Aero-Optical Investigation of Shock-Related Effects on Hemisphere-On-Cylinder Turrets at Transonic Speeds

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Abstract. Aero-optical environment around a hemisphere-on-cylinder turret with both flat- and conformal windows was studied experimentally in-flight using the Airborne Aero-Optical Laboratory (AAOL) for a range of subsonic and transonic Mach numbers between 0.5 and 0.8. Above M = 0.6, the local shock appeared near the top of the turret, causing additional aero-optical distortions at side-looking angles. Using time-resolved wavefronts, instantaneous shock locations were extracted and analyzed. The mean shock location was found to be near a viewing angle, \( \alpha = 80 \) degrees for both window types at M = 0.7 and 0.8. For M = 0.8, the shock has a single frequency peak at StD = 0.15, the same as for the unsteady separation line, indicating a lock-in mechanism between the shock and the separated wake region. Analysis of aero-optical distortions in the wake indicated that the wake dynamics were beginning to be affected by the shock only at high transonic speed of M = 0.8 for the conformal-window turret.

Keywords: optics, lasers, aerodynamics, wavefronts.

1. Introduction

As it is desirable to have airborne directed energy and free-space communication systems that are usable at cruise speeds in the high transonic flow regime with hemisphere-on-cylinder turrets (Ref. [1-4]) a detailed study of the transonic effects on turrets and their aero-optical implications is needed. The hemisphere-on-cylinder turret is geometry-of-choice for laser airborne systems for maximizing the potential field-of-regard of a given system. In the last decade, many experimental studies in tunnels,4-12 and numerous detailed numerical simulations13-23 were carried out to understand the topology, dynamics and aero-optical effects around turrets at fully subsonic speeds below M = 0.5.

Development of Airborne Aero-Optical Laboratory (AAOL) program1 provided a unique opportunity to collect aero-optical data around different turret geometries in realistic flight environment.24,25 The impact of this program is hard to over-estimate; for example, in 2013 a special issue of Journal of Optical Engineering with 19 papers25 was devoted to analysis of aero-optical results collected with AAOL.

Recently, these aero-optical and fluidic studies were extended to transonic (Ref. [15,16,27-34] and supersonic16 flow regimes over various turret configurations. Additionally, further work has been performed on cylindrical turrets to study shock dynamics and topology at transonic Mach numbers (Ref. 35-37]).

Fig. 1 Top: Flow topology around a turret at subsonic speeds. Bottom: Transonic flow features on the turret. (Ref. [4])
Flow over turrets is considered to enter the transonic flow regime for Mach numbers greater than 0.55 (Ref. [4]). Above this critical Mach number, flow becomes locally supersonic on the turret. This locally supersonic flow region can affect the various flow features on the turret. Figure 1, top, shows the general flow features on a turret and Figure 1, bottom, shows additional effects in the transonic regime. The most notable difference from a turret in subsonic flow is the presence of a local unsteady shock on the turret (Ref. [31,32,34]). The behavior of this shock is dependent on the freestream Mach number. This shock also can cause a premature wake separation (Ref. [30-32]), or locally introduce additional optical distortions (Ref. [29,33,36]). Other than the presence of the shock, the subsonic flow features around the turret are still present in the transonic regime. A necklace vortex forms as the boundary layer rolls up near the base of the turret and extends downstream. Whether induced by the shock or the adverse pressure gradient on the downstream portion of the turret, separation occurs and forms a fully turbulent wake, with reattachment on the wall downstream of the turret. The upstream portion of the turret exhibits little turbulence, as the accelerating flow remains attached and the boundary layer is thin.

Tunnel tests with small turret models are very useful to study different physical aspects of the shock-wake interaction. However, to properly study the flow dynamics and related aero-optical effects for realistic turret-based systems, one must assure that the Reynolds number, based on the turret diameter is larger than the critical Reynolds number of about 500,000 (Ref. [4]). It means that the turret model should be large enough to satisfy this condition, requiring the usage of large tunnels. Furthermore, to eliminate blockage effects at high transonic speeds, one must use tunnels with porous tunnel walls. Finally, many large windows with good optical quality should be installed in a tunnel to collect useful aero-optical data at various field-of-regard angles. All these requirements significantly limit the number of available tunnels to perform turret-related aero-optical studies. To overcome these difficulties, a successful AAOL program (Ref. [1]), designed to study aero-optical environment in flight, was extended into Airborne Aero-Optical Laboratory-Transonic (AAOL-T) program (Ref. [38]), using faster Falcon 10 planes, capable of flying up to $M = 0.85$, to specifically study transonic aero-optical effects in flight.

Several recent studies have shown that the separation is prematurely triggered by the shock, resulting in a different separation region size. The details of how the shock affects the flow dynamics, including the unsteady pressure field and resulting unsteady forces, acting on the turret, are not quite clear at this moment. Also, exact effect of this unsteady shock on the aero-optical environment around turrets is still under investigation and is the main objective of this paper.

