Wall-Modeled Large-Eddy Simulations of a Mach 8 Turbulent Boundary Layer over a Flat-Plate for Aero-Optical Distortion Analysis

Authors: P. Castillo (PhD Candidate in AE), A. Gross (New Mexico State University), Mechanical and Aerospace Engineering Department, D.R. Guildenbecher (Sandia, Engineering Sciences Center)

SAND2021-10238PE
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Introduction and Motivation

Turbulent boundary layers at high Mach numbers exhibit strong density fluctuations which affect or distort the optical path of light beams reaching the surface. It is unknown if existing semi-empirical relationships are accurate at hypersonic Mach numbers. Direct numerical simulations (DNS) and wall-resolved large-eddy simulations (WRLES) allow for accurate predictions of the optical distortion. This project explored if less costly wall-modeled large-eddy simulations (WMLES) allow for reasonably accurate and efficient predictions of the aero-optical path distortion (OPD).

Objectives:

- Develop WMLES methodology for accurate prediction of optical distortion
- Validation with reference DNS data and Sandia National Laboratories (SNL) measurements
- Develop new theory and models for predicting optical distortion at high Mach numbers

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Approach

➢ Simulations that provide instantaneous density fields from which OPD can be computed.

Direct Numerical Simulations (DNS) at SNL

- No modeling - All scales are resolved
- Number of grid points: $N \sim Re_L^{37/14}$
- Most accurate and highest computational expense

Large-Eddy Simulation (LES) at NMSU

- Large energy-bearing flow structures are resolved and unresolved (i.e. sub-grid) structures are modeled
- Number of grid points:
  - Wall-resolved: $N \sim Re_L^{13/7}$
  - Wall-modeled: $N \sim Re_L$
- *Computationally less expensive than DNS*

Choi, H., and Moin, P., 2011, "Grid-point requirements for large eddy simulation: Chapman's estimates revisited," Center for Turbulence Research, Annual Research Briefs, Stanford University

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Approach

In-house developed compressible finite volume code

- 9th-order-accurate convective terms (WENO-based)
- 4th-order-accurate viscous terms
- 4th-order-accurate Runge-Kutta time integration

- WALE (Nicoud and Ducros, 1999) and Vreman (2004) subgrid stress model

➢ For wall-modeled LES, two ODEs (momentum and energy equation) are solved near the wall to obtain wall-shear and wall heat flux (isothermal)/wall temperature (adiabatic)

Simulations are run on local cluster at NMSU (“Discovery”) and on SNL cluster (“Solo”)

Nicoud, F., and Ducros, F., “Subgrid-Scale Stress Modelling Based on the Square of the Velocity Gradient Tensor,” *Flow, Turbulence and Combustion*, Vol. 62, No. 3, 1999, pp 183-200
Vreman, A.W., “An Eddy-Viscosity Subgrid-Scale Model for Turbulent Shear Flow: Algebraic Theory and Applications,” *Physics of Fluids*, Vol. 16, No. 10, 2004, pp. 3670-3681

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Approach

Computational setup for Mach 8

- Parameters for isothermal wall case (identical to Zhang et al., 2018):

M_∞	T_w [K]	T_∞ [K]	ρ_∞ [kg/m^3]	Re_θ	Re	Pr
7.87	298	51.8	0.026	9,714	$8.16x10^6$	0.71

- Computational domain
  - Spatial Extent: $1.2288 \times 0.338 \times 0.12$
  - Number of cells:

Case	Streamwise	Wall-normal	Spanwise	Total (Cells)
Zhang et al. DNS	-	-	-	$341x10^6$ (nodes)
Baseline	256	64	40	$6.55x10^5$
Finer in Z	256	64	80	$1.31x10^6$
Finer in X	512	64	40	$1.31x10^6$

Zhang, C., Duan, L., and Choudhari, M.M., "Direct Numerical Simulation Database for Supersonic and Hypersonic Turbulent Boundary Layers," AIAA Journal, Vol. 56, No. 11, 2018, pp. 4297-4311

