INVESTIGATIONS OF FLOW OVER A HEMISPHERE USING NUMERICAL SIMULATIONS (POSTPRINT)

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The research effort discussed here addresses the use of numerical simulations to predict the flow physics of a transonic flow over a hemisphere representing a laser beam director turret. Different computational fluid dynamics codes, including Loci-Chem, CFD++ and Vulcan, were used to ascertain their capability to predict these complex flow surrounding this structure. In addition, various types of turbulence models were tested, such as unsteady Reynolds-averaged Navier-Stokes (URANS), detached eddy simulation (DES), and hybrid RANS/LES. The numerical results were compared with the experiment conducted at Auburn University. Results showed that the URANS simulations using Loci-Chem and CFD++ overdamped the shear layer fluctuation associated with the hemispherical turret. Using the DES and hybrid RANS/LES turbulence models, Loci-Chem was able to capture the unsteady flow structures, such as the shear layer fluctuation, and the rolling motion of the vortex shedding. These solutions agreed well with the experimental data, as measured in the wall-pressure measurements, instantaneous density images, and optical path difference (OPD) analysis. Neither CFD++ nor Vulcan with these high fidelity turbulence models predicted the basic unsteady flow structures, and these solutions were not used to compute the OPD to compare with the experimental data.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The research effort discussed here addresses the use of numerical simulations to predict the flow physics of a transonic flow over a hemisphere representing a laser beam director turret. Different computational fluid dynamics codes, including Loci-Chem, CFD++ and Vulcan, were used to ascertain their capability to predict these complex flow surrounding this structure. In addition, various types of turbulence models were tested, such as unsteady Reynolds-averaged Navier-Stokes (URANS), detached eddy simulation (DES), and hybrid RANS/LES. The numerical results were compared with the experiment conducted at Auburn University. Results showed that the URANS simulations using Loci-Chem and CFD++ overdamped the shear layer fluctuation associated with the hemispherical turret. Using the DES and hybrid RANS/LES turbulence models, Loci-Chem was able to capture the unsteady flow structures, such as the shear layer fluctuation, and the rolling motion of the vortex shedding. These solutions agreed well with the experimental data, as measured in the wall-pressure measurements, instantaneous density images, and optical path difference (OPD) analysis. Neither CFD++ nor Vulcan with these high fidelity turbulence models predicted the basic unsteady flow structures, and these solutions were not used to compute the OPD to compare with the experimental data.

15. SUBJECT TERMS
Unsteady Reynolds-averaged Navier-Stokes (URANS), Detached Eddy Simulation (DES)
Investigations of Flow over a Hemisphere using Numerical Simulations

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Nomenclatures

\( D \) = diameter of the hemispherical turret
\( M \) = Mach number
\( OPD \) = optical path difference
\( OPD_{\text{rms}} \) = root mean squared of OPD
\( P \) = pressure
\( P_0 \) = total pressure
\( P_b \) = exit/back pressure
\( T_0 \) = total temperature
\( t \) = time
\( y^+ \) = nondimensional wall distance
\( \rho \) = density
\( \rho_\infty \) = freestream density

I. Introduction

The propagation of laser beams through turbulent flows has been an important topic for many years, with applications ranging from missile defense, remote sensing, and imaging. An important aspect of these applications is determining the effective beam-on-target characteristics after the beam has propagated through both the near-field turbulent flow field of the vehicle and the far-field turbulent atmosphere. Near-field propagation or aero-optics maintains some similarities to the far-field (atmospheric) propagation, but due to the interactions between turbulence length scales, beam
wavelengths, apertures and distances, the two often require different approaches to tackle.\textsuperscript{1-4} It is well known for aero-optics that the distortion of an optical wavefront is most severe when passing through a turbulent flow characterized by large-scale structures with strong density gradients. In addition, as the distortion is directly proportional to the density gradients, the magnitude of the problem becomes more challenging at high Mach numbers. These types of flows are inherently three-dimensional and unsteady at high Reynolds numbers and are often associated with separation.

