

Predictions of Aero-Optical Distortions Using LES with Wall Modeling

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Large-eddy simulation (LES) with wall-modeling is evaluated for applications to aero-optical predictions at practical Reynolds numbers. Turbulent boundary layers and flow over a cylindrical turret are considered. The results of boundary-layer flows at both subsonic and supersonic speeds show accurate predictions of mean velocity profiles and velocity fluctuations. The density fluctuations and hence wavefront distortions are found to be more demanding in terms of grid resolution. The subsonic separated shear layer over a cylindrical turret is computed at the same Reynolds number as in the experiment conducted by Gordeyev et al.¹ Both flow and optical results show good agreement with the experimental measurements and the previous wall-resolved LES results of Wang et al.² at a reduced Reynolds number.

I. Introduction

In airborne optical systems, turbulent flows including boundary layers, separated shear layers, wakes, and complex vortex systems are formed around the optical aperture. At transonic and supersonic flight speeds, shock waves are also created, which can result in early flow separation and strong density gradients. All these turbulent flow features can lead to detrimental aero-optical distortions, causing beam defocus, jitter, and a dramatic reduction in the effective range.³

The aero-optical distortions are related to the density fluctuations in the compressible turbulent flow field. The index of refraction varies linearly with the density of the air through the Gladstone-Dale relation:⁴

$$n = 1 + K_{GD}\rho, \quad (1)$$

where K_{GD} is the Gladstone-Dale coefficient which is weakly dependent on the optical wavelength. When a collimated optical beam travels through a non-uniform index-of-refraction field, different parts of the beam propagate at different local speeds. The phase of the optical wavefront can be described by the optical path length (OPL), which is the integral of the index of refraction along the beam path:

$$\text{OPL}(x', z', t) = \int_0^L n(x', y', z', t) dy', \quad (2)$$

where x' and z' are the local coordinates in the plane of the aperture and y' represents the coordinate along the beam path. The wavefront distortions are represented by the relative difference in OPL in the plane normal to the beam path. This is called the optical path difference (OPD) and is defined as

$$\text{OPD}(x', z', t) = \text{OPL}(x', z', t) - \langle \text{OPL}(x', z', t) \rangle, \quad (3)$$

where the angle brackets indicate spatial averaging over the aperture. The magnitude of the optical distortions is often characterized by the time average of the spatial root-mean-square (rms) of OPD, $\overline{\text{OPD}}_{rms}$. For a given $\overline{\text{OPD}}_{rms}$, the optical phase distortion, $\sigma_\phi = 2\pi\overline{\text{OPD}}_{rms}/\lambda$ is inversely proportional to the optical wavelength λ , and therefore the aero-optical problem is more severe for short-wavelength beams.

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Numerical prediction of aero-optical distortions requires resolution of a broad range of optically active turbulence scales. It is shown theoretically by Mani et al.⁵ that an adequately resolved large-eddy simulation (LES) is capable of capturing the aero-optical effect of turbulent flows without additional aero-optical resolution requirements. However, LES of wall-bounded flows are prohibitively expensive at high Reynolds numbers. Consequently, previous simulations using full LES were conducted at reduced Reynolds numbers.^{6,7}

As a more affordable alternative, hybrid approaches combining LES with a Reynolds-averaged Navier-Stokes (RANS) method gained attention in recent years. Nahrstedt et al.⁸ applied the partially averaged Navier-Stokes method with the two-equation $k-\varepsilon$ model to simulate the aero-optical flow over a hemisphere-on-cylinder turret as in the experiment of Gordeyev et al.⁹ Ladd et al.¹⁰ studied the same turret configuration using detached-eddy simulation (DES) with the two-equation $k-\omega$ turbulence model. Morgan and Visbal^{11,12} employed a hybrid RANS/Implicit-LES approach with $k-\varepsilon$ model to simulate the same experiment as well as another hemisphere-on-cylinder turret configuration. These hybrid simulations captured some of the global flow features such as the mean surface pressure and wake profiles at some locations, but overall, agreement with experimental data is not satisfactory in terms of both flow and optical results.

Another class of hybrid LES/RANS methods is LES with a wall-layer model.^{13,14} Unlike DES type methods, which treat the entire attached boundary layer with RANS equations and use LES only in separated flow regions, a wall-modeled LES computes most of the boundary layer with LES and uses a RANS model only in the near-wall region of the boundary layer. As a result, it is more accurate and robust but computationally more expensive. In a wall-modeled LES, the LES mesh is designed to resolve the outer flow scales in the boundary layer, resulting in a dramatic reduction in computational expenses. The effect of unresolved near-wall turbulence structures is modeled by a set of RANS-type equations. The wall-model solutions, often in terms of wall shear stress and heat flux, are fed into LES as approximate boundary conditions. Mathews et al.¹⁵ applied this approach to compute the flow over a hemisphere-on-cylinder optical turret, and obtained promising flow and aero-optical results. In the present work, the accuracy of the LES with wall modeling for aero-optical predictions is evaluated in simpler canonical configurations including high-Reynolds number turbulent boundary layers and flow over a cylindrical turret at the full experimental Reynolds number.