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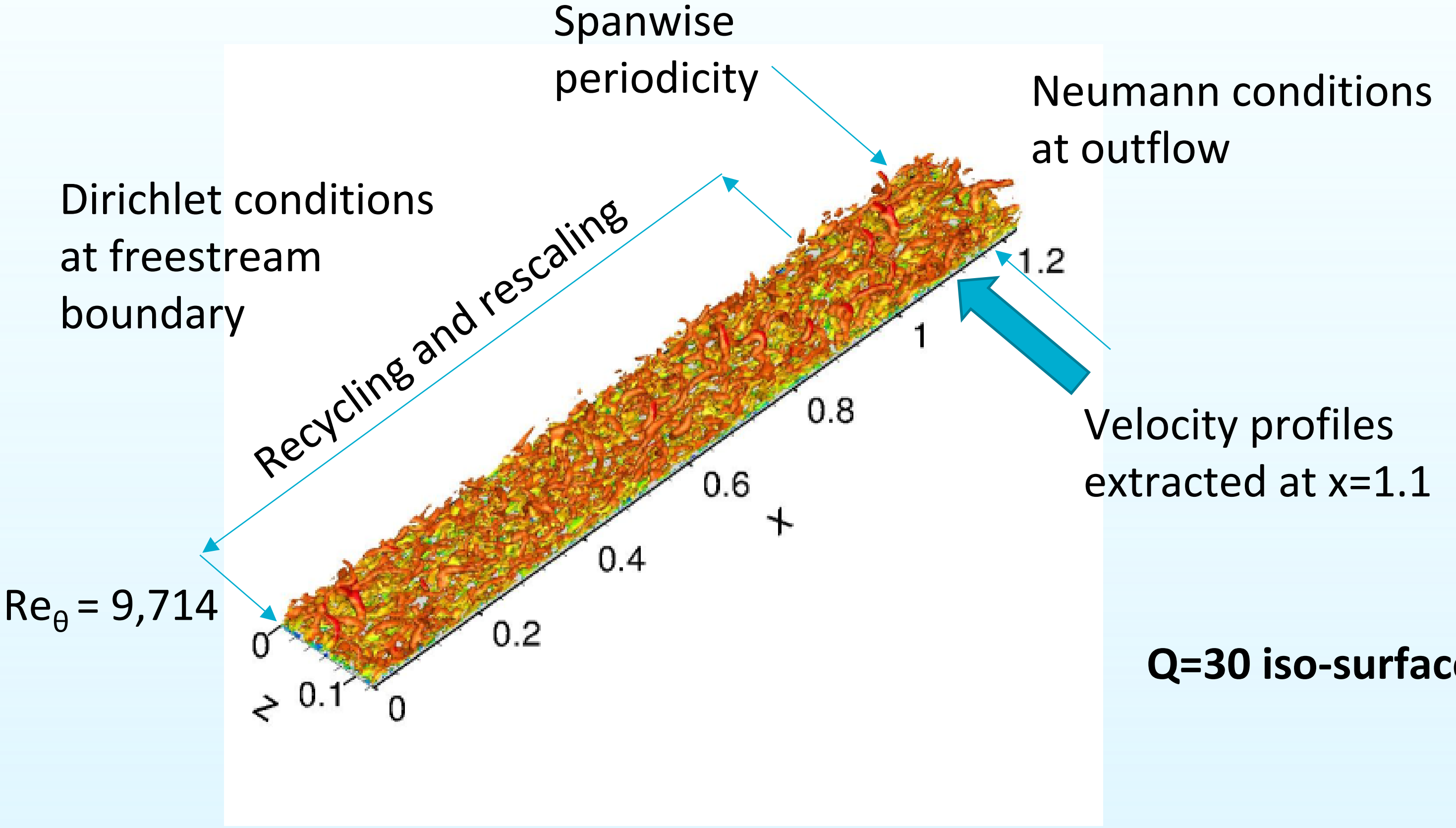
Approach

Boundary Conditions

- Baseline Case



Q=30 iso-surfaces flooded by u-velocity

Stolz, S., and Adams, N.A., "Large-eddy simulation of high-Reynolds-number supersonic boundary layers using the approximate deconvolution model and a rescaling and recycling technique," Physics of Fluids, Vol. 15, No. 8, 2003, pp. 2398-2412