When a laser beam traverses through the interrogated region, resulting aero-optical distortions or wavefronts are proportional to the integral of the density field in the propagation direction. Thus, wavefronts do not have any information along this direction and one should be careful interpreting the wavefront data. For instance, wavefronts cannot measure the extent of the shock into the flow or exact details of the shock lambda-structure near the wall. Nevertheless, spatially-temporally-resolved wavefronts still can provide valuable information about the temporal variation and some spatial information about the turbulent flow.

This paper presents results of recent aero-optical flight measurements for the AAOL hemisphere-on-cylinder turret with different window geometries over a range of elevation and azimuthal angles for a range of Mach numbers between 0.5 and 0.8. Section 2 describes the experimental set-up; the data reduction procedures are given in section 3. Results are presented in section 4, followed by conclusions in section 5.

2. Experimental Setup

Wavefront measurements were performed on the AAOL-T. The turret is a hemisphere-on-cylinder turret, with the diameter of 1ft. and the cylindrical height of 4 in. The turret assembly has an optical window with a 4-in. aperture, which can be either flat or conformal. The turret assembly features a fast steering mirror (FSM) to stabilize the beam on the optical bench. The AAOL-T program consists of two Falcon 10 aircraft flying in closed formation. The laser aircraft projects a diverging laser beam that overfills the aperture by a factor of 2 onto the turret of the laboratory aircraft. Aircraft separation is maintained at approximately 50 m while data is being acquired. Pictures of the turret and optical bench are shown in Fig. 2 and Fig. 3 shows a schematic of the optical setup in the laboratory aircraft.
Two separate flying campaigns were conducted to investigate aero-optics of the turret with different window geometries. During the first campaign, the optical environment around the flat-window turret was investigated at the following Mach/altitudes in feet: 0.5/15,000, 0.6/18,000, 0.7/26,000 and 0.8/26,000. During this campaign, wavefront measurements were performed using a high-speed Shack-Hartmann wavefront sensor. Like the data collection during AAOL program, two different acquisition modes were used for wavefronts: slewing maneuvers and fixed point data. Slewing maneuvers involved the laser aircraft moving relative to the laboratory aircraft while wavefronts were continuously acquired; these maneuvers allow for rapid mapping of the optical environment around the turret.24,25 Fixed point data involved the laser plane maintaining a fixed position with respect to the laboratory aircraft. These acquisitions were performed at a higher sampling rate, as the goal of fixed point data acquisitions is to investigate specific flow phenomena with a better temporal resolution. Wavefronts were collected with the spatial resolution of 32x32 subapertures and sample rates of 25 kHz for 0.7 seconds for fixed points and 3 kHz for 10-30 seconds for slewing maneuvers. Simultaneous with the 2D wavefronts, the overall beam jitter was also measured using a position sensing device. The jitter was acquired along with the turret azimuthal/elevation angle and FSM position information at 25 kHz for 10s. Flight conditions were also recorded with the wavefront and jitter measurements. The aircraft separation was measured using a differential GPS system.

During the second campaign, the turret with both the flat- and the conformal windows was flown at the following Mach/altitudes in feet: 0.5/15,000, 0.6/15,000, 0.7/32,000, and 0.8/32,000 and optical data at both fixed points and slewing maneuvers were collected. During this campaign, wavefronts with collected with a better spatial resolution of 40x40 subapertures and sample rates of 30 kHz for fixed points and 2 kHz for slewing maneuvers. Simultaneous with the 2D wavefronts, the beam jitter was also measured using a position sensing device at 50 kHz for 30 seconds.

3. Data Analysis

Reducing the Shack-Hartmann images gives the measured wavefronts, $W$, as a function of location on the aperture and time. Through least-squares plane fitting, any residual instantaneous piston and tip/tilt were removed from the wavefronts, and the steady lensing was removed by removing the mean of the wavefront at every subaperture. The optical path difference (OPD) is the conjugate of the wavefront, $\text{OPD}(\hat{x},t) = -W(\hat{x},t)$. 
Both the beam direction and any point over the aperture are characterized by the azimuthal (Az) and elevation (El) angles. From a fluid dynamics perspective, it is more useful to recast these angles into a different coordinate system (Ref. [4,24]). This system uses a viewing angle, α, that determines the angle between the incoming flow and the outward normal vector at any point on the turret and the modified elevation angle, β, that quantifies the angular distance from the wall of the aircraft. The viewing angle and the modified elevation angles are illustrated in Fig. 4 and are given by:

\[ \alpha = \cos^{-1}(\cos(Az)\cos(El)) \]  
\[ \beta = \tan^{-1}\left(\frac{\tan(El)}{\sin(Az)}\right) \]

To compare the aero-optical performance of the turret across various Mach numbers, wavefronts were normalized by the flight conditions as,  

\[ \text{OPD}^\text{Norm} = \text{OPD} \left(\frac{\rho}{\rho_{\text{SL}}}\right)^{1/2}M^2D \]  

In this normalization, \( \rho \) is the freestream density, \( \rho_{\text{SL}} \) is the density at sea level (\( \rho_{\text{SL}} = 1.225 \text{ kg/m}^3 \)), \( M \) is the Mach number and \( D \) is the turret diameter. This so-called ‘\( \rho M^2 \)’-scaling has been previously shown to collapse subsonic data acquired in flight and in the tunnel (Ref. [4,24,25]), and it is of interest to see whether this scaling still holds for transonic regimes.