A wall-mounted hemisphere immersed in a transonic crossflow exhibits large spatial and temporal density fluctuations in the shear layer and wake region, and is a highly three-dimensional, high-velocity, compressible flow field. This flow field is similar to the flow over a laser turret mounted to the fuselage of an aircraft. For a laser turret mounted to the fuselage of an aircraft, aero-optic distortion is a problem when the high-powered laser beam passes through the shear layer and the turbulent wake region. This wall-attached hemisphere flow field consists of an upstream flat-plate boundary layer, followed by a horseshoe/necklace vortex that forms just slightly upstream of the hemisphere near the junction of the hemisphere and the wall, as shown in Figure 1.\textsuperscript{5,6} The horseshoe/necklace vortex wraps around the bottom of the hemisphere and moves backward to the wake region. A separated shear layer extends from the top of the hemisphere as well as shedding vortices. These shedding vortices evolve into the turbulent wake downstream of the hemisphere. Shocks also can potentially form on top of the hemisphere at approximately 90º from the horizontal and are typically non-stationary. These complex flow physics pose challenges for computational fluid dynamics (CFD) to model the aberrating flows surrounding the optical apertures.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{Transonic flow over hemispherical turret.}
\end{figure}

The main goal of the current research was to use different CFD codes, including Loci-Chem,\textsuperscript{7,8} CFD++,\textsuperscript{9} and Vulcan\textsuperscript{10,11} to evaluate their capabilities in predicting the aero-optics flow features. In addition, various turbulence models, such as two-equation turbulence models, DES (detached eddy simulation), and hybrid RANS/LES were tested to determine whether these solutions could predict the correct physics associated with the transonic flow over a hemispherical turret. These numerical simulations were compared with the experiments conducted at Auburn University.\textsuperscript{12,13}

\section*{II. Experimental Setup}

The experimental configuration being simulated in this effort was examined in the Auburn University. A fixed wall wind tunnel was used for studying the flow field over a hemispherical turret at or near transonic speed, as shown in Figure 2. The test section consisted of a constant area of 10.16 cm x 10.16 cm with a freestream Mach number varying from Mach 0.75 at the entrance to 0.80 at the exit, presumably due to the boundary layer growth. A hemispherical turret with a 2.54 cm diameter was mounted on the top wall of the test section (Figure 2). Pressure measurements were positioned along the
centerline of one of the sidewall plate. In addition, the test section had three optical access windows located at the bottom wall and sidewalls. Detailed descriptions of the experimental setup are documented by Reid, et al.\textsuperscript{12,13}

![Diagram](image)

Figure 2  Schematic of the transonic wind tunnel at Auburn University.

### III. Numerical Method

Three-dimensional unsteady numerical simulations using Loci-Chem,\textsuperscript{7,8} CFD++,\textsuperscript{9} and Vulcan\textsuperscript{10,11} codes were performed on the transonic flow over a hemispherical turret to compare with the experimental data conducted by Reid, et al.\textsuperscript{12,13} The choice of these numerical codes was based on their capabilities in handling complex flow features, and their available turbulence models. For both Loci-Chem and CFD++ codes, unsteady RANS using two-equation turbulence model, DES, and hybrid RANS/LES were used in this study. DES (2-equation variant) model of Strelets was used in Vulcan.

Using OVERFLOW code,\textsuperscript{14} Coirier, et al.\textsuperscript{15} were able to capture the general flow physics for a subsonic flow over a turret, including the wake recirculation, necklace vortices, and the horseshoe vortex. In the early stage of this research, OVERFLOW was used to simulate the transonic wind-tunnel flow path, which did not include the hemisphere. The numerical solution compared well with the experimental wall-pressure data. However, to accommodate the capability of Vulcan code, the grid topology for the flow over the hemisphere did not consist of overlapping grids, which is required by Chimera overset grid approach\textsuperscript{16} used in OVERFLOW. Since it will be difficult to make direct comparison of each CFD code with different grid topologies, therefore OVERFLOW was not used in this study.

For brevity, the numerical schemes and the discussions of the turbulence models for these CFD codes are omitted, which their detailed descriptions can be found in reference.\textsuperscript{7-11} Note that among the CFD software tested in this study, only CFD++ (developed by Metacomp Technology, Inc.) is a commercial code. Table 1 summarizes the different CFD codes and turbulence models used in this study for the transonic crossflow over a hemispherical turret.