II. Methodology

A compressible unstructured-mesh LES code, CharLES, developed by Cascade Technologies Inc.¹⁶ is employed to obtain the flow field. The fully explicit flow solver uses a third order Runge-Kutta method in time and a low-dissipative finite-volume scheme in space. Non-dissipative central flux is blended with a minimal upwind flux to ensure stability when the mesh quality is not ideal. The Vreman model is used to model the effects of sub-grid scale motions.^{17,18} CharLES also has the capability of capturing shock waves using a hybrid central-ENO scheme. A more thorough description of the numerical techniques used in CharLES can be found in Khalighi et al.¹⁶

In a wall-modeled LES, computational expenses are drastically reduced by imposing approximate boundary conditions on the wall instead of resolving the wall layer with the conventional Dirichlet boundary conditions (e.g. no-slip conditions for the momentum equations and isothermal/adiabatic condition for the energy equation). These approximate boundary conditions are obtained by solving a simplified set of equations in a Reynolds-averaged sense on a secondary mesh with a sufficient resolution in the wall-normal direction, as shown in Figure 1. The top boundary conditions for the wall-model equations are given from LES at the matching point ($y = y_m$). Approximate wall boundary conditions in terms of shear stress and heat flux are calculated from the wall model and provided to LES.

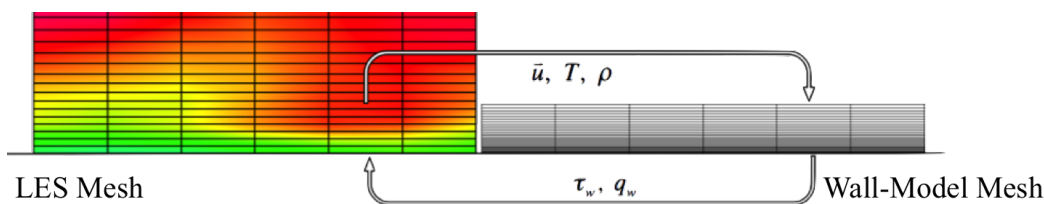


Figure 1. Schematic showing data exchange between LES and wall-model meshes.

Wall-layer equations used in this study are of the form

$$\frac{d}{dy} \left[(\mu + \mu_t) \frac{du}{dy} \right] = 0, \quad (4)$$

$$\frac{d}{dy} \left[(\mu + \mu_t) u \frac{du}{dy} + \frac{\gamma \mathcal{R}}{\gamma - 1} \left(\frac{\mu}{Pr} + \frac{\mu_t}{Pr_t} \right) \frac{dT}{dy} \right] = 0, \quad (5)$$

which represent the simple equilibrium stress-balance model.^{13,19,20} The coordinate y is in the wall-normal direction and x is in the direction of the wall-parallel velocity component u at the matching point $y = y_m$. No-slip and adiabatic conditions are imposed on the wall boundary, while the top boundary conditions for the wall-layer equations are provided by the instantaneous LES field. In Eq. (5) $\mathcal{R}$ is the gas constant and γ is the specific heat ratio. The turbulent eddy viscosity μ_t is provided by the mixing-length model with near-wall damping

$$\mu_t = \mu \kappa y^+ (1 - e^{-y^+/A})^2, \quad (6)$$

where $y^+ = \rho y u_\tau / \mu$ is the distance to the wall in wall units, $\kappa = 0.41$ and $A = 17$. The turbulent Prandtl number $Pr_t = 0.9$. The shear stress τ_w and heat flux q_w are calculated from Eqs. (4) and (5) and provided to LES.

Based on the simulated fluctuating density field in the vicinity of the optical aperture, the instantaneous field of the index of refraction is calculated using the Gladstone-Dale relation,⁴ Eq. (1). The optical wavefront distortions are calculated using Eqs. (2) and (3). To facilitate optical calculations, a beam grid of the same resolution as the LES mesh is constructed along the beam path.⁶ The instantaneous density values on the optical grid are interpolated from the LES grid using a second-order gradient based method. The tilt-removed OPD, which is considered in the present work as a measure of the wavefront distortion, is calculated by removing the spatially-averaged and the spatially-linear components from OPL,

$$\text{OPD}(x', z', t) = \text{OPL}(x', z', t) - [A(t)x' + B(t)z' + C(t)], \quad (7)$$

where $A(t)$, $B(t)$ and $C(t)$ are the instantaneous tilt components in the x' and z' directions and the spatially-averaged OPL, respectively. They are calculated using a least-square method by minimizing the function

$$G = \int \int_{A_p} \{ \text{OPL}(x', z', t) - [A(t)x' + B(t)z' + C(t)] \}^2 dx' dz'. \quad (8)$$

III. Turbulent Boundary Layers

Wall-modeled LES is utilized to simulate turbulent boundary-layer flows at subsonic and supersonic speeds over a wide range of relatively high Reynolds numbers. All the simulations are conducted using the same mesh. The domain size is 45δ , 15δ and 3.1δ , in the streamwise (x), wall-normal (y) and spanwise (z) directions, respectively. For aero-optical calculations, the unsteady density field is collected within a beam grid of size $10\delta \times 3\delta \times 3.1\delta$, where δ is the boundary layer thickness at the aperture center of the target Reynolds number.

