

RESEARCH IN AERO EFFECTS ON AIRBORNE LASER SYSTEMS

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1.0 SUMMARY

The scope of this agreement includes experimental and computational research to explore and understand the physics which gives rise to aero-optical aberrations and aero-mechanical jitter as well as mitigations to their effects on airborne directed energy systems. Aero-optics research activities, proposed to be conducted through this cooperative agreement, fall under one or more of the following broad research task areas

- Area 1: Flight experiments
- Area 2: Wind-tunnel experiments
- Area 3: High-Fidelity Computational Fluid Dynamics (CFD)
- Area 4: Instrumentation and analysis development
- Area 5: Environmental, Safety and Test Planning

Per discussions with the Air Force Research Laboratory (AFRL), four major topics, aligned with research Areas 1, 2, 3 and 4, were investigated,

- Topic 1: Aerodynamic response of the spanwise oscillating turret: experiments and modeling
 - Topic 2: Experimental studies in supersonic flow and related aero-optical effects to validate numerical codes
 - Topic 3: Experimental studies of the aero-optical jitter of the hemisphere-on-cylinder turret at various amounts of protrusion
 - Topic 4: Focused Malley probe as spatially localized aero-optical sensor
- Below a brief summary is provided for each topic.

Topic 1: Aerodynamic response of the spanwise oscillating turret: experiments and modeling

An experimental Pressure Sensitive Paint (PSP) study of the unsteady pressure fields downstream of and on an oscillating hemispherical turret at subsonic freestream Mach numbers between 0.3 and 0.6 and Reynolds numbers of about 2 million is presented. The oscillating turret consisted of a hemispheric shell, mounted on an aluminum rectangular plate and is designed to oscillate in the spanwise direction at a single frequency, which lies within the frequency range of the dominant wake motion. The resonant-based aeroelastic response of the turret to the flow resulted in intermittent turret oscillations. Pressure fluctuations in the wake were found to be less energetic for the oscillating turret and the size of the recirculating region was increased, compared to the stationary turret. Proper Orthogonal Decomposition (POD)-based modal analysis of the pressure fields revealed that the wake dynamics is characterized by global anti-symmetric and symmetric shedding and showed that the oscillating turret primarily suppressed the global anti-symmetric shedding. The analysis of the unsteady forces acting on the turret demonstrated that the oscillating turret reduces the spanwise component of the unsteady force, while keeping other force components mostly unchanged. Intermittent nature of the spanwise force, which is responsible for the intermittent motion of the oscillating turret, was observed and discussed.

To compliment the experimental studies, the high-fidelity CFD simulations were performed at United States Air Force Academy (USAF). The primary objective of the numerical simulations was to quantify the unsteady interaction between flow-induced structural oscillation and its effect on the flow field behind a hemispherical turret. The simulations were designed to match experiments at the University of Notre Dame. To capture the experimental configuration, the simulations include the wind tunnel walls, floor inserts, as well as the hemispherical turret which is mounted on the tunnel floor. The rigid simulations provide the baseline aerodynamic features as well as means to assess the required length and time scales necessary to simulate the massively separated, unsteady flow behind the turret.

Upon attaining a simulation which matched the experiment, the rigid simulation was analyzed in greater detail. The analysis compared surface pressure statistical and time accurate behavior with the

experimental results. The simulation results show that four dominant modes can be identified in the instantaneous pressure distribution on the turret. The time varying nature between the modes, while stochastic in nature, does contain a periodic tendency. The underlying mechanisms triggering the transition between the modes are still under investigation, but a qualitative discussion is provided to elaborate upon a thought model.

The final step was to couple the fluid solver to a structural model to incorporate turret motion into the simulation. In this effort, a simplified structural model was integrated into the simulation to begin these complex Fluid Structure Interaction (FSI) simulations. The design consisted of a rigid turret which is rigidly mounted to a cantilevered beam. The beam is stiff in the stream-wise direction, but weaker in the cross-stream direction to allow for deflections in this direction, providing a one-degree-of-freedom (DoF) structural system with very predictable behavior. This type of structure is realized in the simulation as a rigid turret which is mounted to a fixed ground point using a mass-spring-damper system. The dynamics of the structure were tuned to resonate with the inherent shedding frequencies present in the flow in order to amplify structural motion excited by the flow structures. The results of the coupled simulations show subtle, yet apparent, differences when compared to the rigid simulation. The shedding frequencies present in the wake tend to change and the wake becomes more symmetric. The large scale motion of the separation line is captured by a streamwise surging mode as opposed to an asymmetrically skewed behavior which is dominant in the rigid case. These differences are identified and discussed in further detail throughout the report.

Topic 2: Experimental studies in supersonic flow and related aero-optical effects to validate numerical codes

This work focuses on experimental characterization of a complex flow structure behind a crossflow array of cylindrical pins installed on a wall of a supersonic duct. This geometry simulates several common gasdynamic configurations such as a supersonic mixer, a turbulence-generating grid, or, to some extent, a grid fin. In this work, the instrumentation employed is essentially non-intrusive, including spanwise integrating techniques such as (1) fast schlieren visualization and (2) Shack-Hartmann wavefront sensor; and planar techniques, namely (3) acetone Mie scattering and (4) acetone planar laser-induced fluorescence. An analysis of the data acquired by these complementary methods allows reconstruction of a three-dimensional portrait of supersonic flow interaction with a discrete pin array, including the shock waves structure, forefront separation zone, shock-induced separation zone, shear layer and a mixing zone behind the pins. The main objective of this activity is to demonstrate visualization technique capabilities to acquire essential details of a complex compressible flow in a wide range of temporal-spatial scales, which could be utilized for adequate code validation for numerical simulations. Particularly, a fine structure in the supersonic shear layer generated by the pin tips captured by a Mie scattering technique was identified and discussed.

Topic 3: Experimental studies of the aero-optical jitter of the hemisphere-on-cylinder turret at various amounts of protrusion

Optical measurements of a hemispherical turret were conducted in both a wind tunnel and airborne testing environment to measure aero-mechanical jitter imposed onto a laser beam. A hemispherical turret was positioned in the freestream flow at various protrusion distances, Mach numbers, and azimuthal angles. Lasers and accelerometers were used to quantify the mechanical contamination imposed onto the beam due to the FSI of the incoming freestream flow and the protruding turret body. The results from wind tunnel and in-flight testing were compared. It was shown that the wind tunnel and in-flight tests yielded different results both quantitatively and qualitatively. The possible reasons for the discrepancies between these testing campaigns were also discussed.

To quantify the unsteady pressure and related unsteady forcing, responsible for the unsteady aero-mechanic jitter, surface pressure measurements were taken on a hemisphere-on-cylinder turret in a wind tunnel using PSP and fast response pressure transducers. Four different turret protrusion distances were tested to study the characteristics of the unsteady pressure field on the backside and wake of the turret.

POD was used to identify the dominant spatial surface pressure modes acting on the turret in this parametric study. It was found that the further the turret protruded into the freestream flow, the more the surface pressure field became dominated by spanwise antisymmetric surface pressure distributions resulting from anti-symmetrical vortex shedding at a normalized frequency of approximately $StD=0.2$. For the case of the partial hemisphere, this anti-symmetrical vortex shedding was essentially absent, insinuating that at some protrusion distance, the surface pressure environment on the turret fundamentally changes. The normalized net force rms was calculated on the turret for each configuration. It was found that the greater the turret protrusion, the greater the net force acting in the spanwise direction.

Further investigation into this so-called “mode switching” was performed using Joint Proper Orthogonal Decomposition (JPOD) to identify correlations between turret and wake surface pressure fields. The fluctuations in the surface pressure field around the partial hemisphere were found to be mostly dominated by the wake with little influence from fluidic structures on the turret itself. For the hemisphere and hemisphere-on-cylinder configurations, both symmetric and anti-symmetric unsteady separation grew to be the largest influence and was coupled with the wake fluctuations.

Topic 4: Focused Malley probe as spatially localized aero-optical sensor

This task addressed several experiments to demonstrate the feasibility of the Focused Malley probe as a novel spatially localized aero-optical sensor. As a first step, the preliminary experimental studies of the global beam jitter of a collimated laser beam for different beam diameters due to the turbulent boundary layers on tunnel walls are presented. The global jitter spectra were found to be attenuated at high frequencies due to an aperture-averaging effect. Results for the jitter spectra attenuation of the streamwise jitter component qualitatively agree with a one-dimensional model, developed earlier. For the spanwise global jitter, an empirical curve fit was developed to describe amount of attenuation imposed on the beam. Various contamination effects, potentially corrupting the data, were also presented and discussed.

As a second set of experiments, a point aero-optical measurement technique is presented, where a converging-diverging laser beam passing through a wind tunnel is used to perform localized aero-optical jitter measurements. Validating experiments were conducted using a subsonic speed tunnel. Measurements were performed in both an empty wind tunnel with only turbulent boundary layers present at the walls, and in the wake downstream of a small diameter cylinder placed in the middle of the test section to create local aero-optical distortions. Several measurements were conducted with the focal point placed at various spanwise locations across the flow. The analysis of the beam jitter spectra clearly demonstrates the ability of the focused jitter probe to measure aero-optical jitter primarily near the focal point, and to attenuate the jitter caused by the flow away from the focal point. In the case of the cylinder flow, when the focal point was placed inside the cylinder’s wake, a weak spectral peak corresponding to the shedding frequency was clearly resolved despite the presence of the corrupting effects from the boundary layers at the walls of the tunnel. A traditional jitter probe, however, was unable to resolve this weak spectral peak. Various experimental and data processing requirements to obtain accurate spectra are also discussed.

2.0 INTRODUCTION

Below introductions are provided for each topic.