<table>
<thead>
<tr>
<th>CFD code</th>
<th>Turbulence model</th>
</tr>
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<tbody>
<tr>
<td>Loci-Chem</td>
<td>Menter SST (URANS), DES (1-equation), hybrid RANS/LES</td>
</tr>
<tr>
<td>CFD++</td>
<td>cubic κ-ε (URANS), DES (1-equation), hybrid RANS/LES</td>
</tr>
<tr>
<td>Vulcan</td>
<td>DES (2-equation variant) model of Strelets</td>
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</table>
Initial/Boundary Conditions

The transonic wind tunnel at Auburn University\textsuperscript{12,13} used a nominal $M = 0.78$ nozzle with an inflow total temperature ($T_0$) of $298.6$ K. The test section had a square cross-sectional area of 10.16 cm X 10.16 cm. The numerical simulations modeled from the facility-nozzle plenum to the entrance of the test section to provide the appropriate inflow conditions for the test section (Figure 2). This methodology avoids the use of ad-hoc profiles at the test-section entrance. However in the experiment, there was no measurement of the total pressure ($P_0$) at the entrance of the facility nozzle, or the exit pressure ($P_b$) before the wind tunnel throat section. Therefore the imposed $P_0$ at the transonic nozzle entrance and $P_b$ at the test section were based on trial-and-error approach to match the wall-pressure measurements along the side wall of the test section, which found to be $P_0 = 227.25$ kPa and $P_b = 148.5$ kPa. Note that fixed $P_0$ and $T_0$ inflow conditions were used at the entrance of the facility nozzle for all the simulations, including DES and hybrid RANS/LES turbulence models allowing static pressure relaxation. A no-slip, adiabatic boundary condition was imposed on the solid walls using the wall-function treatment.

Computational Grid

The computational domain was limited in extent to include the region from the transonic nozzle to the entrance of the wind tunnel throat section to reduce the CPU time. Therefore, neither the wind tunnel throat nor diffuser sections were included in the simulations (Figure 2). The total number of grid cells with a structured topology was 53.7 million, with high grid density around the hemisphere to ensure the numerical simulations could capture the lambda-shock structure as observed in the experiment,\textsuperscript{13} as illustrated in Figure 3. With the wall-function technique applied at the solid walls, the $y^+$ for the first cell above the wall around the hemisphere is less than 5. The maximum $y^+$ was as high as 65 located at the vicinity of the nozzle throat.

Data Sampling

Converged steady-state solutions were used to initiate the time-accurate simulations for the unsteady RANS (URANS), DES and hybrid RANS/LES. The time-step used in these simulations was $10^{-6}$ s, which was based on the minimum x-direction grid spacing divided by freestream velocity ($t \approx 3.8 \times 10^{-6}$ s). In addition, ten subiterations were used per global time step. Based on the experimental result,\textsuperscript{12,13} the vortex-shedding frequency was approximately equal to 3 kHz. The unsteady simulations were run to 20 ms (~60 cycles) to allow the initial starting transient to decay, then the data were sampled at a rate of 20 μs for the following 2 ms. However for the Loci-Chem using DES, the simulation was extended to 4 ms to observe the periodicity of the flow field.
IV. Results

The numerical results include comparisons of wall-pressure measurements, instantaneous density images, and OPD with the experiment conducted at Auburn University. The numerical simulations were performed using the unsteady RANS (URANS) to determine whether the two-equation turbulence models, such as Menter SST in Loci-Chem and cubic κ-ε turbulence models using CFD++, could predict the unsteady flow features associated with the shear layer fluctuations behind the hemispherical turret. URANS simulations are considered to be more cost-effective than DES and hybrid RANS/LES, in terms of CPU time. However these models are known to overdamp some unsteady flow features. Figure 4 shows the comparisons of the instantaneous vorticity contours from the experiment and numerical simulations. Loci-Chem predicted the fluctuation in the shear layer (Figure 4b), however the result did not show any distinct vortex shedding, as reported in the experiment (Figure 4a). On the other hand, CFD++ produced a very steady shear-layer flow structure as depict in Figure 4c, which could be due to the high damping effect from the cubic κ-ε turbulence model. The level of unsteadiness in the flow field from the numerical simulations could be observed from the wall-pressure distributions along the center of the side wall, as shown in Figure 5. From the 2 ms data collected using Loci-Chem, the result showed the fluctuations of the wall pressure (Figure 5a), which indicated the unsteady of the flow field. However, the solution did not show the rolling vortex structures. The simulation from CFD++ displayed no variation in wall pressure with respect to time, suggesting that the flow was steady (Figure 5b). Overall, the averaged wall-pressure distribution from the Loci-Chem simulation agreed well with the experimental data, indicating that the prescribed inflow $P_0$ and $P_b$ at the exit of the test section would be consistent with the experiment. Note the experimental data was obtained during the time intervals when the stagnation pressure was constant at the beginning of the test section during the run.