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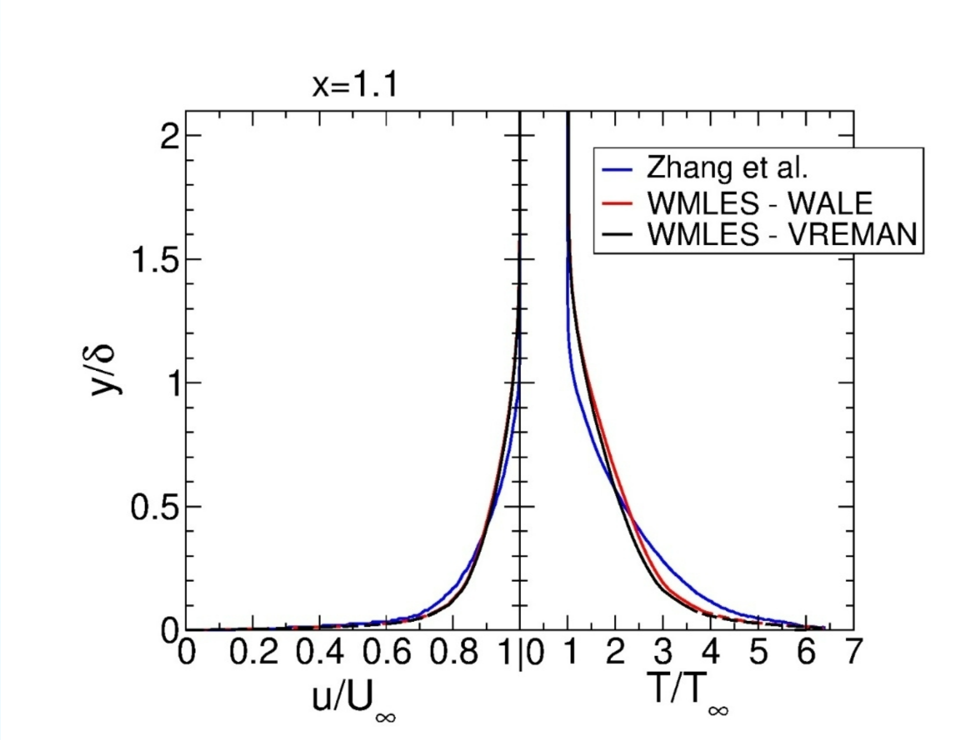
Current Status and Results

Subgrid Stress Model Comparison

- Effect of subgrid stress model



$$RMS\ error = \sqrt{\frac{\sum \frac{1}{2}(y_j - y_{j-1})[(u_j^{LES} - u_j^{DNS})^2 + (u_{j-1}^{LES} - u_{j-1}^{DNS})^2]}{\sum (y_j - y_{j-1})}}$$

RMS error of profiles relative to DNS

Subgrid stress model	u_{RMS}	T_{RMS}
WALE	0.011	0.231
VREMAN	0.0113	0.269

*Slightly lower error for WALE model (employed for all following results).

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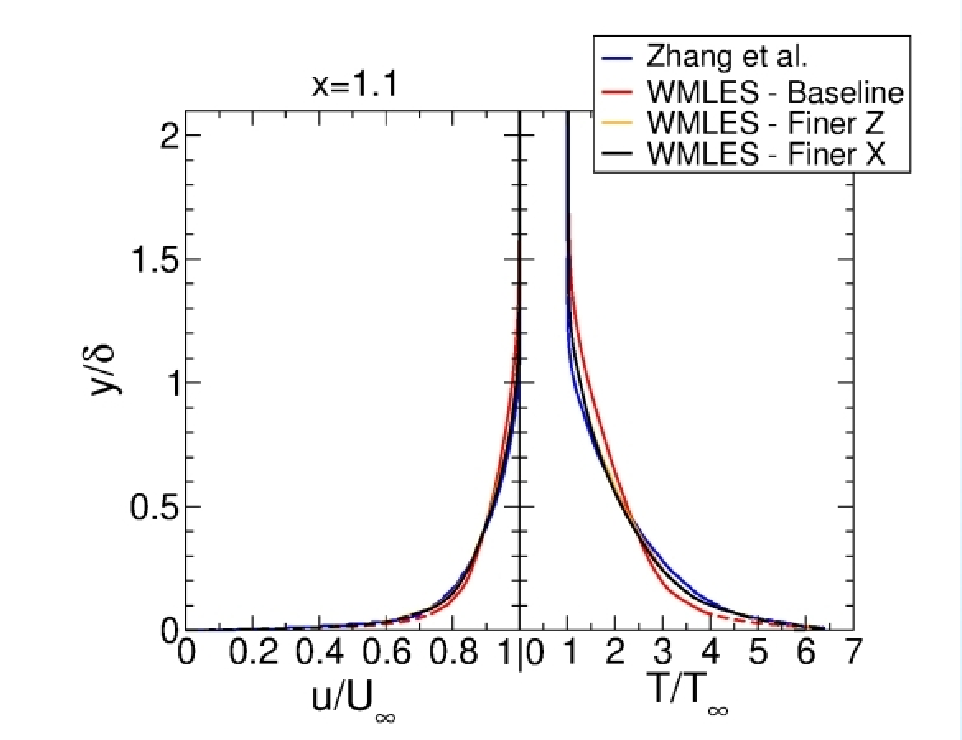
Current Status and Results