Topic 1: Aerodynamic response of the spanwise oscillating turret: experiments and modeling

Hemispherical turrets provide an optimal geometry for maximizing the field-of-regard of airborne laser systems used in a wide variety of adaptive optics and beam control applications. However, when aircraft are instrumented with turret-based systems, turbulent flow around the turret and throughout the wake characterized by density gradients induce variations in fluctuating index-of-refraction due to the protruding nature of the turret. Laser light propagated through regions of air containing spatio-temporal variability in index-of-refraction will aberrate the incident beam. Thus, the ramifications of aero-optical distortions on hemispherical turrets as beam directors are significant in

their effectiveness to potentially degrade the point-and-track capabilities of adaptive-optics systems.

Most of experimental and numerical studies have assumed that the turret surface was rigid and ignored the mechanical vibration of the turret itself. In real applications, however, the turret skin is relatively thin to make the turret assembly lighter. If this is the case or the mounting of the turret is not rigid, turbulent flow around the turret, particularly the dominant shifting mode, will induce unsteady pressure fields that interact with the turret skin and produce unsteady forces on the entire assembly. This aero-elastic effect can potentially result in deformation of the turret surface or mechanical motion of the turret as a whole, causing non-negligible changes of the wake dynamics from previously understood results and consequent modification of aero-optical effects and resulting unsteady forces on the turret. Another case is when the mounting of the turret is not rigid, allowing the turret to vibrate as a whole. Turbulent flow around the turret, particularly the dominant anti-symmetric shedding, will produce unsteady forces on the entire assembly. This aero-elastic effect can potentially result in mechanical motion of the turret as a whole, causing non-negligible changes of the wake dynamics and consequent modification of aero-optical effects. As discussed above, the mechanical motion of the turret might also induce additional vibration of different optical components in the optical set-up, resulting in larger jitter on the outgoing beam.

To study the effect of the oscillating turret on the wake dynamics, the experimental studies of the wake response downstream of an oscillating hemispherical turret at subsonic speeds were conducted. The oscillating turret consisted of a hemispheric turret shell 10 inch in diameter, mounted on an aluminum rectangular plate. The turret assembly was designed for the turret to oscillate in the spanwise direction at a single frequency, coinciding with the main frequency of the dominant wake mode. The resonant-based aero-elastic response from the flow resulted in the turret to be forced to oscillate primarily in the spanwise direction. Multiple accelerometers mounted at different points inside of the turret assembly were used to measure local displacements. It was demonstrated that the turret oscillates at a fixed frequency over a range of subsonic freestream Mach numbers between 0.3 and 0.55, with the oscillation amplitude of approximately one millimeter.

PSP, along with several unsteady pressure sensors, placed on the turret and tunnel wall downstream of the turret, were used to investigate the wake response to the oscillating turret. PSP was painted on the turret and wake region in order to compare the globally reconstructed pressure fields between the oscillating and stationary cases. It was found that pressure fluctuations were less energetic for the oscillating turret and the wake was more organized in the spanwise direction, compared to the stationary turret wake. The pressure field downstream of the oscillating turret was found to be asymmetrically distributed compared to the pressure field of the stationary turret configuration. POD and DMD analysis of the reconstructed pressure fields from PSP revealed the wake is characterized by global shifting and breathing motion and confirmed that the wake dynamics were suppressed when the flow forced the turret to oscillate at a predominantly single frequency. The suppressive effects of the turret oscillations on the wake dynamics were found to become more robust at higher freestream Mach numbers, and the normalized wake response frequency was found to be higher than the normalized resonant frequency of turret oscillations.

The experimental studies were complimented by the high-fidelity CFD simulations, conducted at the US Air Force Academy. The primary objective of this part of the research effort was to quantify the unsteady interaction between flow-induced structural oscillation and its effect on the flow field behind a hemispherical turret. The simulations were designed to match experiments at the University of Notre Dame. A 10-inch diameter hemispherical turret was used to assess the unsteady flow features for both the rigid and flexible models. To capture the experimental configuration, the simulations include the wind tunnel walls, floor inserts, as well as the hemispherical turret which is mounted on the tunnel floor. The rigid simulations provide the baseline aerodynamic features as well as means to assess the required length and time scales necessary to simulate the massively separated, unsteady flow behind the turret. Therefore, a convergence study was conducted on the rigid hemisphere in which the spatial and temporal resolutions were independently varied. The results indicate that resolving the required spatial scales is critical to get

accurate comparisons with the experimental results. The required spatial resolution is on the order of typical Large Eddy Simulations to capture the relevant physics and achieve a match between simulation and experimental results.

Upon attaining a simulation which matched the experiment, the rigid simulation was analyzed in greater detail. The analysis compared surface pressure statistical and time accurate behavior with the experimental results. The simulation results show that four dominant modes can be identified in the instantaneous pressure distribution on the turret. The time varying nature between the modes, while stochastic in nature, does contain a periodic tendency. The underlying mechanisms triggering the transition between the modes are still under investigation, but a qualitative discussion is provided to elaborate upon a thought model.

The next step was to couple the fluid solver to a structural model to incorporate turret motion into the simulation. In this effort, a simplified structural model was integrated into the simulation to begin these complex FSI simulations. A design was collaboratively formulated which was well suited for both experimental and computational investigations. The design consisted of a rigid turret which is rigidly mounted to a cantilevered beam. The beam is stiff in the stream-wise direction, but weaker in the cross-stream direction to allow for deflections in this direction, providing a 1-DoF structural system with very predictable behavior. This type of structure is realized in the simulation as a rigid turret which is mounted to a fixed ground point using a mass-spring-damper system. The dynamics of the structure were tuned to resonate with the inherent shedding frequencies present in the flow in order to amplify structural motion excited by the flow structures. The results of the coupled simulations show subtle, yet apparent, differences when compared to the rigid simulation. The shedding frequencies present in the wake tend to change and the wake becomes more symmetric. The large scale motion of the separation line is captured be a streamwise surging mode as opposed to an asymmetrically skewed behavior which is dominant in the rigid case.

This simplified FSI problem is essential to developing comparisons between experiments and computations. The problem serves as a geometrically simple, yet highly complex, FSI validation problem in which the basic paradigm of such complex fluid-structural interactions can be analyzed. Once a good understanding of this simplified problem is obtained, higher fidelity structural representations can be seamlessly added to the simulation to replicate specific implementations.

Topic 2: Experimental studies in supersonic flow and related aero-optical effects to validate numerical codes

Despite significant progress in CFD, the simulation of a complex compressible flow is still challenging. This is because of the approximate form of a specific gas equation of state and transport coefficients, discrete geometry of meshes applied, and the stochastic nature of turbulence. Challenges in CFD include the prediction of transition and flow separation in viscous turbulent flows, model convergence in turbulent flows involving complex flow physics and/or complex geometries, and mesh refinement and uncertainty quantification in turbulent, unsteady flows, to just list a few unresolved problems. In most cases, codes validation is a predefined procedure. Ideally, the validation requires the consistence of numerical and experimental datasets in as wide range of parameters as needed/possible. In practice, for a supersonic flow, this procedure is frequently reduced to the comparison to the calculated dataset of a wall pressure distribution taken with discrete pressure transducers and of a general flow structure read shock waves positions) visualized by a schlieren method. With such an approach, the details of the flow field will then be discussed based on simulated results alone, with many aspects remaining unvalidated. Presumably, a significant discrepancy might be observed, especially for mixing/shear layers, at SWBLI, vorticity-dominated flows, and other unsteady regions. This work is intended to contribute to a more detailed approach for the validation procedure through a visualization of difficult-to-observe features of a complex compressible flow. Targeting this objective, complementary to the schlieren visualization, three non-intrusive methods were applied to explore the details of a complex flow field consisting of pin array interaction with a supersonic airflow: aero-optical Shack-Hartmann sensing, acetone Mie scattering, and acetone planar laser-induced fluorescence. These methods are sensitive to gas

density gradients, number density/temperature composition, and the gas number density, respectively.

A single cylinder in supersonic crossflow is characterized by a bow shock in front of the cylinder and an unsteady subsonic wake immediately behind the cylinder. Further behind the cylinder the flow is again accelerated to supersonic velocity. The flow field is characterized by a complex interaction between shock waves and vortices generated behind the cylinder. Near the solid boundary, the bow shock in front of a cylinder separates into a forward separation shock and a rear reattachment shock near the base of the cylinder, forming a classic lambda shape. The intersection of these shocks is referred to as the triple point. A separated flow region exists beneath the lambda shock. Just below the triple point a high pressure supersonic jet penetrates the flow separation zone, creating two horseshoe vortices and a supersonic region immediately in front of the cylinder. At the upper end of the cylinder, the bow shock curves around the tip of the cylinder and continues propagating downstream. These characteristics are schematically illustrated in Figure 1(a). The nature of the interaction is complex, leading to many features that are largely under-investigated but may be of a great importance for the mixing efficiency. The current study is focused on a spanwise cylindrical pin array installed on a wall over a supersonic turbulent boundary layer. When multiple cylinders are placed in an array across the flow, the front bow shocks merge [1]. Flow immediately behind the combined bow shocks is subsonic, and a curved sonic line exists between the cylinders past which the flow is again supersonic. The subsonic wake and pin tip vortices continue propagating downstream and may interact with flow structures formed by adjacent pins. The resulting flow field is illustrated schematically in Figure 1(b). The detailed flow structure behind the pin array is largely under-investigated.