Figure 4 Instantaneous vorticity contours comparison between experiment and URANS.
Higher fidelity turbulence models, including DES and hybrid RANS/LES were used to examine their capability to predict the unsteadiness of the shear layer and the vortex shedding associated with the hemispherical turret. Using CFD++ code, neither DES nor hybrid RANS/LES simulations captured the vortex-shedding flow characteristics. In addition, both models showed similar trends. Therefore the solution from the hybrid RANS/LES was used for comparison. Figure 6a shows an instantaneous image of the vorticity contours, where the vortex appeared to be dissipated downstream of the hemisphere and did not form a distinct rolling motion. The wall-pressure distribution along the side wall indicated that the solution predicted some level of unsteadiness in the vicinity of the hemispherical turret, as illustrated in Figure 7a. However, the CFD++ simulations were not able to capture the general flow physics associated with the hemisphere indicated by the experiments.

A simulation using the Vulcan code with the DES turbulence model was attempted to represent the transonic flow over the hemispherical turret. The result showed a certain level of oscillation in the shear layer region, however the vorticity dissipated rapidly downstream of hemisphere, as shown in Figure 6b. The unsteady flow field was picked up in wall-pressure distribution, as depicted in Figure 7b. After performing detailed analysis of the solution, it was discovered that the blending function in the DES model was not activated. Therefore, the current result was a representation of an unsteady RANS simulation. Further effort is underway to improve the DES capability in Vulcan.
Loci-Chem simulations using DES and hybrid RANS/LES turbulence models were performed to predict the flow physics around the hemispherical turret. Figure 8 shows the instantaneous vorticity contours from both turbulence model simulations, which exhibited the shear-layer oscillations and rolling motion of the vortices, as observed in the experiment data (Figure 4a). The unsteadiness within the wall pressure distributions along the center of the side wall was predicted by both models, as illustrated in Figure 9. In addition, the numerical results followed a similar trend as compared to the experimental data. As mentioned early, the simulation using DES model was run to 4.0 ms to ensure that the flow is statistically steady or periodic. Figure 10 shows the time history of the wall pressure at x/D = 0 at the center of the side wall, which indicated the periodicity of the flow field. The oscillation of the shear layer appeared to be caused by the feedback mechanism of the vortex shedding, as depicted in Figure 11. The pressure contours are shown on the wall surface, and the numerical shadowgraph is on the centerplane. Note the numerical shadowgraph was computed based on the density gradients, defined as

$$\sqrt{\left(\frac{\partial \rho}{\partial x}\right)^2 + \left(\frac{\partial \rho}{\partial y}\right)^2}$$

As the vortex rolled up downstream of the hemisphere (Figure 11a), it pushed the shear layer upward away from the hemisphere, which pushed the shock upstream (Figure 11b-d). As the vortex structure behind the wake region diminished, the shear layer would fluctuate downward towards the hemisphere, then another shock structure on top of the turret would start to form, as illustrated in Figure 11e. As a new vortex started to form behind the hemisphere, a larger separation region was created and enhanced the shear layer fluctuation. In other terms, this flow feature would repetitively generate a lambda shock structure on top of the hemisphere (Figure 11f). Although this solution was based on the DES model, hybrid RANS/LES simulation showed similar flow behavior.