Grid resolution Comparison

➢ Effect of grid resolution



$$RMS\ error = \sqrt{\frac{\sum \frac{1}{2}(y_j - y_{j-1})[(u_j^{LES} - u_j^{DNS})^2 + (u_{j-1}^{LES} - u_{j-1}^{DNS})^2]}{\sum (y_j - y_{j-1})}}$$

RMS error of profiles relative to DNS

Subgrid stress model	u_{RMS}	T_{RMS}
Baseline	0.011	0.231
Finer in Z	0.00427	0.0787
Finer in X	0.00395	0.0834

*Similar reduction of error for both finer grid cases
*Good agreement with DNS profiles
*Significant savings for WMLES compared to DNS

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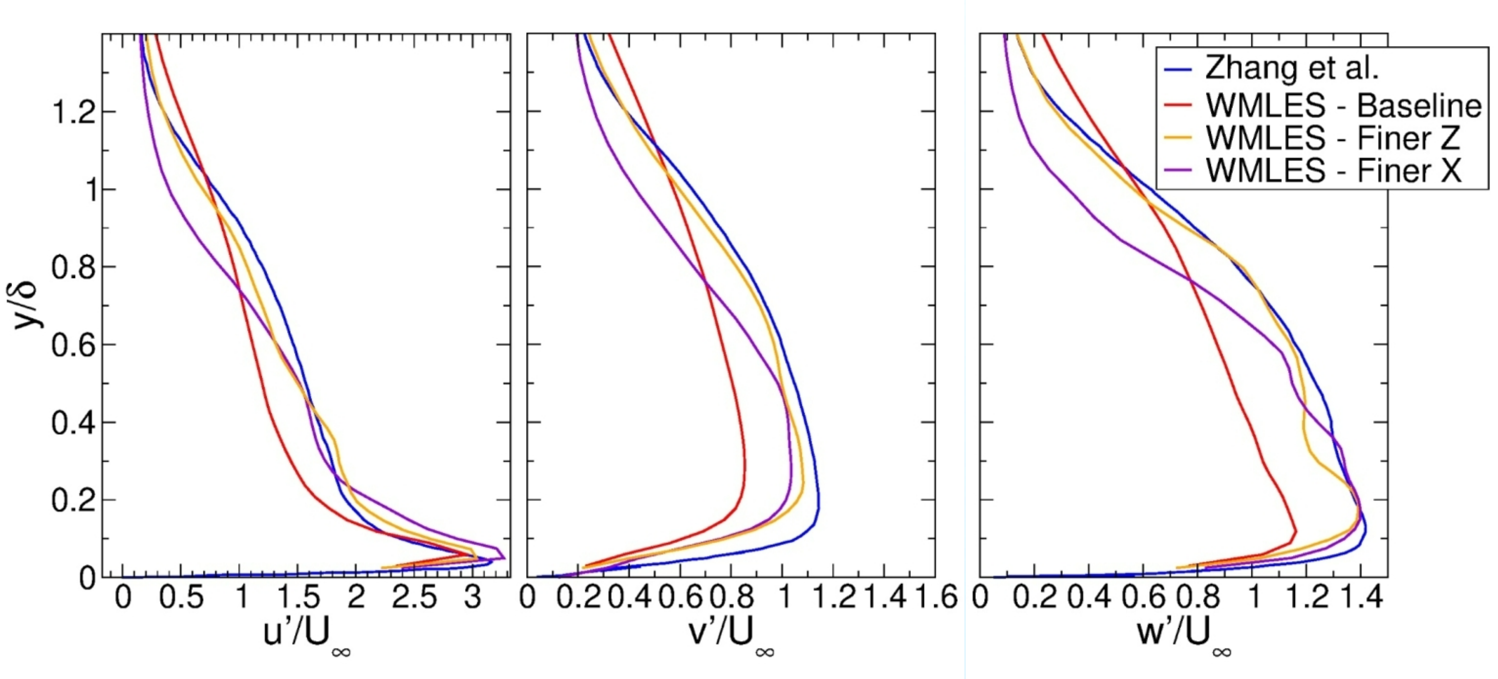
Current Status and Results

Statistics

- Profiles of RMS velocity fluctuations



Turbulence fluctuations determine density gradients and thus optical distortion

*Good agreement with DNS reference data for "Finer Z" case

*Need to continue time-averages to obtain smoother curves.