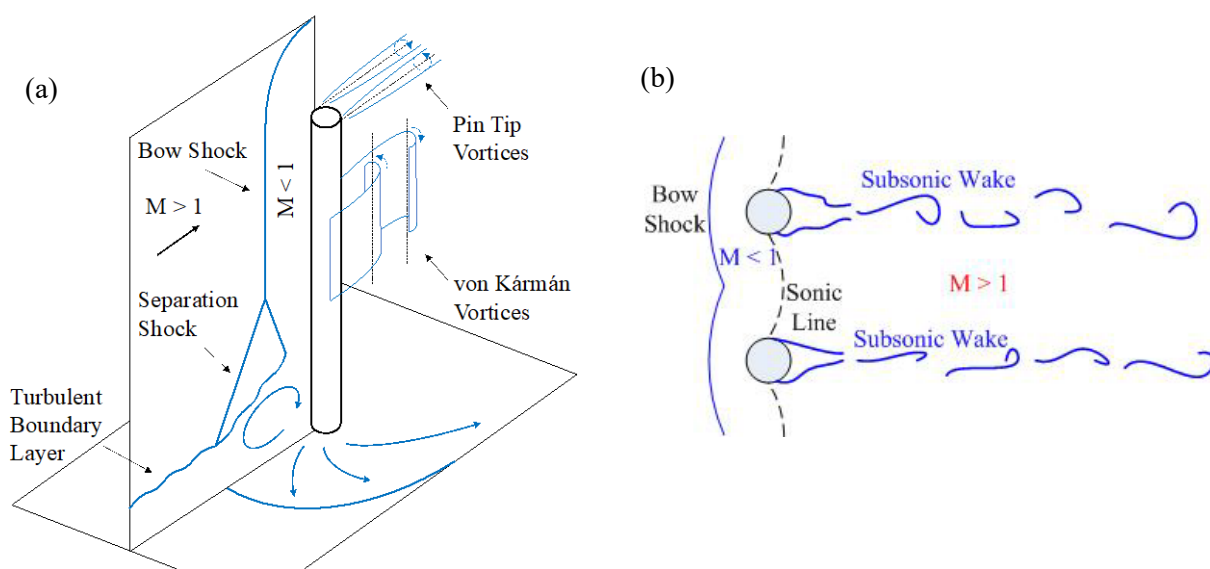


Figure 1. Flow schematics around (a) a single pin and (b) multiple spanwise pins in cross flow

Laser induced fluorescence (LIF) is a technical method used to detect the population density of a chemical species present, or introduced to the flow field, through resonant coupling of selected upper and lower energy levels of the target molecule. In chemically reacting flows, accessible tracer species are produced at reaction zones and heat release areas. In non-reacting flows a target molecule must be introduced. Acetone is frequently selected as a tracer species for LIF or planar laser induced fluorescence (PLIF) measurements due to several favorable photophysical and thermodynamic properties [2,3,4]. These include high partial pressure for simple seeding arrangements, adequate fluorescence quantum yield, low collisional quenching due to short fluorescence lifetimes, and low toxicity for safe user

handling and bulk introduction to test arrangements. As the flammability limits of acetone fall within the range of typical seeding concentrations, the application of inert carrier gas is required in non-reacting test arrangements. In supersonic flow fields where low static temperatures are present, acetone condensation can affect the resulting LIF signal, and variation of stagnation temperature is required to mitigate condensation onset [5]. Acetone is frequently applied to study mixing processes in supersonic flows both locally in injected jets [5, 6], and globally in the bulk flow [7]. This work applies acetone PLIF in the bulk flow for planar visualization of shock structures at varying pin arrays.

After conventional flow diagnostics such as a spanwise-integrated schlieren imaging and wall pressure distribution, further detailed flow visualization may be performed by seeding the flow with tracer particles, with their illumination and visualization. However, obtaining uniform seeding in supersonic flow is challenging due to difficulties in mixing the added tracer particles. Also, the seeded particles must be small enough in order for the particles to faithfully follow the flow without slipping. At the same time, the presence of the particles should not affect the flow structure. These issues can be circumvented by adding a condensable vapor to the high pressure supply of the tunnel. As the static temperature of the gas decreases as it passes through the nozzle, the vapor condenses, forming small (nano/micro-scale), uniformly distributed droplets. These droplets may be then visualized by laser scattering. Since the droplets may be smaller or larger than the wavelength of light used, the scattering of light is described by Mie scattering theory, which converges to the Rayleigh scattering approximation in the limit of very small droplets. Since these droplets will re-evaporate if the gas temperature is increased, this method is also sensitive to temperature changes in the flow, such as those across shocks and in a flow separation zones.

This work focuses on experimental characterization of a complex flow structure behind a crossflow array of cylindrical pins installed on a wall of a supersonic duct. This geometry simulates several common gasdynamic configurations such as a supersonic mixer, a turbulence-generating grid, or, to some extent, a grid fin. In this work, the instrumentation employed is essentially non-intrusive, including spanwise integrating techniques such as (1) fast schlieren visualization and (2) Shack-Hartmann wavefront sensor; and planar techniques, namely (3) acetone Mie scattering and (4) acetone planar laser-induced fluorescence. An analysis of the data acquired by these complementary methods allows reconstruction of a four-dimensional portrait of supersonic flow interaction with a discrete pin array, including the shock waves structure, forefront separation zone, shock-induced separation zone, shear layer and a mixing zone behind the pins. The objective of this activity is to demonstrate visualization technique capabilities to acquire essential details of a complex compressible flow in a wide range of temporal-spatial scales, which could be utilized for adequate codes validation for numerical simulations.

Topic 3: Experimental studies of the aero-optical jitter of the hemisphere-on-cylinder turret at various amounts of protrusion

In recent years, there has been heightened interest into the development of airborne directed energy systems. Hemispherical turrets have been identified as a geometry of interest for beam director design because of their advantageous field of regard. Consequently, the fluidic and aero-optical properties of turrets have been extensively studied both experimentally and numerically in the last decade. The fluid mechanics around hemispherical turrets can briefly be described as follows. When subsonic flow approaches a turret body, the fluid stagnates at the lower frontal portion of the turret and creates a coherent “necklace” vortex, the “legs” of which convect downstream. The fluid that approaches the turret on the upper frontal area stagnates, and then accelerates over the top of the turret. This frontal region of the turret is fairly steady. After accelerating over the top of the turret body, separation eventually occurs. The exact location of flow separation is dependent on the state of the boundary layer near the top of the turret. Typically, however, for Reynolds numbers greater than 3×10^5 , separation occurs around 120° relative to the incoming freestream direction. After separation, a shear layer forms between the flow convecting over the top of the turret and the separated region located directly downstream of the turret. Counter-rotating, symmetrical “horn” vortices form in the region directly downstream of the turret. At higher Mach numbers, this wake region becomes even more complicated. The horn vortices lose their symmetry and the formation of additional vortices originating from the back of the turret manifest. It is

clear that the fluidic structures downstream of the turret are complicated, highly unsteady, three-dimensional phenomena.

The aero-optical induced effects of propagating a laser through these intricate turret wake environments have been extensively studied. However, in addition to the deleterious aero-optical distortions associated with backward looking turret angles, the unsteady environment described above results in mechanical forcing imposed onto the beam director. The aero-mechanical contamination, resulting from the unsteady pressure field around the turret, can be a major source of performance degradation to these optical systems. The unsteady wake dynamics associated with the forcing on the turret can also excite mechanical modes in other optical system components such as mirrors inside the turret or on the optical bench. The aero-mechanical contamination imposed onto the laser beam manifests as tip and tilt. This results in pointing issues at the target plane, colloquially referred to as beam "jitter." Adaptive optics system components such as an optical inertial reference unit (OIRU) coupled with a fast-steering mirror (FSM), and a position sensing device (PSD) can be used in a corrective loop to alleviate the undesirable effects of mechanical corruption however, there are bandwidth limitations to these hardware components. Previous studies have been conducted that specifically target investigating the unsteady wake dynamics of turrets. In this work, the mechanical contamination imposed onto the laser beam due to the forcing on the turret is the emphasis. The main goal is to distinguish mechanical distortions associated with the unsteady forcing on the turret, excited optical system components, and facility specific distortions.

In this parametric study, a hemispherical turret is used in both wind tunnel and in-flight testing environments to measure aero-mechanical jitter as a function of Mach number, aperture angle relative to the incoming flow, and turret protrusion distances. Wind tunnel testing took place in the University of Notre Dame's Mach 0.6 White Field wind tunnel facility. In-flight testing employed the Airborne Aero-Optics Laboratory for Beam Control (AAOL-BC). The results of wind tunnel and in-flight campaigns were compared and relationships between test parameters and resulting aero-mechanical jitter were made. The results from wind tunnel and in-flight testing were compared. It was shown that the wind tunnel and in-flight tests yielded different results both quantitatively and qualitatively. The possible reasons for the discrepancies between these testing campaigns were also investigated.

Complimentary to direct measurement of the aero-mechanical jitter, wind tunnel tests were conducted where fast-response PSP is coupled with several fast response Kulite pressure transducers to study the surface pressure field on different hemisphere and hemisphere-on-cylinder turret geometries at various Mach numbers. Four different turret protrusion distances were tested to study the characteristics of the unsteady pressure field on the backside and wake of the turret. POD was used to identify the dominant spatial surface pressure modes acting on the turret in this parametric study. It was found that the further the turret protruded into the freestream flow, the more the surface pressure field became dominated by spanwise antisymmetric surface pressure distributions resulting from anti-symmetrical vortex shedding at a normalized frequency of approximately $St_D=0.2$. For the case of the partial hemisphere, this anti-symmetrical vortex shedding was essentially absent, insinuating that at some protrusion distance, the surface pressure environment on the turret fundamentally changes. The normalized net force rms was calculated on the turret for each configuration. It was found that the greater the turret protrusion, the greater the net force acting in the spanwise direction.

This mode switching suggests that there is a transition in flow field phenomena as protrusion is changed from partially submerged to a full hemisphere configuration. Further investigation into this mode switching was taken. This analysis heavily relied on modal analysis to identify correlations between turret and wake surface pressure fields. The fluctuations in the surface pressure field around the partial hemisphere were found to be mostly dominated by the wake with little influence from fluidic structures on the turret itself. For the hemisphere and hemisphere-on-cylinder configurations, both symmetric and anti-symmetric unsteady separation grew to be the largest influence and was coupled with the wake fluctuations.