The “rescale and recycle” technique^{21,22} is employed to generate fully-developed turbulent boundary layers within a relatively short domain as shown in Figure 2. The flow quantities in a y - z plane at $x/\delta = 11$ from the inlet is rescaled and reintroduced into the inlet. The outlet boundary is preceded by a sponge layer with a thickness of 10δ to damp out the vortical structures and acoustic disturbances before the flow approaches the outlet. Free-stream conditions are imposed on the top boundary. There is a layer of thickness 5δ , adjacent to the top boundary, where an upwind scheme is used to dissipate acoustic waves. The wall is assumed adiabatic. Periodic boundary conditions are imposed in the spanwise direction.

The grid spacings in terms of the boundary-layer thickness are $\Delta x = 0.05\delta$, $\Delta z = 0.032\delta$ and $\Delta y_{min} = 0.01\delta$, respectively. The wall-layer thickness is set to be 0.05δ , which contains five cells in the wall-normal direction as suggested by Kawai and Larsson.²⁰ 64 cells are distributed in the wall-normal direction from $y = 0$ to 1.5δ . The total mesh size is 9 million cells. A CFL number of unity is applied in all simulations.

A. Subsonic Boundary Layers

Turbulent boundary layers at free-stream Mach number $M_\infty = 0.5$ and momentum-thickness Reynolds numbers Re_θ from 2.8×10^3 to 3.1×10^4 are simulated. The spacings in terms of viscous wall units are

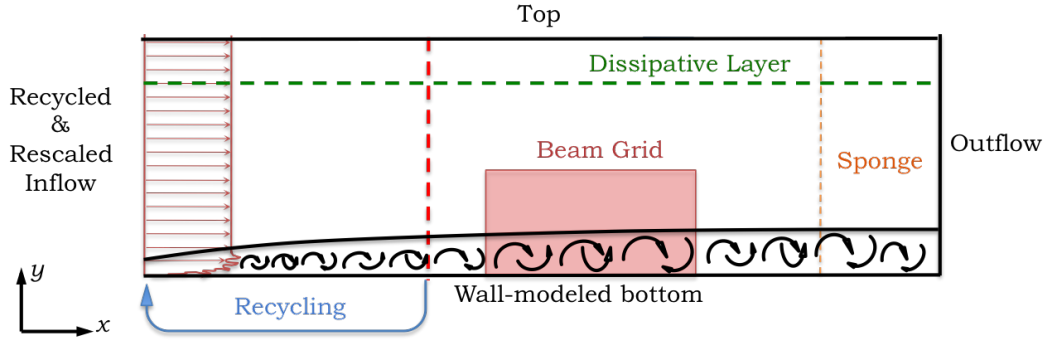


Figure 2. Schematic of the computational set-up for turbulent boundary layers.

presented in Table 1. By comparing the number of mesh points and time step size to those of the wall-resolved LES of Wang and Wang⁶ at $Re_\theta = 3550$, the computational expenses are reduced by two orders of magnitude due to wall modeling.

Re_θ	Δy_{min}^+	Δx^+	Δz^+
2.8×10^3	12	60	40
5.6×10^3	23	115	75
1.3×10^4	50	250	160
3.1×10^4	110	550	350

Table 1. Grid spacings in terms of wall units for subsonic turbulent boundary layers at $M_\infty = 0.5$ and different Reynolds numbers.

Mean streamwise velocity profiles are plotted in Figure 3(a). The coordinates are defined as $y^+ = yu_\tau/\nu$, and $U^+ = U/u_\tau$, where $u_\tau = \sqrt{\tau_w/\rho}$ is the friction velocity and ν is the kinematic viscosity. In the log region, the mean velocity profiles show good agreement with the log law. In Figure 3(b), the rms of the streamwise velocity fluctuations are compared to the experimental measurements of DeGraaff and Eaton²⁴ at Reynolds numbers $Re_\theta = 2.9 \times 10^3, 5.2 \times 10^3, 1.3 \times 10^4$ and 3.1×10^4 , which are the closest match to the Reynolds numbers in the simulations. The rms values of streamwise velocity fluctuations show a reasonable agreement with the experimental measurements.

B. Supersonic Boundary Layers

Three simulations at supersonic Mach numbers and high Reynolds numbers are conducted and their parameters are listed in Table 2. The $M = 1.7$ case corresponds to the experiments of Souverein et al.²⁵ and $M = 2.0$ and 3.0 cases correspond to Gordeyev et al.,^{26,27} respectively.

Case	M_∞	Re_θ	Re_δ	C_f
1	1.7	5.0×10^4	6.0×10^5	1.74×10^{-3}
2	2.0	6.9×10^4	8.4×10^5	1.62×10^{-3}
3	3.0	5.0×10^4	7.6×10^5	1.41×10^{-3}

Table 2. Simulations of supersonic turbulent boundary layers at different Mach numbers and Reynolds numbers.