A traditional way to represent aero-optical distortions over the aperture at different viewing angles is to determine a time-averaged spatial variation of the OPD across the aperture:

\[ \text{OPD}^\text{Norm}_{\text{RMS}}(\alpha, \beta) = \left( \langle \text{OPD}^\text{Norm}((\vec{x}, t))^2 \rangle_{\text{over aperture}} \right)^{1/2} \]  

Here the square brackets denote spatial averaging and the overbar defines temporal averaging, \( \vec{x} \) is the position on the aperture, and \( t \) is time. This time-averaged \( \text{OPD}^\text{Norm}_{\text{RMS}} \) quantifies the amount of aberration present in the beam for a specific viewing direction and can be used to estimate the far-field intensity on a target (Ref. 39, 40).

Another way to quantify the aero-optical distortions is to compute the spatial distribution of the temporal variation of the wavefronts (Ref. [25]),

\[ S(\alpha, \beta) = \left( \langle \text{OPD}^\text{Norm}(\alpha, \beta; t)^2 \rangle_{\text{over aperture}} \right)^{1/2} \]

Later in this paper this quantity will be called the spatial distribution of the wavefronts for brevity. It is important to distinguish between the quantities defined in Eqs. (1) and (2). \( \text{OPD}^\text{Norm}_{\text{RMS}}(\alpha, \beta) \) describes the spatial deviation of the aero-optical distortions over a given aperture and is directly related to the far-field intensity (Ref. [39,40]). This quantity depends on the aperture size and angles \( \alpha \) and \( \beta \) define the location of the middle of the aperture. \( S(\alpha, \beta) \) describes the temporal variation of aero-optical wavefronts at a given direction, characterized by \( \alpha \) and \( \beta \), over the turret and is directly related to the strength of aero-optical flow features over the turret; it is largely independent on the aperture size. Only fixed points were used to compute the spatial distribution of the wavefronts.

To quantify the temporal behavior of the wavefronts for a given aperture viewing angle, the aperture-averaged, normalized wavefront spectra, also known as temporal PSD of the wavefronts, were calculated,

\[ S_W(f; \alpha, \beta) = \left( \langle \text{W}^\text{Norm}(f, \vec{x}) \rangle_{\text{over aperture}} \right)^2 \]

Where \( f \) is frequency, and \( S_W \) is the aperture-averaged, normalized wavefront spectra.
Since the shock causes a high density gradient, which in turn causes high OPD variation, studying spatial-temporal variation of the wavefronts provides valuable insight in the dynamics of the shock motion. While the wavefront may not provide an exact shock location of the turret, simultaneous measurements of the wavefronts, shadowgraphs and unsteady pressure of the surface revealed that there is a good correlation between the shock location and the sharp changes in the wavefront. Since in this paper only optical results are analyzed, any mention of the shock will mean the sharp increase in the wavefront and the instantaneous shock location can be estimated by analyzing OPDs at each time step. To track the shock motion, a single $\beta$-angle is chosen and the one-dimensional OPD at that angle is extracted, represented by the black line in Fig. 5. The shock location was chosen to be the location of the highest positive slope in the 1-D OPD, which was found by locating the maximum of its derivative; a similar shock-tracking technique was used in.\textsuperscript{25}

4 Results

A. Conformal-Window Turret

Experimental and numerical studies of the effects of different dynamical features, outlined in Fig. 1, left, on aero-optical environment around turrets at fully subsonic speeds were addressed in detail in the Introduction. Here relevant subsonic results will be described only briefly for the sake of completeness, as the focus of this paper is the discussion of the additional aero-optical effects caused by the presence of the unsteady shock around the turret at high transonic speeds.

Temporal sequences of wavefronts at fixed points and during slewing maneuvers were analyzed and normalized values of OPD RMS were computed. Results as a function of the viewing angle, $\alpha$, and Mach number for high-$\beta$ angles, $\beta = 60-90$ degrees, are presented in Fig. 6, top and the results for low $\beta = 20-60$ degrees are shown in Figure 6, bottom. Convergence and uncertainty analysis, similar to one in (Ref. [24]), (not presented here) gave the approximate relative error of aero-optical measurements as 5-10%. At subsonic speeds of $M = 0.5$ the flow is subsonic everywhere around the turret. As discussed in the Introduction, above the critical Mach number of 0.55, the local supersonic region with the resulting unsteady shock appears over the turret. However the shock is really weak and intermittent at $M = 0.6$ and does not affect the dynamics of the separated region (Ref. [25]). The flow stays attached over the turret up to the viewing angle of approximately 100 degrees with the low resulting OPD RMS as the conformal-window does not trip the flow around the window. Above $\alpha = 100$ degrees, the flow separates (Ref. [4,11,36]), and forms the unsteady separation wake downstream of the turret, resulting in progressively-increased levels of the aero-optical distortions with the increasing viewing angle. Thus, the location of where OPD RMS starts increasing can be used to estimate the location of the separation line. The “horn” vortices, formed on both sides of the turret close to the center plane, outlined in Fig. 1, left, caused additional distortions at high $\beta$-angles, see Fig. 6, top, compared with the distortions at the low $\beta$-angles, Fig. 6, bottom.
Fig. 6 Normalized OPD$_{RMS}$ versus viewing angle for $M = 0.5$-0.8 for the conformal-window turret for a range of $\beta = 60$-90 degrees (top) and $\beta = 20$-60 degrees (bottom) at Mach 0.5 ($\blacktriangledown$), 0.6 ($\blacksquare$), 0.7 ($\blacklozenge$), 0.8 ($\blacklozenge$). Dashed red arrow indicates an approximate location of the flow separation. The wake region is identified by large values of OPD$_{RMS}$ above $\alpha = 100$ degrees. Comparison with results for the conformal-window turret with "smiles" from Ref. 25 is also presented.