Topic 4: Focused Malley probe as spatially localized aero-optical sensor

As a laser beam passes through turbulent flow, aero-optical structures of fluctuating densities will impose optical aberration on the beam and, among other things, will cause the beam to propagate in a different direction. This is known as a beam deflection or beam jitter. For small beam diameters, Huygens principle states [8] that the beam will be deflected by amount proportional to the 2-D gradient of Optical Path length (OPL),

$$\theta_x(t) = \frac{\partial}{\partial x} OPL(x, y, t), \theta_y(t) = \frac{\partial}{\partial y} OPL(x, y, t). \quad (1)$$

OPL, in turn, is an integral of the density field along the beam propagation,

$$OPL(x, y, t) = K_{GD} \int \rho(x, y, z, t) dz, \quad (2)$$

where K_{GD} is Gladstone-Dale constant. If the convective speed is known, OPL can be reconstructed from the deflection angle signals using the Taylor frozen field hypothesis [9,10]. Thus, by projecting a single small-aperture laser beam through turbulent flows, wavefronts can be directly measured if the convective speed is known. As wavefronts are proportional to the integrated density field, analysis of the time series of deflection angles is very informative way to learn about the underlying turbulent flow. This approach was successfully used to study boundary layers, shear layers and flows around turrets.

The main issue with this approach is that wavefronts are integrated quantities and do not provide any information about where along the laser beam the optical distortions happen. For spanwise-uniform flows, this problem can be addressed by collecting wavefronts in both wall-normal and spanwise directions [11], but in general it is a drawback of any optical technique which involves a collimated laser beam.

While the source of beam jitter cannot be located along the beam, the amount of jitter depends on the beam aperture size, or to be exact on the ratio of the size of optical structures and the beam aperture. Smaller aberrating optical structures will have little effect on the global beam jitter, while aberrating optical structures on the same order as or larger than the beam aperture will have an effect on the global jitter. When the beam aperture is large, compared to the typical aberrating optical structures in the flow, the contribution to the overall beam deflection from this flow is very small due to an aperture-averaging effect, which works as a low-pass filter, effectively suppressing high spatial frequencies, present in the wavefronts [12].

While conventional Malley probes and Wavefront sensors are non-intrusive measurement techniques, capable of measuring line-integral OPL and an overall convective speed of the aberrating structures, the results can be corrupted by other optically aberrating flows along the laser beam, like a boundary layer on the tunnel wall, for instance. The same comment goes to Schlieren or interferometry techniques. If optical distortions of the flow of interest are dominant, compared with the optical distortions due to the boundary layer, the corrupting effects are small. However, if these optical distortions are the same order, it is very difficult to isolate the corrupting effects from the boundary layer.

To overcome this averaging-along-the-line issue, a Focused Schlieren technique [13] and Focused Laser Differential Interferometry (FLDI) [14] were developed and found to be capable of measuring optical distortions inside a compact region along the beam. Both of these techniques are intensity based, that is the optical distortions result in the intensity changes on a receiving optical element, a digital camera for the Focused Schlieren system or a photodiode for FLDI. As laser intensity or its spatial distribution can be affected by non-ideal optical elements, these techniques require good quality optical set-ups and the careful alignment of its elements. They are also very sensitive to the vibrations of its optical elements.

Shack-Hartmann type wavefront sensors, including the Malley probe, on the other hand, record instantaneous dot displacements behind the lenslet array and reconstruct the wavefront from these dot displacements using Southwell method. As the dot position is insensitive to the intensity, these sensors are much less sensitive to the beam non-uniformity, non-ideal optics or other factors which can locally affect the beam intensity. Also, effects of overall beam vibrations are relatively easy to remove from the

wavefronts, allowing these sensors to collect reliable data in large industrial wind tunnels, for instance. Thus, it would be beneficial to develop a Shack-Hartmann type sensor with a focusing ability. One way to do this is to utilize the aperture averaging property, discussed before, which would suppress the overall beam deflection in regions with a large beam diameter. One possible configuration is a convergent-divergent laser beam, schematically shown in Figure 2, passing through a tunnel with the boundary layers present on the wall. A collimated beam with a large diameter is focused on a point inside the tunnel. After the focusing point, the beam diverges and, after passing through a second focusing lens, is forwarded to a PSD, which measures the overall beam jitter. The total beam deflection is an integral of averaged-over-area beam deflections along the beam. Where the beam diameter is large compared to the aberrating optical structures, the contribution to the overall beam deflection is very small due to the aperture-averaging effect. Consequently, boundary-layer-related optical effects on both sides of the tunnel windows, while large in amplitude, should not significantly contribute to the overall beam deflection. Only the focal point region, where the beam diameter is small, has the largest effect on the total beam deflection. This results in the main contribution to the deflection of the beam occurring primarily along the portion of the beam near the focal point, where the beam has the smallest diameter,

$$\theta_x(t) = \frac{\partial OPD(x, y, t)}{\partial x} \approx K_{GD} \frac{\partial}{\partial x} \int_{-L/2}^{L/2} \rho(x, y, z, t) dz = K_{GD} L \frac{\partial}{\partial x} \langle \rho(x, y, z, t) \rangle_L$$

$$\theta_y(t) \approx K_{GD} L \frac{\partial}{\partial y} \langle \rho(x, y, z, t) \rangle_L$$
(3)

where L is the length of the beam with the small diameter and brackets denote along-the-beam averaging. Thus, the deflection angle or beam jitter is proportional to the density gradient near the focal point.

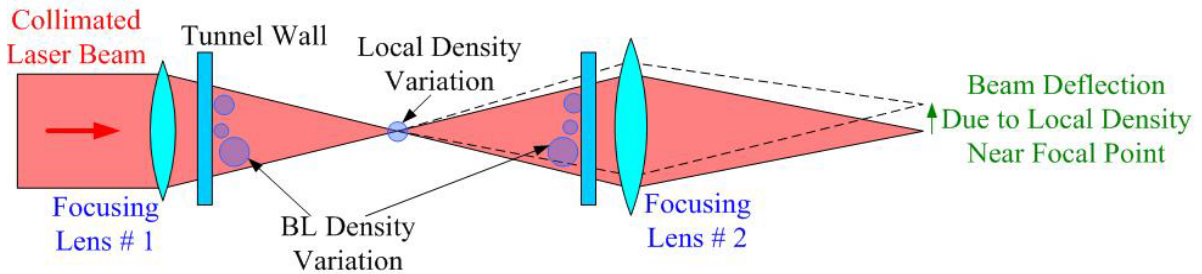


Figure 2. Conceptual schematics of convergent-divergent beam experiment

This effect has important implications in that it could potentially lead to a new way of non-intrusively measuring density fluctuations near the region of the focal point. This measurement technique could be used in hypersonic tunnels, for instance, where a number of measuring sensors are limited. Hotwires, for example, are generally too delicate for hypersonic measurements, while sonic anemometers have the disadvantage of lacking scalability when compared with a point measurement technique. In addition, both of these techniques are intrusive. Conventional Malley probes and Wavefront sensors would have significant interference from the perpendicular tunnel walls due to the line-integral method of these techniques, while yet other techniques such as PIV, PTV, DGV, LDA, and others have the disadvantage of needing to seed the flow with tracer particles.

In this work, we experimentally measured jitter spectra due to a subsonic boundary layer using various beam diameters. Validating experiments were conducted using a subsonic speed tunnel. Measurements were performed in both an empty wind tunnel with only turbulent boundary layers present at the walls, and in the wake downstream of a small diameter cylinder placed in the middle of the test section to create local aero-optical distortions. Several measurements were conducted with the focal point

placed at various spanwise locations across the flow. The analysis of the beam jitter spectra clearly demonstrates the ability of the focused jitter probe to measure aero-optical jitter primarily near the focal point, and to attenuate the jitter caused by the flow away from the focal point. In the case of the cylinder flow, when the focal point was placed inside the cylinder's wake, a weak spectral peak corresponding to the shedding frequency was clearly resolved despite the presence of the corrupting effects from the boundary layers at the walls of the tunnel. A traditional jitter probe, however, was unable to resolve this weak spectral peak. Various experimental and data processing requirements to obtain accurate spectra are also discussed.

Results of the convergent-divergent beams were used to develop a novel local aero-optical measurement technique, termed the focused Malley probe, where two converging-diverging laser beams passing through a wind tunnel are used to perform localized aero-optical jitter and convective speed measurements. Validating experiments were conducted using a subsonic speed tunnel with a small diameter cylinder placed in the middle of the test section to create local aero-optical distortions in the wake downstream. Measurements were performed in the wake downstream of the cylinder, in the freestream upstream of the cylinder, and in the turbulent boundary layer upstream of the cylinder. Spectral analysis of the cross-correlations between two beams in these preliminary experiments clearly demonstrate the ability of the focused Malley probe under certain conditions to measure convective velocity primarily near the focal point. In the case when the focal points were placed inside the cylinder's wake, a spectral peak corresponding to the shedding frequency was clearly resolved despite the presence of the corrupting effects from the boundary layers at the walls of the tunnel. Various experimental and data processing requirements to obtain accurate results are also discussed.

3.0 METHODS, ASSUMPTIONS, AND PROCEDURES

Below an introduction is provided for each topic.