In Figures 4(a) and 4(b), Van Driest transformed velocity statistics are presented. The mean velocity profiles match the logarithmic law very well. The predicted rms of velocity fluctuations at $M = 1.7$ shows a reasonable agreement with the experimental data of Souverein et al.²⁵

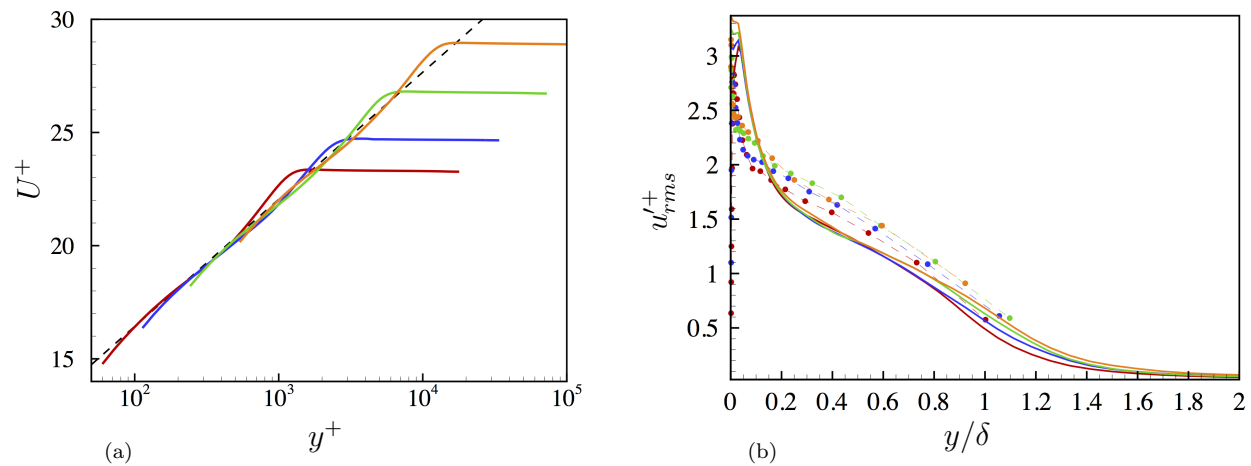


Figure 3. Streamwise velocity statistics in Mach 0.5 subsonic turbulent boundary layers: (a) Mean velocity profiles; (b) rms of velocity fluctuations. Wall-modeled LES: —, $Re_\theta = 2800$; —, $Re_\theta = 5600$; —, $Re_\theta = 13000$; —, $Re_\theta = 31000$. Experimental measurements of DeGraaff and Eaton:²⁴ —•—, $Re_\theta = 2900$; —•—, $Re_\theta = 5200$; —•—, $Re_\theta = 13000$; —•—, $Re_\theta = 31000$. — —, logarithmic law $U^+ = (1/0.41) \ln y^+ + 5.2$.

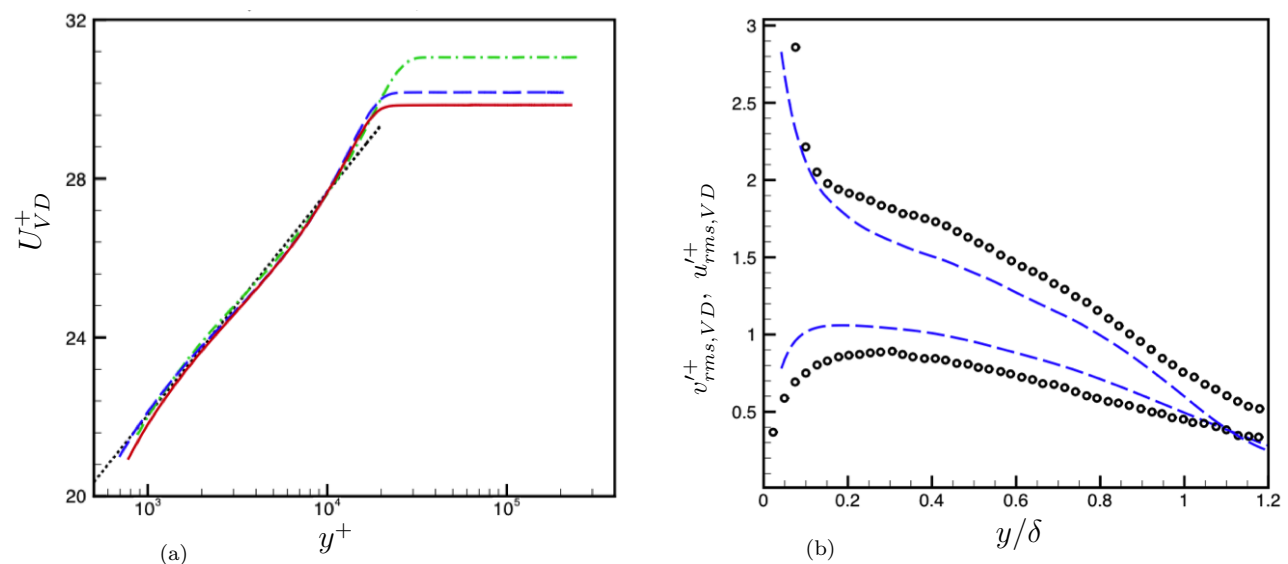


Figure 4. Van Driest transformed velocity statistics: (a) Mean streamwise velocity; (b) rms of streamwise and wall-normal velocity fluctuations. —, $M_\infty = 1.7, Re_\theta = 5.0 \times 10^4$; —, $M_\infty = 2.0, Re_\theta = 6.9 \times 10^4$; —, $M_\infty = 3.0, Re_\theta = 5.0 \times 10^4$; ○, experimental measurement of Souverein et al.²⁵ at $M_\infty = 1.7$ and $Re_\theta = 5.0 \times 10^4$; ···, $U^+ = (1/0.41) \ln y^+ + 5.2$.