Results from previous flight tests at $M = 0.5$ of the same turret but with "smiles" uncovered$^{25}$ at high $\beta$ angles are also shown as a shaded region in Fig. 6, top. As the "smiles" were covered in the present tests and they were present in the tests, reported in Ref. 25, comparison of aero-optical distortions with and without "smiles", shown in Fig. 6, top, did not reveal any significant differences. It is an expected result, as the effect of the "smiles" on the vortical structures in the separated wake was shown to be confined primarily near the base of the turret, corresponding to low $\beta$ angles.

At higher transonic Mach numbers of 0.7 and 0.8 the unsteady shock intensifies and additional optical distortions related to the shock motion$^{36}$ appear at the viewing angle of approximately 80 degrees, seen as a local increase of the normalized OPD$_{RMS}$ in Fig. 6. The flow is prematurely tripped by the shock at these speeds, causing an earlier separation over the turret.$^{30}$ Nevertheless, the normalized aero-optical distortions above $\alpha = 100$ degrees for $\beta > 60$ degrees, see Fig. 6, top, are approximately the same for both the subsonic and transonic Mach numbers, with slightly-less values for $M = 0.8$, compared with $M = 0.7$ case. For low $\beta$-angles, normalized optical distortions for $M = 0.8$ are also less than for the $M \leq 0.7$, see Fig. 6, bottom. Oil visualization of the surface flow topology around a hemisphere, reported in,$^{30}$ had revealed that at high transonic speeds the increased interaction between the shock and the separated wake modified vortical structures in the wake. This increased interaction causes the "horn" vortices to move closer to the centerline, resulting in smaller distortions at low $\beta$-angles at high transonic Mach numbers, observed in Fig. 6, bottom. More on the wake response to the unsteady shock will be further discussed later in this paper.

Although not perfect, the approximate collapse of aero-optical data at high $\beta$-angles in the wake region for $\alpha = 100$-120 degrees indicates that the "pM"-scaling, used to normalize aero-optical data, still can be used to re-scale data to different turrets and subsonic and transonic speeds. However, at side-looking angles the presence of the shock creates additional aero-optical effects and the scaling fails to collapse the data at these angles. A similar lack of collapse is evident for large $\alpha > 120$ degrees, which in part might be attributed to sparse data at these angles.

Another way to study spatial distribution of the aero-optical distortions is to inspect the spatial distributions of the wavefronts, defined in Eq. (2), over the turret. As the conformal window does not change the turret shape, this spatial distribution is independent of the window viewing angle and is only related to various vortical features of the separated wake. The spatial distributions of wavefronts for different aperture locations were projected on the turret and were averaged in overlapping regions. The spatial distribution of the wavefronts over the turret surface for $M = 0.6$ is presented in Fig. 7. Aero-optical distortions are small at the forward portion of the turret where the flow is attached. A region of increased distortion, related to the separation or wake region, which is dominated by "horn" vortices, is clearly visible. As the vortices are present on both sides of the turret, they create an additional velocity downwash in between them along the centerline, see Fig. 1, left. This increased downwash results in smaller wake size along the center plane, with the correspondingly smaller levels of aero-optical distortions for the increased range of $\alpha$ up to 125-130 degrees. This region is labelled as "quiet valley" in Fig. 7 and was also observed around flat-window turrets,$^{24}$ and in numerical simulations of the flow around the conformal-window turret (Ref. [13]).
Similarly, spatial distributions of the wavefronts were computed for transonic Mach numbers of $M = 0.7$ and $0.8$ and the results are presented in Fig. 8. As the optical system inside the turret has a small, one-inch in diameter, middle obscuration, wavefronts are known only inside rings, seen in Fig. 8. The shock creates additional localized distortions and it is clearly visible as a line of the increased distortions around $\alpha = 80$ degrees. The shock-related optical intensity increases with Mach number, as expected. The average shock location is independent of the elevation angle, $\alpha$. The “quiet valley”, while still present at these transonic speeds, is weakened and does not extend as far downstream, as for $M = 0.6$ case. The “horn”-vortex-related region weakens as well and moves closer to the center plane at $M = 0.8$, compared to $M = 0.7$ case, indicating the changes in the separation wake dynamics due to the unsteady shock. Similar trends were also observed around hemisphere-only turrets.29

A similar analysis of aero-optical environment around hemisphere-only turrets have shown that the shock is located further downstream, around $\alpha = 85$ degrees (Ref. [29]). The exact reason why the shock appears more upstream for the full turret, compared to the hemispherical one is not quite clear at this moment and additional studies should be performed to see whether it is related to a particular flying platform or not.