Topic 1: Aerodynamic response of the spanwise oscillating turret: experiments and modeling

Experimental Studies

The concept of an oscillating turret, when a rigid hemispherical turret is mounted on a thin, wide rectangular aluminum plate, is schematically shown in Figure 3(a). The plate is aligned along the streamwise x-direction, so the turret can only move in the spanwise z-direction. In this investigation transverse oscillating cantilever uniform Euler-Bernoulli beam theory for a beam with tip mass attachment, presented in [15, 16], was used to model, design, and construct an oscillating turret system. The Euler-Bernoulli cantilever bar dynamic equations were used to demonstrate that the plate and turret system behaves as a pendulum and has a dominant oscillating frequency. This frequency depends on the elastic properties of the plate, mechanical dimensions of the plate, and the mass and inertia of the turret. The vibrational response of this system to the input forcing, $F_z(t)$, applied at the free end of the beam, are governed by the following differential equation,

$$m \frac{\partial^2 v(y,t)}{\partial t^2} + \gamma m \frac{\partial v(y,t)}{\partial t} + E \cdot I_p \frac{\partial^4 v(y,t)}{\partial y^4} = 0 \quad (4)$$

The clamped-free boundary conditions for this system are given by

$$\left[E \cdot I_p \frac{\partial^2 v(y,t)}{\partial y^2} + I_t \frac{\partial^3 v(y,t)}{\partial t^2 \partial y} \right]_{y=L} = 0, \quad \left[E \cdot I_p \frac{\partial^3 v(y,t)}{\partial y^3} + M_t \frac{\partial^2 v(y,t)}{\partial t^2} \right]_{y=L} = F_z(t) \quad (5)$$

$$v(y=0,t) = 0, \quad \left. \frac{\partial v(y,t)}{\partial y} \right|_{y=0} = 0 \quad (6)$$

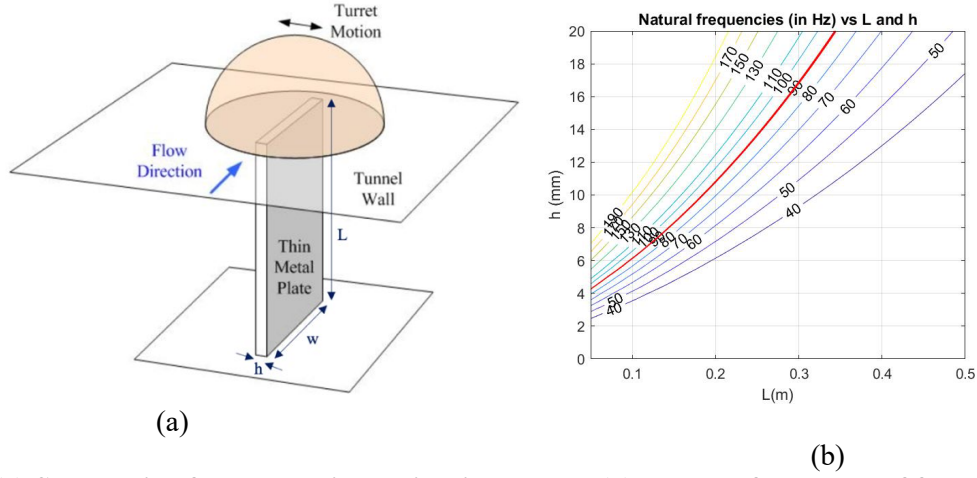


Figure 3. (a) Schematic of the spanwise-oscillating turret. (b) Natural frequency of free oscillations for the main vibrational mode of the turret system as a function of plate length, L , and thickness, h . The target frequency line of 90 Hz is indicated in thick red line

In this model, $v(y,t)$ describes the local displacement along the plate in the z -direction due to the unsteady forcing in the spanwise direction, E is Young's modulus for aluminum and ρ is the density of the aluminum plate. L is the length of the plate, w is the plate width, h is the plate thickness, $m = wh$ is the plate mass per unit length of the beam, $I_p = wh^3/12$ is the moment of inertia of the cross-sectional area of the plate and γ is the damping coefficient of the aluminum plate. $M_t = M_{shell} + M_{disk}$ is the total mass attached at the end of the beam, which consists of a thin plastic turret shell with the mass M_{shell} and an aluminum mounting disk 3 mm thick with the mass M_{disk} . Finally, I_t is the total moment of inertia of the turret shell and the mounting disk about the attachment line $y = L$,

$$I_t = \frac{1}{4} M_{disk} R^2 + \frac{1}{3} M_{shell} R^2 \quad (7)$$

Following the approach, outlined in [15, 16], the solution of the Eqs. 4-6 was found using the separation of variables and assuming a harmonic response to a unit single harmonic input, $F_z(t) = \exp(i\omega t)$ and $v(y,t) = Y(y; \omega) \exp(i\omega t)$. From the solution, a spectral transfer function, $G(\omega) = Y(y=L; \omega)$, between the input harmonic forcing and the resulted harmonic motion of the turret, was calculated to be

$$G(\omega) = G_{steady} \frac{3 \left[\sin(\lambda) \cosh(\lambda) - \cos(\lambda) \sinh(\lambda) + \frac{\omega^2 L \cdot I_t}{\lambda E \cdot I_p} (\cos(\lambda) \cosh(\lambda) - 1) \right]}{\lambda^3 \cdot \Delta}, \quad (8)$$

where

$$\Delta = 1 + \cos(\lambda) \cosh(\lambda) + \frac{\omega^2 L^3 \cdot M_t}{\lambda^3 E \cdot I_p} [\cos(\lambda) \sinh(\lambda) - \sin(\lambda) \cosh(\lambda)] - \frac{\omega^2 L \cdot I_t}{\lambda E \cdot I_p} [\cosh(\lambda) \sin(\lambda) + \sinh(\lambda) \cos(\lambda)] + \frac{\omega^4 L^4 \cdot M_t \cdot I_t}{\lambda^4 (E \cdot I_p)^2} [1 - \cos(\lambda) \cosh(\lambda)] \quad (9)$$

and

$$\lambda = L \left[\frac{(\omega^2 - i\gamma\omega)m}{E \cdot I_p} \right]^{1/4} \quad (10)$$

In Eq. (8), $G_{steady} = \frac{L^3}{3E \cdot I_p}$ is a steady turret spanwise displacement under steady unit forcing.

To measure the damping coefficient of the aluminum plate, γ , additional measurements were conducted on a separate rectangular aluminum bar of the same thickness. One end of the bar was clamped, and the free end of the beam was deflected and suddenly released. The resulted damping motion of the bar was recorded by a single-axis accelerometer, mounted on the free end of the bar. Analysis of the bar response was conducted and the damping coefficient was measured to be $\gamma = 65.2$ 1/s, see [17] for additional details of the experiment and the analysis.

For the presented studies, the turret diameter was chosen to be $D = 0.254$ m and the freestream Mach number to be between $M = 0.3$ and 0.6 . For these parameters, $St_D = 0.15$ corresponds to a range of frequencies between 80 and 100 Hz, so the target oscillating frequency of the system was chosen to be 90 Hz. The plate material was 7075-T651 aluminum alloy, which was selected for its fatigue-resistant properties. All relevant parameters of the turret and the plate used to compute the resonant frequency are presented in Table 1. To find the relationship between the main resonant frequency of the oscillating turret system as a function of plate length, L , and plate thickness, h , a location of the first resonant peak of $G(\omega)$ was computed for given values of L and h . Figure 3(b) shows a plot of the predicted main oscillating frequencies for different plate thicknesses and lengths. The red curve describes the desired frequency of 90 Hz. Based on this plot, the thickness of the aluminum plate was chosen to be $h = 12.7$ mm and the plate length was selected to $L = 230$ mm. The plate width was chosen to be $w = 254$ mm. All relevant parameters of the oscillating turret assembly are summarized in Table 1.

Table 1. Parameters of the oscillating turret system

Plate Thickness, h	Plate Width, w	Plate Length, L	Plate Moment of Inertia, I_p	Damping coefficient, γ
12.7 mm	254 mm	230 mm	0.812 kg·m ²	65.2 1/s
Total Turret Mass, M_t	Total Turret Moment of Inertia, I_t	Young's Modulus for 7075-T651 Aluminum alloy, E		Density for 7075-T651 Aluminum alloy, ρ
1.511 kg	$6.4 \cdot 10^{-3}$ kg/m ³	71.7 GPa		2,810 kg/m ³

Using the parameters in Table 1, the theoretical transfer function, $G(\omega)$, normalized by the steady position, G_{steady} , was numerically calculated and it's amplitude and phase is shown in Figure 4. The first resonant frequency was found to be 89.4 Hz, where the amplitude reaches 32 dB and the phase drops from 0 to -180 degrees. Above this frequency, the amplitude decays at a rate of -40 dB/decade and the phase stays at -180 degrees. The only exception is near the second resonant frequency of 423.3 Hz, where the amplitude has a drop, followed by a secondary peak, while the phase approaches zero before dropping back to -180 degrees. With the exception of this narrow frequency range, it was concluded that the oscillating turret can be modeled as a linear second-order underdamped system with the main resonant frequency of 89.4 Hz.

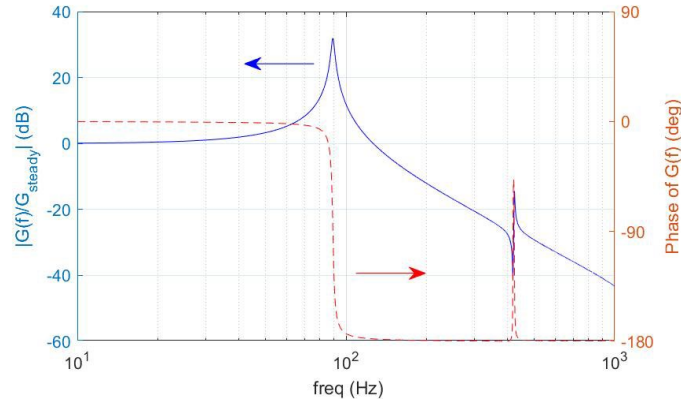


Figure 4. Amplitude and phase of the theoretical spectral response to the input forcing, Eq. (8) for the parameters in Table 1

Experimental Set-Up

Based on the theoretical studies, outlined above, the turret assembly was designed and built. A photograph of the oscillating turret assembly and a schematic of the oscillating turret design are presented in Figure 5. To allow for the turret motion, the bottom of the mounting plate with the hemisphere affixed to it was aligned with the tunnel wall with a small gap in between, in the order of a millimeter. The oscillating turret assembly was converted to the stationary turret configuration by inserting metal spacers between the mounting disk and the vibrating plate, so the mounting disk was pressed against the tunnel wall. These configurations enabled two different sets of experiments to be made in order for the wake flow physics and dynamic effects of the oscillating turret to be compared to the same, but stationary turret configuration.

