Finding Computationally Inexpensive Methods to Model the Flow Past Heavy Vehicles and the Design of Active Flow Control Systems for Drag Reduction

David E Manosalvas, Thomas D Economon, Francisco Palacios, Antony Jameson
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Motivation

End-Use Sector Shares of Total Consumption, 2011

- Residential: 22%
- Commercial: 19%
- Transportation: 28%
- Industrial: 31%

Motivation
Flow Control Methods

Experimental studies have shown that the use of active flow control systems can reduce the drag coefficient by more than 22%, corresponding to a net power savings of 15% (Pfeiffer 2012).
Research Goals

• We are interested in reducing drag of Heavy Vehicles using active flow control.
• For separated flows LES is considered to be the most reliable, but its prohibitively expensive for design optimization.
• Goal:
  • Find a combination of currently available methods that can be used to design active flow control systems.
  • Demonstrate the capabilities of computational tools for the analysis and design of active flow control systems.
Heavy Truck model selection

- Although features such as mirrors, wheels, and antennas will contribute to the wake and base drag, a simplified clean models such as the Ground Transportation System (GTS) is used to facilitate the understanding of base drag mechanisms (van Leeuwen, 2009).

- A 0.065 scale GTS model was used for this study due to the availability of experimental data in the literature (Englar 2000 & 2001).
Base Case 3D Model

- For the reference case, a 3D model of the truck was generated in SolidWorks using the geometry from Englar 2000 and 2001.

Scale 0.065 - Dimensions in meters
Enhanced Geometry 3D Model

- Taking the base geometry, and adding the Coanda surfaces, using the dimensions published by Englar 2000 & 2001.
2D Analysis Justification

• Most of the flow characteristics that we are interested on are present in the 2D flow
  • Boundary layer effects
  • Flow separation
  • Vortex shedding
  • Lateral forces

• The 2D top-view analysis uses a simpler configuration which requires significantly less computational time.
Coanda Jet Geometry

Flow Properties

• **Free Stream**
  - $V = 31.3 \text{ m/s (70 mph)}$
  - $T = 288.15 \text{ m/s}$
  - $R = 287.87$
  - $\gamma = 1.4$
  - $M = 0.0918$
  - $Re = 2.75 \times 10^6$

• **Jet Properties**
  - $T = 477.594 \text{ K}$
  - $P = 101325 \text{ – 106870 Pa}$
  - $\frac{dm}{dt} = 0 \text{ – 0.042 kg/s}$

• **Non-Dimensional Coefficients**
  - **Momentum Coefficient**
    \[
    C_\mu = \frac{\dot{m} \cdot V_c}{q \cdot W}
    \]
  - **Drag Coefficient**
    \[
    C_D = \frac{D}{q \cdot W}
    \]
  - **Lateral Force Coefficient**
    \[
    C_{LF} = \frac{LF}{q \cdot W}
    \]
  - **Power Coefficient**
    \[
    C_P = \frac{D \cdot U_\infty + P_{compressor}}{q \cdot U_\infty \cdot W}
    \]
Base Case Mesh

- Hybrid mesh with 88,275 cells and 52,915 points.
- Far field is 15 truck lengths long by 11 truck lengths wide.
Enhanced Geometry Mesh

- Hybrid mesh 136,087 cells and 84,837 points.
- Far field is 15 truck lengths long by 11 truck lengths wide.
Numerical Tools

• SU2
  • Jameson - Schmidt - Turkel (JST) Numerical Scheme
  • Shear Stress Transport (SST) Turbulence Model
  • Two levels of W multi-grid
  • Dual time stepping \( | dt = 0.0005 \) s

SU2.stanford.edu
Optimization Setup

• **Primary Objective**
  • Minimize the drag in the GTS model

• **Secondary Objective**
  • Minimize lateral forces in the GTS model

• **Variables**
  • Momentum coefficients which is controlled by changing the pressure in the plenum
Optimization Tools

• Time integration is expensive.
• Surrogate model generated by using a Gaussian Process Regression.
• Expected Improvement was implemented to minimize the number of function evaluations (max: 10).
• Boundaries of the problem were set to be between $C_{\mu} = 0.0$ and $C_{\mu} = 0.0501$ based on previous simulations and the work of Englar in 2001.
Results Summary

- Values averaged over 3 periods

<table>
<thead>
<tr>
<th>$C_\mu$</th>
<th>Plenum Pressure (Pa)</th>
<th>$\bar{C}_D$</th>
<th>$\tilde{c}_D$</th>
<th>$\bar{c}_{LF}$</th>
<th>$S_t$</th>
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<td>7.940E - 07</td>
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</tr>
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</table>

Table 3. Results for the GTS model and the enhanced GTS model injecting flow through Coanda Jets in the trailing end at momentum coefficients ranging from 0.0 to 0.0501. $C_\mu$ is the jet momentum coefficient, $\bar{C}_D$ is the time averaged drag coefficient, $\tilde{c}_D$ is the drag coefficient variance, $\bar{c}_{LF}$ is the lift coefficient variance, and $S_t$ is the Strouhal number.
Surrogate Model

- Power is calculated using a compressor model with an isentropic efficiency of 90%

\[ C_D = \frac{D}{q \times W} \]

\[ C_P = \frac{D \times U_\infty + P_{compressor}}{q \times U_\infty \times W} \]
Flow Past the GTS Model

Base

Enhanced (Optimum)
GTS Conclusion

• The addition of the Coanda surfaces have a big effect in the integrated forces, this phenomenon is due to the lack of 3D effects.

• As the jet flow is increased the $C_D$ and $C_{LF}$ drop and reach a minimum when $C_\mu=0.0336$.

• As the $C_\mu$ further increases, the drag increases and the behavior of the drag and lateral forces returns to being oscillatory. This behavior is attributed to the extra energy of the jet disturbing the flow of the wake.

• The trend followed by the integrated forces is similar to the one shown by Englar in 2001.
Future Avenues of Research

- Use of shape optimization techniques to better understand the effect of the shape and position of the Coanda surfaces.
- Study the flow past the 3D GTS model with the JST–SST combination.
- Explore the use of periodic and asymmetric jet injection effects.
- Use the available experimental data to validate the numerical results
References

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