C. Grid Convergence Study

The low Reynolds number cases $M = 0.5$, $Re_\theta = 3550$ and $M = 2.0$, $Re_\theta = 2650$ are used for a grid convergence study and the results are compared to the wall-resolved LES of Wang and Wang.^{6,23} Three levels of grid resolution are employed. In addition to the aforementioned mesh (mesh B hereafter), a coarser resolution (mesh A) and a finer mesh (mesh C) are also employed, as listed in Table 3. In all meshes, the first off-wall spacing is $\Delta y_{min} = 0.01\delta$ and the wall-layer thickness is set to be 0.05δ , which contains five equally-spaced cells in the wall-normal direction as suggested by Kawai and Larsson.²⁰ The vertical grid spacing is stretched smoothly from the wall up to $y = 1.5\delta$, followed by a uniform vertical spacing of $\Delta y = \Delta x$ up to $y = 3\delta$, and then a smooth stretching again up to the top boundary. Δx is constant from the inlet to the edge of the sponge and then stretched smoothly towards the outlet inside the sponge layer.

Mesh	$\Delta x/\delta$	$\Delta z/\delta$	$\Delta y_{min}/\delta$	N_y (within 1.5δ)	Mesh Size
A	0.077	0.048	0.01	45	3.5×10^6
B	0.05	0.032	0.01	64	9.0×10^6
C	0.033	0.021	0.01	85	2.68×10^7

Table 3. Computational grids of grid resolution for turbulent boundary layer simulations.

The rms profiles of streamwise and wall-normal velocity fluctuations in the subsonic and supersonic boundary layers obtained from the three meshes are depicted in Figure 5(a) and (b), respectively. It is observed that the velocity fluctuations are grid converged as are the mean velocity profiles (not shown). In Figures 6(a) and (b), the rms of density fluctuations of the subsonic and supersonic boundary layers are presented for the three meshes and compared to the wall-resolved LES results.^{6,23} It is noted that the density fluctuations are close to the predictions from wall-resolved LES, but show more sensitivity to grid resolution than the velocity field. While grid convergence has been achieved for velocity statistics on the current meshes as displayed in Figure 5, the density still shows a small level of grid sensitivity.

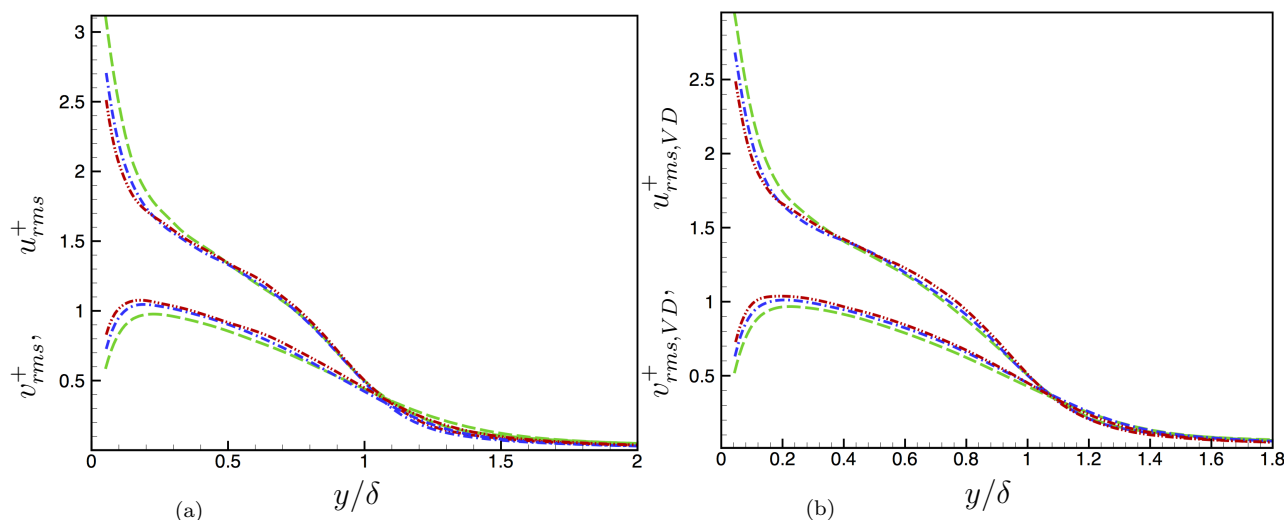


Figure 5. Root mean square of streamwise and wall-normal velocity fluctuations in turbulent boundary layers: (a) $M_\infty = 0.5$, $Re_\theta = 3550$; (b) $M_\infty = 2.0$, $Re_\theta = 2650$. — — —, mesh A; — · — · —, mesh B; · · · · ·, mesh C.

In Table 4, the normalized OPD_{rms} values are listed for the three mesh resolutions using wall-modeled LES and compared to the results from wall-resolved LES.^{6,23} The results show a converging trend with mesh refinement. The differences in OPD_{rms} between the most refined mesh and the intermediate mesh are 1.3% and 6.6% for the subsonic and supersonic boundary layers, respectively. Therefore, the intermediate mesh resolution results in a reasonable prediction of OPD_{rms} and is thus employed for all the optical calculations in the following section.