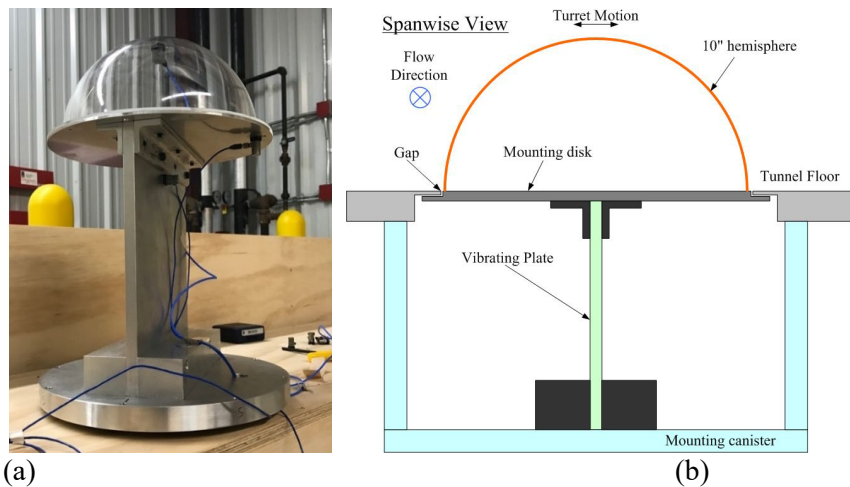


Figure 5. (a) Photograph of the turret assembly, without a mounting canister. (b) Schematic of the oscillating turret assembly

Both the oscillating and stationary turret configurations were tested in the University of Notre Dame White Field 3' x 3' wind tunnel facilities at freestream Mach numbers of $M = 0.3, 0.4, 0.5$ and 0.6 . The corresponding range of Reynolds numbers was $1.7 \times 10^6 \leq Re_D \leq 2.6 \times 10^6$. A schematic of the experimental setup is presented in Figure 6. A fast-response PSP was used to collect unsteady pressure fields on and

around the turret. A very thin uniform layer, $< 1\text{mm}$, of PSP was sprayed on the plastic dome and the surrounding aluminum mounting wall section before testing was conducted. The binder material was polymer-ceramic pressure sensitive paint (PC-PSP), which consisted of Silicone RTV as the polymer and bathophen ruthenium as the luminophore. Four 400 nm ultraviolet (UV) lights (ISSA LM2-400 type) were used to illuminate the PSP on and around the turret. Two high-speed cameras, Phantom v1611 and Phantom v2512, were used to simultaneously record the fluorescence intensity fluctuations emitted by the PSP. Both cameras were ran at a sampling frequency of $f_{\text{samp}} = 3\text{ kHz}$ at the maximum pixel resolution of 1280×800 . The v1611 camera collected 16,541 frames over 5.51 seconds, and the v2512 camera collected 49,685 frames over 16.56 seconds. Seven subminiature differential pressure transducers, Type XT-140(M), were used to perform in-situ calibration of the PSP; four pressure transducers were installed on the turret model and three pressure transducers were instrumented on the tunnel wall in the wake region. Independent calibration curves for each pressure transducer were constructed using a pressure chamber before the pressure transducers were installed. The transducers were sampled at 30 kHz for 30 seconds. The origin of the frame of reference was chosen to be at the center of the hemispherical turret, with the x-axis denoting the streamwise direction, the y-axis denoting the wall normal direction, and the z-axis denoting the spanwise direction.

In addition to pressure measurements, a total of eight 1-axis accelerometers, made by PCB Piezotronics, Model 352C33, were affixed to various locations inside of the turret and on the mounting plate and the mounting canister to monitor the turret response. The analysis of the accelerometer data is removed from this report for brevity, and an interested reader is referred to [17] for a full discussion of the accelerometer data.

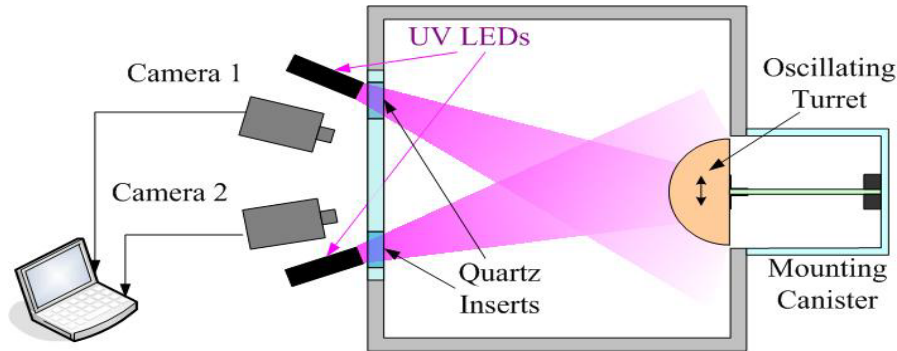


Figure 6. Schematic of the experimental setup

Data Analysis

The instantaneous intensity variations, I , emitted by PSP are related to the instantaneous local static pressure values, P , via the Stern-Volmer equation,

$$\frac{I_{\text{ref}}}{I} = A + B \frac{P}{P_{\text{ref}}}, \quad (11)$$

where I_{ref} and P_{ref} describe the instantaneous intensity and pressure values, respectively, under a set of reference conditions, and A and B are experimentally determined coefficients. Reference data was collected before each test under no flow conditions with the UV lights turned on. The spatio-temporal averaged intensity from PSP inside a small annular region immediately surrounding each of the seven pressure sensors were extracted and computed under the reference conditions and at each of the four Mach numbers tested, and the static pressures from the pressure transducer were used in order to determine A and B for each test case. The resulting calibration curve from the in-situ calibration is presented in Figure 7(a). By computing a linear fit to this curve, the A and B coefficients in Eq. (11) were found to be $A = 0.64$ and $B = 0.33$.

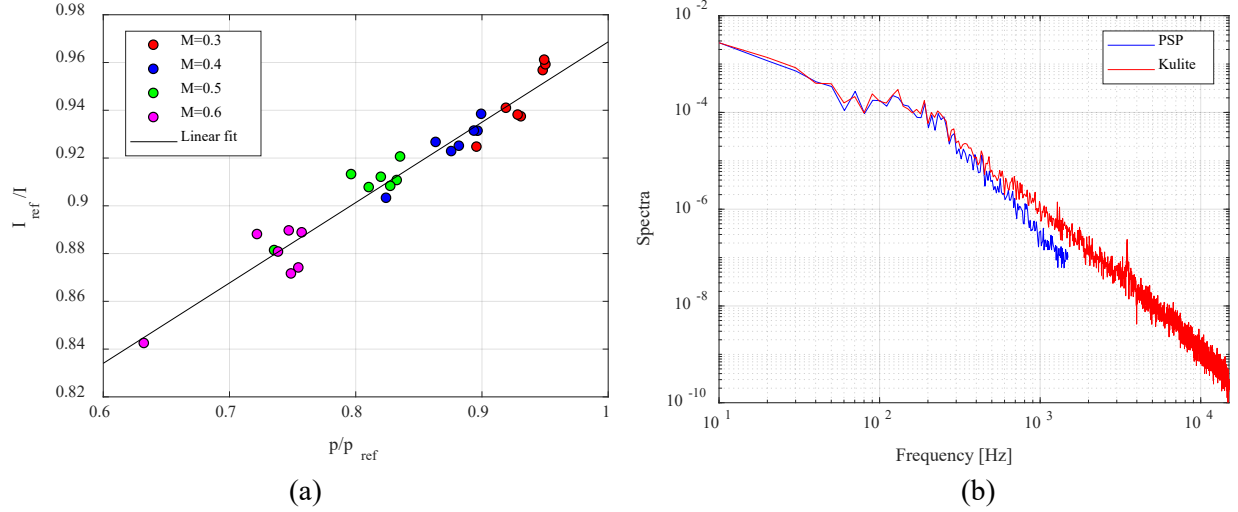


Figure 7. (a) Calibration curve using in-situ PSP data for freestream Mach numbers $M = 0.3 - 0.6$. (b) Comparison of normalized PSP pressure spectra for the oscillating turret at $M = 0.5$ with unsteady pressure spectra in the middle of the wake

To investigate the frequency response of the PSP, time-resolved spatial-average intensities of PSP around the unsteady pressure sensor, located in the middle of the wake, were extracted. After converting the unsteady intensity into the unsteady pressure using Eq. (11), the pressure power spectrum from PSP intensity data was computed and compared to the power spectrum of the unsteady pressure sensor; the result is presented in Figure 7(b). The agreement between the spectra is reasonable, and the PSP was found to correctly resolve the unsteady pressure spectrum up to approximately 700 Hz. A similar agreement was found using the PSP at the other six pressure transducer locations (not shown), verifying the accuracy of the in-situ calibration. The slight deviations at higher frequencies are likely attributed as a characteristic of the PSP response.

The calibration coefficients in Eq. (11) also depend on the temperature variations [18], potentially affecting the accuracy of the pressure measurements. To study this effect, a coupon painted with PSP was placed into a test chamber where both the pressures and the temperatures were varied, and A and B coefficients were calculated at different temperatures. Results (not shown) has revealed that both constants increased with the increasing temperature at the rates of approximately 1.2%/°C for the A coefficient and about 1.3%/°C for the B coefficient in the range of 20 - 25 °C. As the temperature changes during the tunnel runs were measured to be less than 2°C, the temperature variation of A and B coefficients in Eq. (11) was neglected in these studies.