A final comment about the maps of the spatial distribution of the wavefronts, presented in Figs. 7 and 8 is that it provides useful non-intrusive means of studying spatial extent and intensity of density-varying structures in turbulent flows.
To further study the temporal dynamics in the shock, spatial-temporal evolution of 1-D slices of the wavefronts were extracted at different β-locations and Mach numbers and the instantaneous shock location was extracted, as it was described before. Figure 9 shows a one-dimensional slice of wavefronts for a conformal-window turret taken at $M = 0.7$ with $β = 76$ degrees and $M = 0.8$ at $β = 67$ degrees, respectively. The black dots represent the shock location for each time step. The shock motion is not periodic for either case, although the shock for $M = 0.8$ clearly has a single preferred frequency. Shocks are present consistently for each Mach number. The shock location for $M = 0.7$ varies from 79 degrees to 86 degrees, while for $M = 0.8$ it has a larger range of 81 degrees to 85 degrees. The $M = 0.8$ case also has a larger non-dimensional time between peaks than the $M = 0.7$ case, indicating a lower oscillation frequency content.

Figure 10 depicts the mean shock locations at different β-angles with bars representing the range of $α$ where the shock is present 90% of the time. As it was already observed in Figure 8, the mean shock location angle does not change significantly with changing β. For $M = 0.7$ the mean shock location tends to be at slightly lower angles than the mean angular values for a given β for $M = 0.8$. 

![Figure 9](image1.png)

**Fig. 9** Spatial-temporal evolution of 1-D slice of wavefront data with $M = 0.7$ (top) at $β = 76$ degrees and $M = 0.8$ (bottom) at $β = 67$ degrees. Black circles indicate the approximate shock location.

![Figure 10](image2.png)

Figure 10 depicts the mean shock locations at different β-angles with bars representing the range of $α$ where the shock is present 90% of the time. As it was already observed in Figure 8, the mean shock location angle does not change significantly with changing β. For $M = 0.7$ the mean shock location tends to be at slightly lower angles than the mean angular values for a given β for $M = 0.8$. 

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The normalized spectra of the shock position for a conformal window at $M = 0.7$ and $M = 0.8$ are shown in Fig. 11. The most discernable difference between the two is that the $M = 0.7$ case has two peaks around $St = 0.18$ and $St = 0.4$, while the $M = 0.8$ case has only one peak near $St = 0.15$; this lower-frequency dynamic was already observed in Figure 9. Pressure measurements in the turret wake have showed similar peaks for both $M = 0.7$ and $0.8$.\textsuperscript{42} To understand a possible mechanism of this low-frequency dynamics, let us recall that a weaker, intermittent shock was observed over the conformal-window turret in flight at lower $M = 0.65$ with a typical frequency of $St \sim 0.5$ (Ref. [25]). Also, $StD = 0.15$ has been associated with the unsteady separation line motion over a wide range of subsonic\textsuperscript{6} and transonic\textsuperscript{42} Mach numbers. At low transonic speeds the shock dynamics is mostly independent of the separation region dynamics. At higher Mach numbers the shock becomes strong enough to force a premature separation, effectively coupling or locking-in the shock and the separation line dynamics. In Ref. 36 a strong coupling between shock location and strength with the location and size of the separated region was studied over cylindrical turrets and an acoustical feedback was proposed as a possible mechanism for locking the dynamics of the shock and the shock-induced separation region. Whether a similar lock-in mechanism is present over the three-dimensional turret is currently under investigation.

To further study the temporal dynamics of the shock and the wake, the aperture-averaged wavefront spectra, defined in Eq. (6), were computed for all tested Mach numbers. Figure 12 presents the wavefront spectra at the viewing angle of 80 degrees, where the shock is present at high transonic speeds. While spectra at low speeds of $0.5$ and $0.6$ are fairly weak, with one peak around the unsteady-separation-related value of $StD = 0.15$, the spectrum for $M = 0.7$ shows two peaks around $0.15$ and it’s harmonic around $0.3$. At higher $M = 0.8$, the peak around $0.15$ becomes dominant. At these Mach numbers, the optical distortions are primarily shock-driven, so these peaks correspond to the peaks, observed in the shock-motion spectra in Fig. 11.
Figure 13 shows the normalized wavefront spectra in the wake region, for $\alpha = 120$ degrees, Fig. 13, top, and for $\alpha = 140$ degrees, Fig. 13, right. At $\alpha = 120$ degrees, the spectra exhibit self-similar behavior for subsonic and transonic speeds with a peak at a higher frequency of around $St_D = 1.3$. This value is associated with smaller shear-layer structures forming in the wake (Ref. [41]). Thus, while the shock causes the premature flow separation near the apex of the turret at high transonic speeds, when the flow is separated, the presence of the shock does not affect the dynamics of the shear-layer structures in the separation region, except for the highest Mach number of 0.8, where an additional small peak appears in the spectra at $St_D = 0.15$. Thus, the shock motion, associated with the lower frequency of $St_D = 0.15$, starts modulating or affecting the temporal evolution of the shear-layer structures in the wake at high transonic speeds. The modulation effect can also be observed at $\alpha = 140$ degrees, see Figure 13, bottom, where the peak at $St_D = 0.15$ is the same order of magnitude, as the shear-layer-related peak of $St_D = 1.3$ for $M = 0.7$ and $M = 0.8$.