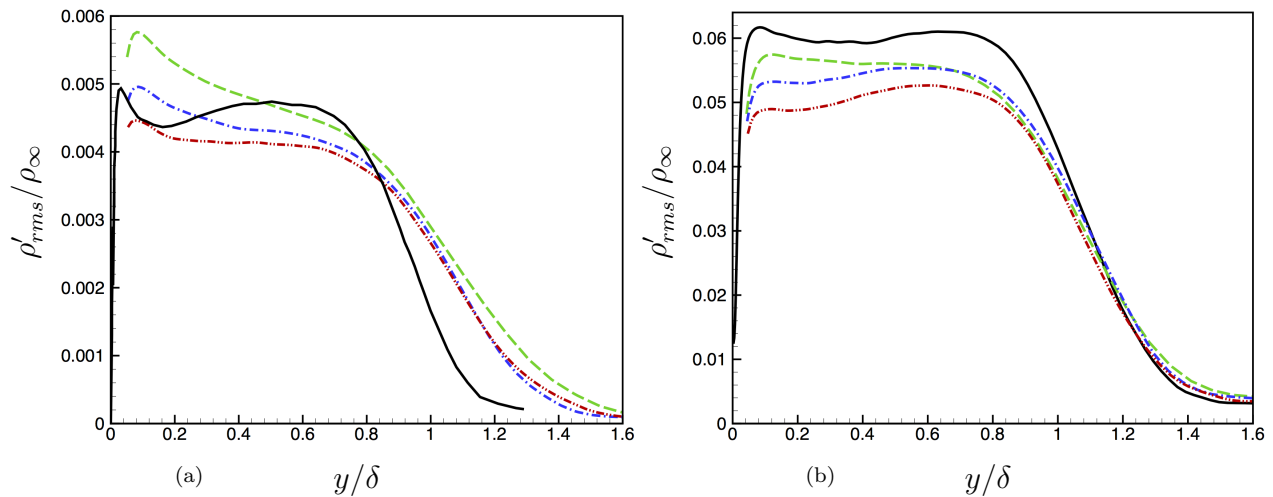


Figure 6. Density fluctuations in turbulent boundary layers: (a) $M_\infty = 0.5$ and $Re_\theta = 3550$; (b) $M_\infty = 2.0$ and $Re_\theta = 2650$. Wall-modeled LES: ---, mesh A; - · - · -, mesh B; - · · - · -, mesh C. —, wall-resolved LES.^{6,23}

	OPD _{rms} / ($\frac{\rho_\infty}{\rho_{SL}} \delta M^2$)	
	$M_\infty = 0.5, Re_\theta = 3550$	$M_\infty = 2.0, Re_\theta = 2650$
Mesh A	3.56×10^{-6}	2.78×10^{-6}
Mesh B	3.03×10^{-6}	2.57×10^{-6}
Mesh C	2.99×10^{-6}	2.41×10^{-6}
Wall-resolved LES	2.73×10^{-6}	2.28×10^{-6}

Table 4. Magnitude of wavefront distortions predicted by wall-modeled LES on three different meshes compared to wall-resolved LES results.^{6,23}

D. Aero-optical Predictions of Turbulent Boundary Layers

The aero-optical calculations are performed with an aperture size $10\delta \times 3\delta$. Figure 7 compares the normalized OPD_{rms} at $M_\infty = 0.5, Re_\theta = 2.7 \times 10^4$; $M_\infty = 2.0, Re_\theta = 6.9 \times 10^4$; and $M_\infty = 3.0, Re_\theta = 5.0 \times 10^4$ to the experimental measurements and the prediction by a model developed by Gordeyev et al.²⁷ A reasonable agreement is observed, but the rate of decrease of the predicted optical distortions with Mach number is slower than that of the experimental measurements. The causes of this discrepancy need further investigation.

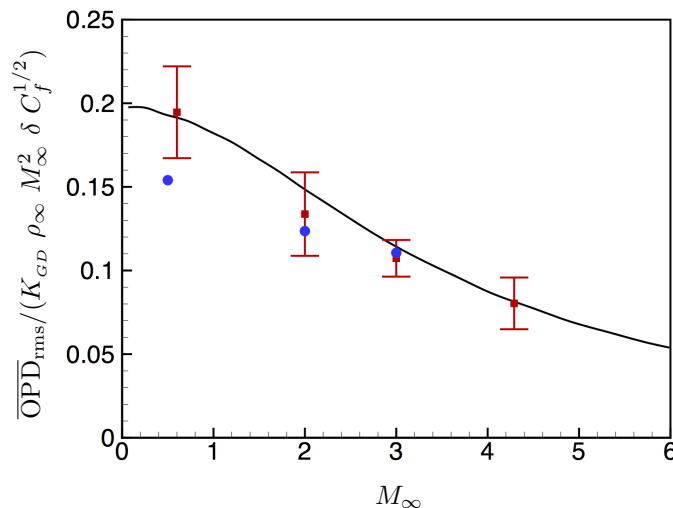


Figure 7. Normalized magnitude of wavefront distortions: •, Wall-modeled LES; ■, experimental measurements;^{26,27} —, model prediction.²⁷