After extracting the surface pressure fields, the time-averaged fields were computed and removed from the instantaneous pressure fields to produce the fluctuating pressure fields, $p(x, y, t)$, for different test cases and Mach numbers. Using these data, the normalized mean-removed coefficients of pressure distributions, C_p , were computed for each Mach number and turret configuration as $C_p(x, y, z, t) = (p(x, y, z, t) - p_\infty)/q_\infty$, where p_∞ and q_∞ denote the freestream static and dynamic pressures, respectively. The spatial distribution of the temporal root-mean-squared coefficients of the fluctuating pressure,

$C_{p,rms}(x, y) = \sqrt{\overline{C_p^2(x, y, t)}}$, were calculated in order to study the unsteady pressure distribution in the wake. The overbar here and later in this report denotes time averaging.

An alternative way to characterize the surface pressure fields in the wake of the turret is to compute an associated surface convective velocity field, $(U(x, z), V(x, z))$, assuming that the surface pressure field is a primarily convecting field,

$$\frac{\partial p(x,z,t)}{\partial t} + U(x,z) \frac{\partial p(x,z,t)}{\partial x} + V(x,z) \frac{\partial p(x,z,t)}{\partial z} = 0. \quad (12)$$

This equation is commonly known as the optical flow equation. One way to solve it to use the Lucas-Kanade method [19]. If the pressure field is given at several consecutive time points, Eq. (12) at every spatial point can be treated as an overdetermined system of equations for the two velocity components at this spatial point [19, 20, 21]. It can be solved using the least-squares minimization technique, resulting in the following equations for the velocity components,

$$\begin{aligned} U(x,z) &= \frac{\sum_t \frac{\partial p}{\partial t} \frac{\partial p}{\partial x} \sum_t \left(\frac{\partial p}{\partial z} \right)^2 + \sum_t \frac{\partial p}{\partial t} \frac{\partial p}{\partial z} \sum_t \frac{\partial p}{\partial x} \frac{\partial p}{\partial z}}{\left(\sum_t \frac{\partial p}{\partial x} \frac{\partial p}{\partial z} \right)^2 - \sum_t \left(\frac{\partial p}{\partial x} \right)^2 \sum_t \left(\frac{\partial p}{\partial z} \right)^2} \\ V(x,z) &= \frac{\sum_t \frac{\partial p}{\partial t} \frac{\partial p}{\partial z} \sum_t \left(\frac{\partial p}{\partial x} \right)^2 + \sum_t \frac{\partial p}{\partial t} \frac{\partial p}{\partial x} \sum_t \frac{\partial p}{\partial x} \frac{\partial p}{\partial z}}{\left(\sum_t \frac{\partial p}{\partial x} \frac{\partial p}{\partial z} \right)^2 - \sum_t \left(\frac{\partial p}{\partial x} \right)^2 \sum_t \left(\frac{\partial p}{\partial z} \right)^2} \end{aligned} \quad (13)$$

This approach was proposed in [20,21] to compute the global skin friction fields, using luminescent oil-film images. An alternative way to solve Eq. (12) is to use the Horn-Schunck method, as described in [22] and [23], but it requires computing second-order partial derivatives of the pressure field and thus it is more sensitive to measurement noise. Eq. (13) uses only the first-order partial derivatives, which are less sensitive to the noise. In addition, if many time instances are used, the system of equations, Eq. (12), is an over-determined system and, as a result, the error in computing the velocity components is further reduced. All derivatives in Eq. (13) were numerically estimated from the surface pressure field using a first-order discrete approximation.

POD is commonly used as a means for creating a low-order reconstruction of the spatio-temporal data, where the data can be adequately represented using a reduced number of spatial modes [24]. In POD, the globally-reconstructed spatio-temporal signal, $p(s,t)$, where $s = (x, y)$ denotes a spatial point, is decomposed into a series of orthonormal spatial POD modes, $\varphi(s)$, and corresponding temporal coefficients, $a_n(t)$, such as $p(s,t) = \sum_n a_n(t) \varphi_n(s)$. The energy of each mode is $\lambda_n = \overline{a_n^2(t)}$.

Although an optimal set of modes can be obtained for each data set using POD, the spatial modes are different for each case, so comparing POD modes and related energies for different cases becomes complicated. An alternative way, called JPOD, was proposed as a data analysis technique to compute the common or joint modes from different data sets [25]. JPOD is a specialized version of POD, in which the spatio-temporal data for different cases are combined into a single joint data set, and POD algorithm is used to extract the joint spatial modes. By design, this set of spatial JPOD modes is the same to all cases. When the individual data sets for each case are projected onto these spatial JPOD modes, the temporal coefficients and the corresponding energies will be different. Thus, the differences among cases will be reflected in the temporal coefficients and the energy distributions.

In the present studies, the pressure fields in the wake region for the oscillating and the stationary turret configurations were combined to compute spatial JPOD modes. The temporal coefficients of JPOD modes were also computed and their power spectra were analyzed. From the temporal coefficients, individual energies of JPOD modes were computed.

By integrating the unsteady fluctuating pressure field over the hemispherical turret surface, the unsteady fluctuating forces acting on the turret, $\vec{F}(t) = \{F_x(t), F_y(t), F_z(t)\}$, were computed. All three components of the force were normalized by the dynamic pressure and the cross-sectional area of the turret, $S_{cross} = 0.5\pi R^2$, yielding a non-dimensional time-dependent force coefficients,

$\{C_x(t), C_y(t), C_z(t)\}$. Using these force coefficients, temporal root-mean-squared values and the power spectra were calculated for each force component.

The temporal spanwise displacement of the turret in the oscillating case was measured directly by optically tracing the motion of the turret edge. This was accomplished by extracting a single 1 x 30 column of pixels (0.5 mm x 1.6 mm) spanning the gap region and tracking the relative position of the intensity threshold corresponding to the turret edge. The exact position of the turret edge was resolved for each frame by interpolating the intensity values of adjacent pixels in order to achieve displacement resolution within the subpixel range. The edge position of the oscillating turret, z_{turret} , was computed for the entire time series at all three tested Mach numbers.

Finally, in order to study the intermittency of the applied forcing and the turret motion during the stationary and the oscillating cases, a conditional analysis using a Morlet wavelet analysis [26] was used. The wavelet transformation of a continuous signal, $g(t)$, is generally defined as,

$$G_{\Psi}(\kappa, \tau) = \kappa \int_{-\infty}^{\infty} g(t) \Psi^*(\kappa(t - \tau)) dt \quad (14)$$

where $\Psi(\eta)$ is the wavelet mother function, κ is a dilatation parameter, τ is a translation or shift parameter and an asterisk denotes a complex conjugate. Morlet mother function is defined as $\Psi(\eta) = \exp\left(id\eta - \frac{\eta^2}{2}\right) - \exp\left(\frac{d^2}{2} - \frac{\eta^2}{2}\right)$, where $d = 6$ was chosen for this study. The Morlet wavelet transform is useful to study temporal amplitude variation of the signal at a given frequency. The frequency is related to the dilatation parameter as $f\kappa = (d\kappa) / (2\pi) \approx 0.96\kappa$. The local amplitude of the Morlet wavelet transform was computed as $A_{\Psi}(\tau, f) = |G_{\Psi}(f(\kappa), \tau)|$.

High-Fidelity Simulations

The turret geometry under consideration is a 10 inch (25.4 cm) diameter hemispherical turret. Initial simulations modeled a rigid turret which was mounted to a rigid wind tunnel, i.e. no FSI was considered. These rigid simulations not only serve as a baseline for comparisons with the flexible geometry, but also prove to be a useful tool to determine the characteristic length and time scales associated with the unsteady flow features in the wake of the turret.

The turret is modeled inside the wind tunnel which was identical to the Notre-Dame subsonic wind tunnel. Computer models were acquired from the University of Notre Dame and used as the basis for the grid generation of the computational simulations. The geometry of the subsonic wind tunnel is shown in Figure 8.

As shown, the geometry includes inserts on the floor and ceiling of the tunnel which allow for higher speeds to be attained in the tunnel test section. The hemispherical turret is shown in the center of the test section. All tunnel walls were modeled as no-slip boundary conditions. In order to match the incoming boundary layer flow profile present in the experiment, a turbulent boundary profile was generated with a momentum thickness of 40 mm and prescribed as the inflow profile.



Figure 8: Sideview of the Notre Dame subsonic wind tunnel with turret model

Initially, the Department of Defense High Performance Computing Modernization Program CREATETM-AV/Kestrel v8.0 simulation environment was used to compute the flow around the aero-optical turret. KCFD, the solver component, is an implicit, unstructured finite-volume code with a discretization that is 2nd order accurate in space and time. The solver supports one- and two-equation turbulence models in RANS and DDES simulations. For this study, the two-equation Menter shear stress transport (SST)-Menter turbulence model was used in time-resolved DDES simulations. KCFD has been verified and validated for a number of benchmark aerodynamic problems for steady, unsteady, and aeroelastic solutions [27, 28, 29, 30]. The code allows for fully coupled fluid-structure interaction simulations using a second order modal solver with beam, infinite-plate, and thin-plate spline interpolation. In addition, externally controlled boundary conditions can be utilized, e.g. for flow control applications. Finally, rigid body motion, including full 6-DoF capabilities, is included. It should be noted that all these capabilities can be utilized in conjunction, i.e. a 6-DoF simulation of a flexible aircraft with moving control surfaces is possible.

