (for stiffness representation)
Simple Time Averaging vs. Weighted Avg.

- For Heat Tranfer Coefficient (HTC) distribution necessary for FE thermal analysis; **standard averaging method** is used (over 720°CA)

\[
HTC_i = \frac{\sum_{1}^{720} HTC_i}{720}
\]

- For gas side HTC reference temperature distribution necessary for FE thermal analysis; **weighted averaging method** is used

\[
\bar{T}_i = \frac{\sum_{1}^{720} T_i \times HTC_i}{720 \times HTC_i}
\]

\[
\bar{T}_i = \frac{\sum_{1}^{720} T_i}{720}
\]

- The affect of using standard averaging vs. weighted averaging for the gas side HTC reference temperature on the interface convection thermal loading was assessed and shown leading to significant differences in the results

CA: Crank Angle
Negligible change after 2nd iteration

**Time Avg. Local HTC [W/m²K] over 720CA**

**HTC**: Heat Transfer Coefficient

**CA**: Crank Angle
The iterative loop starts with STAR-CCM+ run assuming uniform wall temperature identical with Abaqus initialisation temperature.

- Slight change after 3rd iteration
- Heavily affected by wall temperature distribution
Interface Temperature [°C]

- Negligible change after 3rd iteration
Manifold Temperature [C]

iteration 1

iteration 2

iteration 3

iteration 4

iteration 5

Slight change after 3rd iteration

K

K+300

Manifold Temperature [C]

iteration 1

iteration 2

iteration 3

iteration 4

iteration 5

Slight change after 3rd iteration

K

K+300
• the data exchange process and all STAR-CCM+ & Abaqus runs are handled by the inhouse developed Java scripts.

• 5 iterations (going back & forth between STAR-CCM+ & Abaqus) took ~ 2 days (with 16 cpus for STAR-CCM+ runs, and 32 cpus for Abaqus runs)

• Results show that at least 3 iterations need to be done to achieve convergence in temperature
2nd Method
STAR-CCM+ & STAR-CCM+ Cosimulation
STAR-CCM+ - STAR-CCM+ CoSimulation Method (transient)

- STAR-CCM+ - STAR-CCM+ cosimulation method enables using different time steps for the solid and fluid domains.
- One CCM file, containing the fluid domain (transient) – (300k trim cells)
- One CCM file, containing the solid domain (transient) – (2000k poly cells)
- Iterative approach between STAR-CCM+ & STAR-CCM+
- Thermal load data is exchanged between Fluid and Solid Domains at the interface; every 5 time steps.

- Cosimulation requires large number of data exchange; 5333 times -> to achieve high accuracy

Run for 40 engine cycles
Timestep: 1.0e-5 sec.

Run for 600 sec.
Timestep: 0.1125 sec.
Temperature Results [C]
HTC [W/m2K] and Gas Temperature [°C]
Sensitivity Study

- Sensitivity study is carried out to assess the effect of following parameters on the results; (coupling of one engine cycle with 600 sec. warmup period)
- **Fluid domain is meshed with polyhedral cells (2000k poly cells)**
- **Exchange frequency between fluid and solid domains is increased (267 times vs. 1333 times)**
- **Solid domain time step size is reduced (0.45 sec. vs. 0.09 sec.)**
- **Solid domain inner iteration number is increased (8 vs. 50)**

Above parameters which come up with computational run time cost were shown to have negligible affect (~ 0.5%-2%) on the results. Not all results are presented in this presentation.
• Cosimulation enables using different time steps for fluid and solid domains
• 40 engine cycles is coupled with 600sec. solid domain warm up period
• Sensitivity study carried out
• Run time ~ 4 days (24 cpus for fluid domain and 24 cpus for solid domain)
3rd Method
Conjugate Approach
Conjugate Approach

- Both fluid and solid domains are modeled in the same environment; STAR-CCM+
- **Conjugate approach** solves the temperature field of the structure simultaneously with the fluid flow, and hence, eliminates the need to define thermal boundary conditions on structure-fluid interface (i.e. iterative data exchange process between CFD & FE is avoided)
- Due to very long run times; it is not feasible to run the case for 600 sec.
- The case is run only for 110 sec. (w 48 cpus) which takes almost a month
- Time step: $[1.0e-5 – 5.0e-5]$ sec.; inner iteration: 15
Temperature Results [C] @110sec.
Temperature Results Comparison [C] @110sec.

3rd Method

Predicts lower ~ 30°C

2nd Method

1st Method

Temperature Results Comparison [C] @110sec.

3rd Method

Predicts lower ~ 30°C

2nd Method

1st Method

Temperature Results Comparison [C] @110sec.
Warmup for 110sec. (Temperature[C] vs. time)

Method 2 vs. Method 3

- The max. discrepancy between Cosimulation and Conjugate is ~ 20-25°C
Temperature Results [C] @ 600 sec.
Method 1 vs. Method 2

- Temperature prediction of the 2nd method turns out to be up to 50-60°C higher than the 1st method.
Thermal Survey vs. CAE results
Thermal Camera

Method 1

Method 2

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Thermal Camera vs. CAE

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<th>Point</th>
<th>Method2</th>
<th>Method1</th>
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<tr>
<td>Point 8</td>
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Thermal camera

Method2-Cosimulation
Thermal Assessment - Conclusion

- @600sec.; temperature results of 2nd method is higher than the 1st method (up to 50-60°C) however 1st method predicts faster warm up period.
- @110sec.; temperature results of 3rd method is about 25-30°C lower than the other methods.

- Cosimulation method results are in good agreement with thermal camera results (~up to 4% higher when compared with thermal survey results).
- 1st method temperature predictions are ~9%-10% lower than thermal camera results.

- 2nd method (Cosimulation) run time (40 engine cycles) is ~ 1/35 of the conjugate case (2nd Method Cosimulation run time; 5 days with 24cpus for fluid, 24cpus for solid).
- 1st method (averaging) run time is ~ 1/75 of the conjugate case.

Main Conclusion

- The outcomes of coupled approaches tried with the aim of adopting a more reliable CAE method to carry out thermal/structural analysis of exhaust manifold and the scripts developed to fully automate the data exchange process between CFD and FE are explained.
Q & A

THANKS!