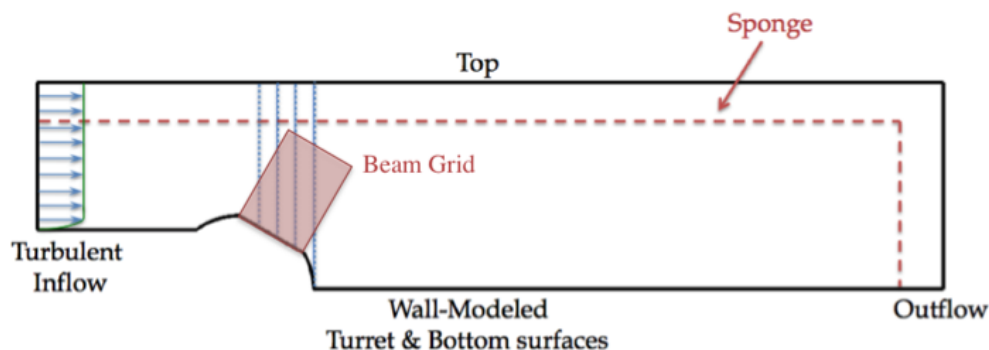


Figure 8. Schematic of the computational setup for subsonic flow over a cylindrical turret with a flat window. Dashed blue lines are the locations where comparisons are made with the experimental data and previous simulation results.

IV. Subsonic Flow over a Cylindrical Turret

The subsonic flow over a cylindrical turret is experimentally studied by Gordeyev et al.,¹ where a cylindrical turret of radius R is mounted between two flat plates of different altitudes. A flat window with a length of R is installed on the cylinder, which can be rotated to project the laser beam at different elevation angles. The Reynolds number based on the free-stream velocity and turret radius is $Re_R = 5.6 \times 10^5$. The free-stream Mach number at the inlet is $M_\infty = 0.5$.

In the present study, this flow is simulated at the experimental Reynolds number. As shown in Figure 8, the inlet station is located at $x = -2.75R$ upstream of the turret axle and the elevation angle of the

turret is fixed at 120° . The inflow data are generated by a separate wall-modeled LES using the rescale-and-recycle technique. The inlet boundary-layer thickness δ_{in} is approximately $0.14R$ and the momentum-thickness Reynolds number is $Re_\theta = 7650$. The domain size is approximately $12.6R$, $2.81R$ and $0.422R$ in the streamwise (x), vertical (y) and spanwise (z) directions, respectively. The mesh spacings at the inlet are $\Delta x \approx 0.05\delta_{in}$ ($\Delta x^+ \approx 300$), $\Delta y \approx 0.01\delta_{in}$ ($\Delta y_{min}^+ \approx 30$) and $\Delta z \approx 0.05\delta_{in}$ ($\Delta z^+ \approx 150$). The mesh has approximately 4.9 million grid cells. At CFL number of unity, the time step size is approximately $1.5 \times 10^{-4} R/U_\infty$. The computational expense of this wall-modeled LES is approximately 10% of that of the wall-resolved LES by Wang et al.² at a reduced Reynolds number that is 16% of the experimental value.

Four streamwise locations are indicated in Figure 8 where the results are compared to the experimental measurements and previous results from wall-resolved LES (Figure 9). Reasonable agreement is observed among the current results, the experimental data and previous numerical results. There is a small over-prediction in the mean velocity profiles in the upper part of the separated shear layer, and the velocity fluctuation levels are mildly under-predicted. In Figure 10, the rms values of density fluctuations are compared with the results of wall-resolved LES in the separated shear layer, and reasonable agreement is again observed.

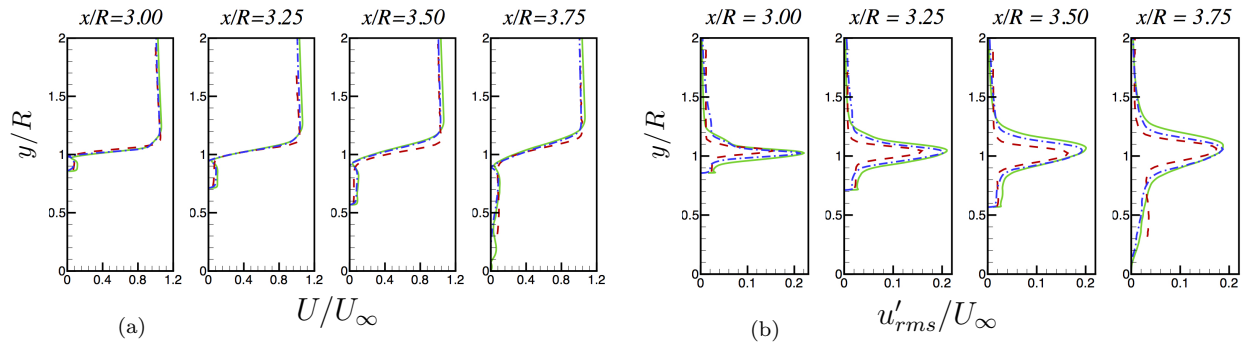


Figure 9. (a) Mean streamwise velocity profiles and (b) rms of velocity fluctuations at four locations above the optical window: —, Wall-modeled LES; - - -, wall-resolved LES² at reduced Reynolds number; —, experiment of Gordeyev et al.¹