B. Flat-Window Turret

The effect of the presence of the flat window on the flow and related aero-optical distortions around turrets at subsonic speeds was discussed in Ref. 24. The main effect was observed at side-looking angles around $\alpha = 100$ degrees, where a small separation bubble forms over the window, causing additional aero-optical aberration over a range of viewing angles between 90 and 100 degrees. Figure 14 shows the normalized $OPD_{RMS}$ values for the flat-window turret as a function of Mach number and the viewing angle. As $M = 0.5$-case was extensively studied in in Ref. 24, only few points for $M = 0.5$ were collected during this work, mainly for comparison and repeatability purposes. $OPD_{RMS}$ values, measured during these tests are very similar to values from Ref. 24, shown in Fig. 14 as a gray-shaded region. For both $M = 0.5$ and 0.6, $OPD_{RMS}$ values are small for $\alpha < 90$ degrees, as the flow is attached over the flat-window aperture. At $M = 0.6$ the local shock on top of the turret is too weak to modify the otherwise subsonic flow over the turret, so a similar, separation-bubble-related peak in $OPD_{RMS}$ around $\alpha = 90$ degrees is present at $M = 0.6$; the peak location is slightly shifted forward $\alpha = 90$ degrees, compared to $M = 0.5$-case. At $\alpha = 110$ degrees the flow separates, so for large viewing angles $\alpha > 110$ degrees $OPD_{RMS}$ continuously increase due to looking through the separated wake of the turret. Again, this behavior is very similar to $OPD_{RMS}$ results at $M = 0.5$.

For a higher $M = 0.7$, the location of the local peak due to the separation bubble over the flat window is around 90 degrees and approximately unchanged from $M = 0.6$. The local peak is sharper, compared to $M=0.6$ case; inspection of wavefronts has revealed the presence of the shock approximately in the middle of the aperture. The flow separates around 110 degrees as well, and the normalized aero-optical distortions in the wake appear to be unchanged.

Fig. 14 Normalized $OPD_{RMS}$ versus viewing angle for Mach 0.5 (▼), 0.6 (■), 0.7 (♦), and 0.8 (▲) for the flat-window turret for a range of $\beta = 50-90$ degrees at different Mach numbers. Dashed red arrow indicates an approximate location of the flow separation. Comparison with results for the flat-window turret with “smiles” from Ref. 24 is also presented.
For M = 0.8, a stronger shock was found to be present over the flat aperture between viewing angles 75 and 90 degrees, so the overall levels of OPD$_{\text{rms}}$ are significantly higher, compared values at the same angle range at lower Mach numbers. The separation is also affected by the shock presence and appears to occur slightly upstream, at $\alpha = 105$ degrees, compared to M = 0.6 and M = 0.7.

The normalized spatial distributions of wavefronts are shown in Fig. 15 for two different Mach numbers. Both the M = 0.7, Fig. 15, left, and M = 0.8, Fig. 15, right, show an increase in OPD$_{\text{rms}}$ in a narrow band near the center of the aperture due to the presence of the unsteady shock. This is the mean shock location for both cases. Because the shock location is near the center of the aperture, even though the viewing angle and Mach number are slightly different between the two cases, it appears that the flat window has an “anchoring” effect on the shock in that it forces it to be near the center of the aperture, on average. One possible reason for this “anchoring” effect is that the separation bubble forms a fluidic curved surface over the aperture. The topology of the separation bubble is very sensitive to the flat-window position, as well as the flow environment. For M = 0.7 the shock is formed over the curved fluidic surface, but the shock is weak to modify it. The shock becomes stronger at M = 0.8, significantly modifying or even potentially destroying the bubble. Compared with the results for the conformal-window turret, presented in Fig. 6, the resulted OPD$_{\text{rms}}$ for both the flat- and the conformal-window are very similar at M = 0.8, confirming that at high transonic speeds the aperture geometry becomes a secondary factor, compared to the shock-induced effects. Also, similar to the conclusions with the conformal-window turret, presented earlier, the “$\rho M^2$” scaling, used to normalize aero-optical data, is still useful to re-scale data at high $\alpha$-angles above 100 degrees to different turret sizes and subsonic and transonic speeds.

Figure 16 shows a one-dimensional slice of wavefronts taken at M = 0.8 for the window center located at $\alpha = 82$ degrees and $\beta = 43$ degrees. The shock location was captured in $\alpha$-$\beta$ coordinates for given fixed $\beta$. The black filled circles show the location of maximum positive wavefront slope, which is presumed to be related to the instantaneous shock position. The shock moves between a relatively wide range of $\alpha = 70$ degrees and 88 degrees; this unsteady shock motion is as a cause of the increase in OPD$_{\text{rms}}$ observed in the M = 0.8 data from Fig. 14. The shock movement, although oscillatory, doesn’t appear to be periodic in nature, unlike the shock motion for the conformal-window turret, and the shock does not “wander” off the aperture. Analyzing of the shock position in time for...
both $M = 0.7$ and $0.8$ (not shown), is was found that the shock was present between 71 and 87 degrees 90% of the time, with the average location is at 80 degrees.