Comparisons of the instantaneous density images were made between Loci-Chem simulation using DES and the experiment data, as shown in Figure 12. Overall, the numerical simulation was able to capture the main flow features as observed by the experiment, such as the rolling motions of the vortex (Figure 12a and Figure 12e), and the wake structures behind the hemisphere (Figure 12b-d). Note, the density for the numerical simulation was normalized by $\rho_\infty = 2.06$ kg/m$^3$, which was the mass-flow-averaged quantity at the entrance of the test section. Figure 13 shows the comparisons of OPD between the experiment and Loci-Chem using DES and hybrid RANS/LES simulations at two different time intervals. Overall the results from both models provided good agreement as compared to the experimental data. In addition, the temporal OPD$_{rms}$ value or the standard deviation of the OPD of this wavefront propagation angle was compared between the numerical results and experiment, as depicted in Figure 14. Both models predicted the general trends within the experimental data; however the numerical
simulations underpredicted the values between $0 < x'/D < 0.17$. This discrepancy could be due to absence of flow structures in the shear layer region of the simulations. In order to improve the numerical predictions, one approach is to increase the grid resolution near the shear layer and the wake region. The other technique which could potentially improve the simulations is to change the wall-treatment boundary condition from wall-function to solve-to-the-wall methodology. These issues will be investigated in the future effort.

Figure 8  Instantaneous vorticity contours using Loci-Chem.

Figure 9  Wall-pressure comparisons along the side wall between Loci-Chem CFD code and experiment.

Figure 10  Time history of wall pressure at $x/D = 0$ at the center of the side wall.
Figure 11  A typical cycle of the vortex shedding.
Figure 12  Instantaneous density images comparisons between experiment and Loci-Chem.
Figure 13  Instantaneous density images comparisons and OPD between experiment and Loci-Chem.
Figure 14 Temporal OPD comparisons between experiment and Loci-Chem.

V. Conclusions and future work

Numerical simulations were performed using three different CFD codes, including Loci-Chem, CFD++, and Vulcan, to predict the transonic crossflow over a hemispherical turret. Unsteady RANS, DES, and hybrid RANS/LES turbulence models were used to determine the ability to capture the flow physics, such as shear layer fluctuations and vortex shedding. The numerical results were compared with the experiment conducted by Auburn University, in terms of wall-pressure distributions, density images and OPD. In general, the numerical simulations were able to match wall-pressure distributions, and followed the trends within the experimental data.

Unsteady RANS simulations were performed using Loci-Chem with Menter-SST, and CFD++ with a cubic $\kappa$-$\epsilon$ turbulence model. Although Loci-Chem was able to predict shear-layer oscillations behind the hemispherical turret, the solution did not show any distinct rolling motion of the vortex shedding as observed in the experiment. On the other hand, CFD++ produced a very steady shear-layer flow feature. These results indicated that the unsteady RANS overdamps the unsteady flow structures behind the hemisphere.

Using the CFD++ code with either DES or hybrid RANS/LES turbulence models, both simulations could not capture the vortex shedding flow characteristics. With the Vulcan code, the blending function in the DES turbulence model was not functioning correctly, therefore the solution was showing a representation of an unsteady RANS simulation. Due to the lack of capturing the flow features associated with the hemispherical turret, these solutions were not used to compute the OPD and compare with the experimental data.

Both DES and hybrid RANS/LES turbulence models in Loci-Chem code were able to predict the shear layer fluctuation and the rolling motion of the vortex shedding, which observed in the experiment. Quantitative comparisons, in terms of instantaneous OPD and OPD$_{rms}$, were made between the numerical simulations and experiment data. The instantaneous OPD showed good agreement between CFD and experiment, however both models underpredicted the OPD$_{rms}$ at $x'/D < 0.17$. This discrepancy could be due to some flow structures not being captured near the shear layer region.

The ongoing research is to improve the numerical prediction using Loci-Chem. One method is increase the grid resolution within the shear layer and the wake region. The other technique is to change the wall-treatment boundary condition from wall-function to solve-to-the-wall methodology. In addition,
OVERFLOW and Kestrel CFD codes will be used to determine their capabilities of capturing the flow physics associated with the hemispherical turret.

VI. Acknowledgments

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VII. References

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