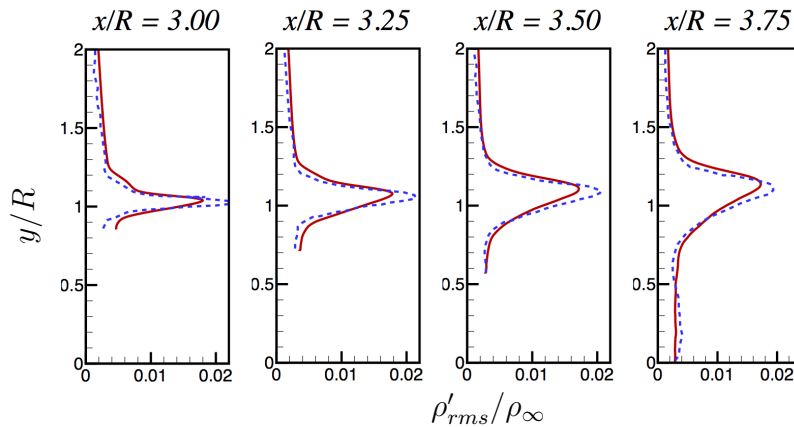


Figure 10. RMS of density fluctuations: —, Wall-modeled LES; - - -, wall-resolved LES² at reduced Reynolds number.

For aero-optical calculations, the aperture size is $1.0R \times 0.42R$ in the local $x'-z'$ plane, and the height of the beam grid is $2.0R$. An instantaneous optical wavefront is illustrated in Figure 11. In Table 5, the time-averaged OPD_{rms} values from the wall-modeled LES, the experimental measurement and the previous fully-resolved LES are listed. The magnitude of optical distortions between the two simulations agree very well, and both are approximately 10% higher than the experimentally measured value. The two-point correlation contours of OPD describing the wavefront structures are shown in Figure 12 with the origin located at the aperture center. Compared to that from the wall-resolved LES,²⁸ the shapes of the correlation contours

	$\overline{\text{OPD}}_{\text{rms}}/R$
Experimental measurement	6.39×10^{-7}
Wall-resolved LES	7.10×10^{-7}
Wall-modeled LES	7.17×10^{-7}

Table 5. Magnitude of aero-optical distortions from wall-modeled LES compared to the experimental measurements¹ and wall-resolved LES results² at reduced Reynolds number.

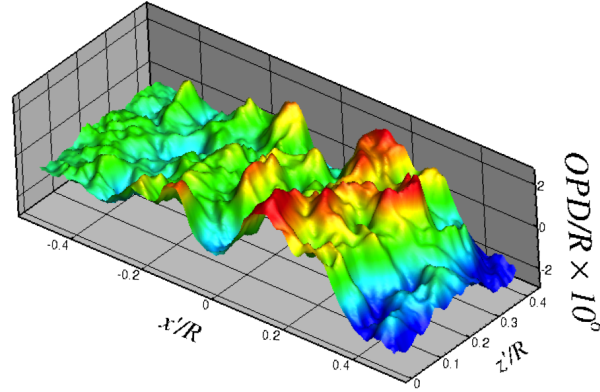


Figure 11. Instantaneous wavefront distortions obtained using wall-modeled LES.

from the two simulations are similar, but the wall-modeled results show larger streamwise and spanwise correlation lengths, which is a typical effect of coarser grid resolution.

V. Conclusion

Wall-modeled LES is utilized to simulate turbulent boundary layers and separated flows over a cylindrical turret at practical Reynolds numbers. Turbulent boundary layers are computed at a subsonic Mach number $M_\infty = 0.5$ and Reynolds numbers $Re_\theta = 2800$ – 31000 and at three supersonic Mach numbers, $M_\infty = 1.7, 2.0$ and 3.0 and corresponding experimental Reynolds numbers. There is a good agreement between the predicted velocity statistics and experimental measurements. It is found that predictions of density fluctuations and optical distortions are more demanding in terms of mesh resolution compared to velocity fluctuations, but promising results have also been obtained. For the subsonic flow over a cylindrical turret at $M_\infty = 0.5$ and $Re_R = 5.6 \times 10^5$ based on the turret radius, wall-modeled LES is employed to compute the flow at the same experimental conditions. The flow and aero-optical results show good agreement with the experimental measurements and results from a previous wall-resolved LES at a reduced Reynolds number. The results of this study demonstrate that wall-modeled LES can provide a cost-effective high-fidelity simulation tool for

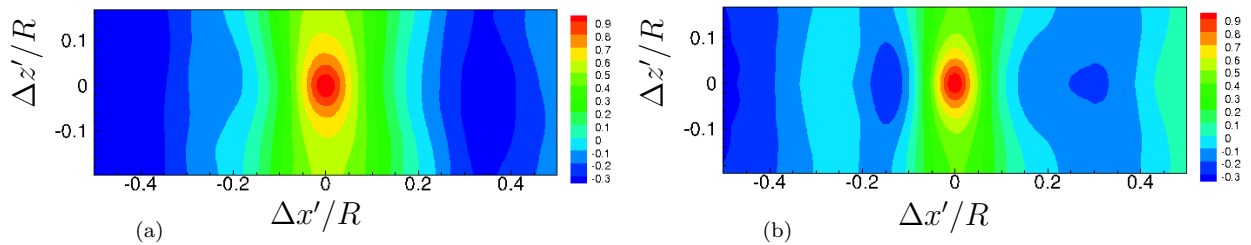


Figure 12. Two-point spatial correlations of OPD: (a) Wall-modeled LES ($Re_R = 5.6 \times 10^5$); (b) wall-resolved LES²⁸ ($Re_R = 8.8 \times 10^4$).

aero-optical flows at realistic flow conditions.

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