Fig. 16 Spatial-temporal evolution of 1-D slice of wavefront for $M = 0.8$ at $\alpha = 80$ degrees, $\beta = 43$ degrees. Black circles indicate the approximate shock location.

The temporal spectra of the shock position for both $M = 0.7$ and $M = 0.8$ are shown in Fig. 17. There isn’t much discernable difference between the frequency content of the shock movement for the two Mach numbers. Both exhibit a single peak near $St_D = 0.15$, unlike for the conformal-window turret, where two peaks at 0.15 and 0.3 were observed for $M = 0.7$ case. As stated before, this peak has been associated with the movement of the separation line on the turret. As the local separation bubble is sensitive to the global environment, which is primarily governed by the separated region downstream of the turret, this single peak in the shock spectra indicates that the shock dynamics is linked to the dynamics of the separation line.

Fig. 17 Shock location spectra for $M = 0.7$ (dashed line) and 0.8 (solid line), at $\alpha = 84$ degrees, $\beta = 43$ degrees.

To further study the effect of the shock on the separated region over the flat-window turret, the spatial distributions of the wavefronts on the downstream portion of the turret were computed and the results for different Mach numbers are presented in Fig. 18. Technically, the wake dynamics depends on the position of the flat window, but in reality, the effect is mainly present only at side-looking angles, when the local separation bubble forms over the window. For this reason, wavefronts at side-looking angles were not used to compute the spatial distributions and therefore the shock presence is not visible in Fig. 18 for $M = 0.7$ and 0.8. Still, comparing the spatial distributions of the wavefronts in Fig. 18 with the ones for the conformal-window turret, presented in Figs. 7 and 8, several conclusions about the shock effect on the wake can be drawn. Firstly, the “quiet value”, although somewhat weaker, is still present for $M = 0.6$. Similar to the conformal-window turret, the “quiet valley” is reduced at $M = 0.7$ and 0.8. Overall, the spatial distributions of the wavefronts in the wake region are very similar between the conformal- and the flat-window turrets, confirming that the presence of the flat window affects the flow primarily at side-looking angles.
Temporal wavefronts spectra for different Mach numbers were calculated for a side-looking angle of \( \alpha = 90 \) degrees, presented in Fig. 19, top, and looking through the wake at \( \alpha = 120 \) degrees, shown in Fig. 19, bottom. At the side-looking angle, spectra for \( M = 0.5, 0.6 \) and 0.7 are similar, with the shear-layer-related peak near \( St_D = 1.3 \). Only at \( M = 0.8 \) the spectrum is changed, with the peak moving toward lower frequencies. It further supports the earlier conclusion that the dynamics of the local separation bubble, present over the window at this angle, is not affected by the shock, unless the shock becomes strong enough.

5. Conclusions

Using the AAOL-T program, wavefront measurements were collected in-flight for a hemisphere-on-cylinder turret with either conformal or flat windows in a transonic flow regime. Data were taken at different viewing angles, and the aero-optical environment was characterized by computing the overall levels of OPD_{RMS}, as well as the spatial
distribution of the wavefronts and aperture-averaged wavefront temporal spectra at selected viewing angles. Shock dynamics were studied by using sharp positive gradients in the wavefronts to estimate shock instantaneous locations.

The normalized OPD RMS was calculated for Mach numbers ranging from 0.5 to 0.8 on both the flat and conformal window turrets for different field-of-regard angles. For both geometries, it was found that normalized aero-optical distortions have additional local increase near α = 80 degrees for the M = 0.7 and 0.8 cases. This peak was attributed to the presence of the unsteady shock appearing on top of turret. The shock location was found to be almost independent of the modified elevation angle; based on optical data, the shock extent appears to increase with increasing Mach number.

The spectra of the shock motion, extracted from optical data, was calculated for the M = 0.7 and 0.8 cases. For the conformal window the shock-related spectra revealed two peaks at StD = 0.3 and 0.18 at M = 0.7 and only a single peak at StD = 0.15 at M = 0.8. As the StD = 0.15 was observed at M = 0.7 and 0.8 in the shock region motion. 

The wake-related wavefront spectra in both window geometries revealed a dominant peak at StD = 1.3, which is associated in earlier studies with the shock extent appearing on top of turret. The spectra of the shock motion, extracted from optical data, was calculated for the M = 0.7 and 0.8 cases. For the conformal window the shock-related spectra revealed two peaks at StD = 0.3 and 0.18 at M = 0.7 and only a single peak at StD = 0.15 at M = 0.8. As the StD = 0.15 was associated in earlier studies with the unsteady motion of the separation line over the turret, it was hypothesized that while at low transonic speeds around M ~ 0.6 - 0.65 the shock has its own dynamics with a higher frequency of StD ~ 0.5, when the shock grows strong enough to cause a premature separation, it becomes locked with the wake dynamics, having the same frequency as the unsteady separation line. This

lock-in mechanism was observed in other studies of the shock-wake interaction.