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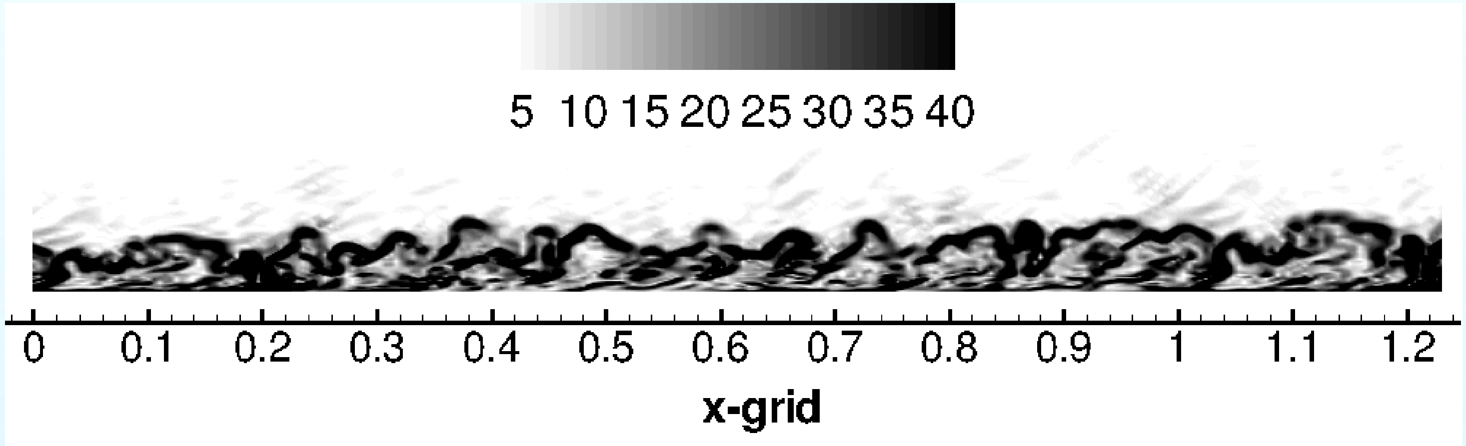
Current Status and Results

Instantaneous Flow Visualization

- Numerical Schlieren (magnitude of density gradient for constant z-plane)



Baseline Case

"Refraction index" is proportional to density:

$$n = 1 + K_{GD} \times \rho$$

$K_{GD} = 2.35{\times}10^{-4} m^3/kg$ is the Gladstone-Dale constant.

*Strong density gradients cause large optical distortions

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Current Status and Results

Optical Distortion

1. Integration of refraction index through boundary layer gives optical path length (OPL):

$$OPL(x,z,t) = \int_0^{\delta} n(x,y,z,t)dy$$

2. Tilt correction (Wang and Wang, 2012) to obtain optical path difference (OPD):

$$OPD(x,z,t) = OPL(x,z,t) - (m_x x + m_z z + b)$$

3. Tilt correction is obtained from bilinear least-squares fit:

$$R = \int_x \int_z \left(OPL(x,z,t) - (m_x x + m_z z + b)\right)^2 dzdx$$

4. Average in time and spanwise direction gives RMS OPD: $OPD(x)_{RMS} = \sqrt{\langle OPD(x,z,t)^2 \rangle_{z,t}}$
5. RMS OPD is normalized:

$$f(M_\infty) = \frac{OPD_{RMS}}{K_{GD}\rho_\infty C_f^{0.5} M_\infty^2 \delta}$$

Wang, K., and Wang, M., "Aero-optics of subsonic turbulent boundary layers," Journal of Fluid Mechanics, Vol. 696, 2012, pp. 122-151

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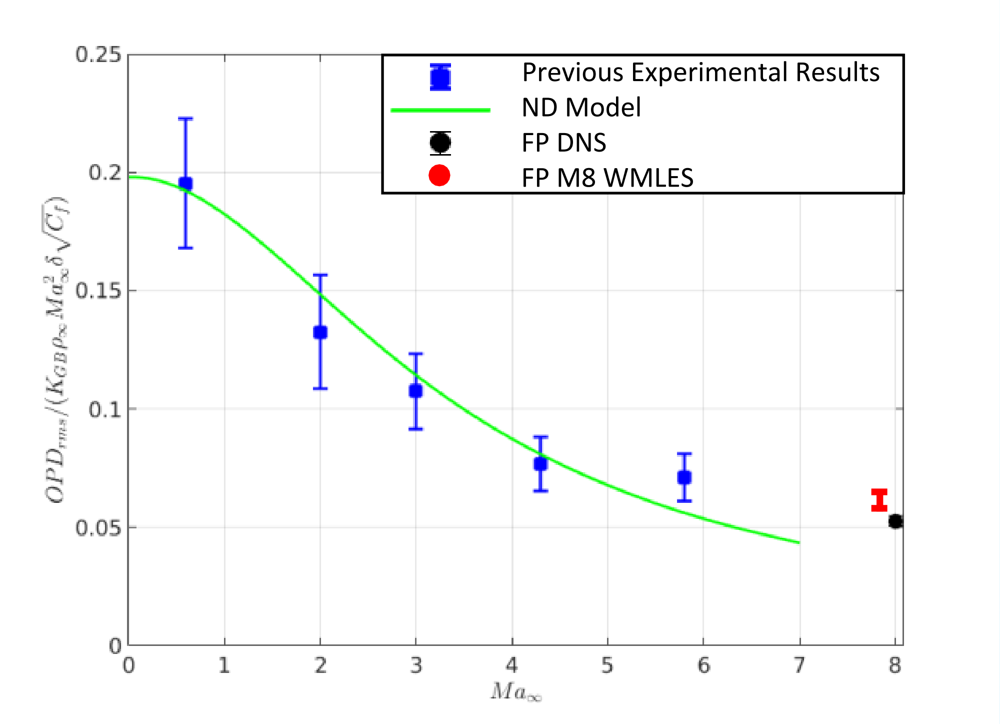
Current Status and Results

RMS and Normalized RMS Optical Path Distortion

- Aperture: 6δ x 2.4δ
- 2000 snapshots over $\Delta t = 0.5$

Case	C_f	δ/L_{ref}	OPD_{RMS}/L_{ref}	$f(M_\infty)$
Zhang et al. DNS	-	-	-	0.0584
Baseline	0.00112	0.0405	$33.582x10^{-9}$	0.0632
Finer Z	0.001	0.0493	$37.672x10^{-9}$	0.0636
Finer X	0.00095	0.0481	$39.833x10^{-9}$	0.0696

- The flat plate length was chosen as reference length "L_{ref}"
- Experiments by Gordeyev and Juliano (2016)
- Notre Dame (ND) model by Jumper and Gordeyev (2017)
- OPD obtained from DNS and LES are close



Gordeyev, S., and Juliano, T.J., "Optical Characterization of Nozzle-Wall Mach-6 Boundary Layers," AIAA-2016-1586, 2016

Jumper, E.J., and Gordeyev, S., "Physics and Measurement of Aero-Optical Effects: Past and Present," Annual Review of Fluid Mechanics, Vol. 49, No. 1, 2017, pp. 419-441

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Impact of Work

Turbulent boundary layers at high Mach numbers exhibit strong density fluctuations which result in aero-optical distortions that can affect the accuracy and effectiveness of i.e., air-borne sensors or lasers. Thus, the prediction of the magnitude and character of the aero-optical distortions is of great interest. The project makes the following contributions:

- Assessment of WMLES as low-cost alternative to DNS
- New OPD data (in addition to experiments and DNS) for development of theory and models

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Challenges and Risks / Next Steps and Future Work

Challenges

- Obtain data that is accurate enough compared to experiments and DNS
- Push towards higher Mach number (Mach 14) and adiabatic wall cases that are numerically challenging

Moving Forward

- WMLES of Mach 8 boundary layer with adiabatic Wall
- WMLES of Mach 14 boundary layer with isothermal Wall
- Proper Orthogonal Decomposition (POD):
  - Test different POD kernels
  - Reconstruction of unsteady flow field based on dominant POD modes
  - Compute OPD from reconstructed flow field

*Detailed results will be presented (and published in proceedings) at 2022 AIAA Scitech Forum