For the flat-window aperture, only a single peak at StD = 0.15 was observed at M = 0.7 and 0.8 in the shock motion spectra. Based on optical data, the shock dynamics is linked to the local separation bubble over the flat window at side-looking angles, which, in turn, is also linked to the wake dynamics.

The wake-related wavefront spectra in both window geometries revealed a dominant peak at StD = 1.3, which is associated with small scale shear layer structures. The dynamics of the shear layer structure in the wake was found to be mostly unaffected by the presence of the shock for both window geometries, although some evidence of shock-related modulation at StD = 0.15 at high Mach number of M = 0.8 was noticed for the conformal-window turret. It is expected that this modulation will become stronger at higher transonic Mach numbers.

Future work will include collecting more data using the AAOL-T to acquire more information on the shock motion and to further study the proposed locking mechanism between the shock and wake. Additionally, wind tunnel tests will be performed to gather simultaneous pressure and wavefront measurements to track shock motion and its relation to the separated region motion.

References

Caption List

**Fig. 1** Left: Flow topology around a turret at subsonic speeds. Right: Transonic flow features on the turret. Both images are from.4

**Fig. 2** The AAOL turret, with “smiles” covered, installed on AAOL-T, left and the instrumented optical bench, right.

**Fig. 3** Schematic of the optical setup.
Fig. 4 Relationship between azimuthal (Az) and elevation (El) angles to viewing angle (α) and modified elevation angle (β) and the definition of turret and aperture-related frames of reference. From Ref. 24.

Fig. 5 2-Dimensional normalized OPD with black line representing 1-D slice (left) and 1-D slice of OPD with red line corresponding to shock location (right).

Fig. 6 Normalized OPD_{RMS} versus viewing angle for M = 0.5-0.8 for the conformal-window turret for a range of β = 60-90 degrees (top) and β = 20-60 degrees (bottom) at Mach 0.5 (▼), 0.6 (■), 0.7 (♦), 0.8 (▲). Dashed red arrow indicates an approximate location of the flow separation. The wake region is identified by large values of OPR_{RMS} above a = 100 degrees. Comparison with results for the conformal-window turret with “smiles” from Ref. 25 is also presented.

Fig. 7 The top view of spatial distribution of the normalized wavefronts, S(α,β), (in μm/m) for the conformal-window turret at M = 0.6, with various flow features indicated. Flow goes from left to right.

Fig. 8 The top view of spatial distribution of normalized wavefronts, S(α,β), (in μm/m) for the conformal-window turret for M = 0.7 (left) and M = 0.8 (right), with the average shock location indicated. Flow goes from left to right.

Fig. 9 Spatial-temporal evolution of 1-D slice of wavefront data with M = 0.7 (left) at β = 76 degrees and M = 0.8 (right) at β = 67 degrees. Black circles indicate the approximate shock location.

Fig. 10 Shock mean locations and 90%-range for M = 0.7 (dashed line) and M = 0.8 (solid line) for conformal-window turret.
Fig. 11 Conformal-Window normalized shock location spectra for $M = 0.7$ and $0.8$, $\beta = 60$ degrees.

Fig. 12 Aperture-averaged wavefront spectra, $S(f)$, for the conformal-window turret for $\alpha = 80$ degrees at different Mach numbers.

Fig. 13 Aperture-averaged wavefront spectra, $S(f)$, for the conformal-window turret for $\alpha = 120$ degrees (left) and for $\alpha = 140$ degrees (right) at different Mach numbers.

Fig. 14 Normalized OPD_{RMS} versus viewing angle for Mach 0.5 (▼), 0.6 (■), 0.7 (♦), and 0.8 (▲) for the flat-window turret for a range of $\beta = 50$-90 degrees at different Mach numbers. Dashed red arrow indicates an approximate location of the flow separation. Comparison with results for the flat-window turret with “smiles” from Ref. 24 is also presented.

Fig. 15 Spatial distribution of the normalized wavefronts, $S(\alpha, \beta)$, (in $\mu m/m$) over the flat-window aperture. Left: Az = 82 degrees and El = 36 degrees ($\alpha=84$ degrees) $M = 0.7$. Right: Az = 72 degrees and El = 56 degrees ($\alpha=80$ degrees) $M = 0.8$. Flow goes from left to right.

Fig. 16 Spatial-temporal evolution of 1-D slice of wavefront for $M = 0.8$ at $\alpha = 80$ degrees, $\beta = 43$ degrees. Black circles indicate the approximate shock location.

Fig. 17 Shock location spectra for $M = 0.7$ (dashed line) and 0.8 (solid line), at $\alpha = 84$ degrees, $\beta = 43$ degrees.

Fig. 18 The top view of spatial distribution of normalized wavefronts, $S(\alpha, \beta)$, (in $\mu m/m$) for the flat-window turret for $M=0.6$ (left), $M= 0.7$ (middle) and $M=0.8$ (right). Flow goes from left to right.
Fig. 19  Aperture-averaged wavefront spectra, $S(f)$, for $\alpha = 90$ degrees (left) and for $\alpha = 120$ degrees (right) at different Mach numbers.