As the research effort progressed and the structural model (described in more detail below) of the turret became more defined, it was determined that Loci/CHEM-Abaqus (Dassault Systemes Simulia) was a more appropriate tool to model the fully coupled fluid-structural interactions. This decision was made because initial attempts to couple Kestrel to a linear modal structural model were not successful. This code instability was retested on other HPC systems and verified, which suggests that there are problems in Kestrel when performing FSI simulations on very large CFD grids. Because of these problems the simulations were performed using Loci/CHEM-Abaqus. Importantly, the convergence study, which was performed using Kestrel for the rigid geometry was not rerun due to timing and CPU hour constraints. The converged parameters (spatial resolution and time step) from the Kestrel simulations were used for the Loci/CHEM-Abaqus FSI simulations.

The coupling is accomplished by the Dassault Systems Co-simulation engine at every time step. The extension to Loci/CHEM to allow communication with the Co-simulation engine was developed by ATA Engineering. Loci-CHEM is, similar to Kestrel, a second-order in space and time finite-volume solver for the compressible Navier-Stokes equations. Both RANS and DDES simulations are available and the code includes the SST Menter turbulence model.

The grid setup is shown in Figure 9. This figure shows four views of the finest grid used in the convergence study. As shown, the turret sits on the tunnel floor on one of the wind-tunnel inserts. Surface mesh sizing was specified on the turret, in the refinement region; in addition, the first layer height normal to the wall was specified. Each of these parameters was non-dimensionalized by wall-distance. The refinement region was added to the computational domain to capture details of the spatial development of the wake structures. This region extended a diameter around the turret and was elongated five diameters downstream.

A boundary layer grid was generated for both the tunnel floor and the turret. The side walls and ceiling are set to slip boundary conditions. The inlet and outlet boundary conditions were specified as modified Riemann invariants where the total pressure and temperature are specified. Importantly, the inlet and outlet boundary conditions were set to a Mach number of 0.4 to attain a Mach of 0.5 within the test section due to the tunnel contraction. Additionally, the incoming boundary layer profile with a 40 mm momentum thickness was applied to the inlet condition to enforce an incoming turbulent boundary layer. It was found that the incoming boundary layer thickness has a direct influence on the size and shape of the necklace vortex at the base of the turret. A 40 mm momentum thickness was chosen to best match companion experiments at Notre Dame.

The flow conditions for the simulations were matched with the Notre-Dame facility and are given as: $U_{\infty} = 170$ m/s, $P_T = 120192$ Pa, $T_T = 302$ K, $\rho = 1.22$ kg/m³, $Re = 2,950,000$.

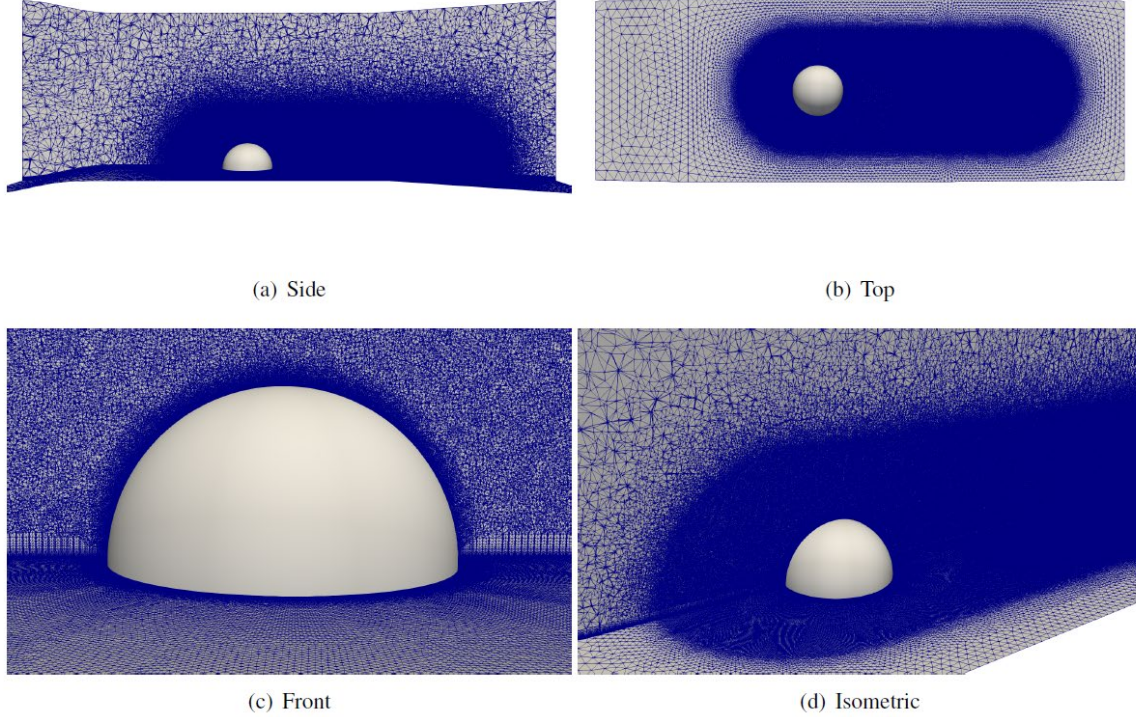


Figure 9: Grid description of the hemispherical turret

Structural Dynamics Solver

Dassault Systems Abaqus allows for a broad range of structural simulations. It allows for adaptation of the complexity of the structural model from simplistic canonical models to fully detailed replicates of highly sophisticated non-linear structural configurations. While the initial goal of this research is primarily to understand the complex fluid-structure interaction with a simplified 1-DoF structural model, future research will extend to much more detailed structures which can all be modeled in Abaqus.

The structural setup in the experiment is such that a nominally rigid turret is mounted on a cantilevered beam which is very stiff in all direction except the cross stream direction as shown in Figure 10(a). The stiffness and mass of the cantilever beam with the turret at the free end were tuned to match the frequency of the switching mode observed in the experiments in the wake of the turret [31]. The goal was that the vortex shedding behind the turret would resonate with the structural cross-stream oscillation to excite the fluid-structure interaction and amplify the contributing flow features.

While the experimental cantilever beam setup could have been modeled in Abaqus, it was decided to approximate the beam as a linear spring and attach the rigid hemisphere to ground through a Mass, Damping and Stiffness (MDK) system. A graphical representation of this approximation is shown in Figure 10(b). With anticipated deformations on the order of 10 mm, this linearization was well justified. From the experimental setup, the following beam parameters were determined:
 $E = 73.1 \text{ GPa}$, $r = 2.78\text{e}3 \text{ kg/m}^3$, $I = 4.336\text{e}-8 \text{ m}^4$, $L = 0.23 \text{ m}$, $t = 0.5 \text{ in}$, $w = 10 \text{ in}$, $\zeta = 0.03$, $M = 1.5 \text{ kg}$, $I = 0.0063 \text{ kg m}^2$.

A MDK system is commonly defined by a 2nd order ordinary differential equations,

$$m\ddot{y} + D\dot{y} + Ky = F(y) \quad (15)$$

where y is the cross-stream coordinate and $F(t)$ are the external fluid forces. From the experimentally obtained structural parameters, the following quantities for the single DoF MKD system were computed:
 $K = 3E \cdot I / L^3 = 781.5 \text{ KN/m}$, $D = 2\zeta(KM)^{1/2} = 65 \text{ kg/s}$, $M = 1.5 \text{ kg}$, $\omega_n = (K/M)^{1/2} = 115 \text{ Hz}$

The convergence study showed that the finest grid (226 million cells) is necessary to capture the relevant near wall flow physics. For the simulations presented below, the time step of $dt = 4.25\mu\text{sec}$ was chosen in order to maintain a non-dimensional time step of smaller than 0.01. In future simulations, it may be observed that a coarser time step could be used to capture a longer time history as there was hardly any dependence of the results on the time step.

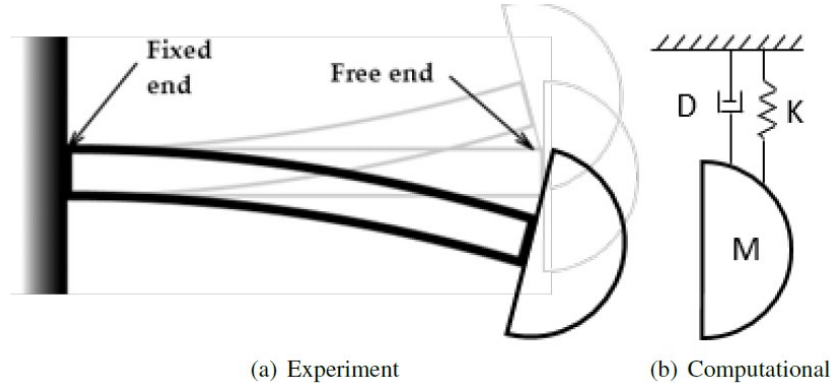


Figure 10: Graphical representation of a turret on a cantilever beam as in the experimental setup and the computational approximation

Topic 2: Experimental studies in supersonic flow and related aero-optical effects to validate numerical codes

Experimental Setup and Instrumentation

The SBR-50 facility at the University of Notre Dame, used in these experimental studies, is a supersonic blowdown wind tunnel with interchangeable Mach 2 and Mach 4 nozzles. The test section has an upstream cross section of $76.2 \times 76.2\text{mm}$ with a 1-degree expansion on the top and bottom walls and a total length of 610mm. Quartz side windows and fused silica upper and lower windows provide optical access to the test section. Stagnation conditions of the facility are $P_0 = 1\text{-}4\text{ bar}$ and $T_0 = 300\text{-}750\text{ K}$ provided by resistive heaters, with steady-state runtimes of approximately 0.5-1 s. Working fluids include filtered, dried air as well as pure N_2 and gas mixtures. A total of 48 static pressure ports are distributed along the upper and lower test section walls, and a 16-probe Pitot rake may be installed at the end of the test section. Standard instrumentation of the facility includes a 64-channel pressure scanner (Scanivalve MPS4264) with 800 Hz acquisition rate and a high-speed schlieren system.

Test Geometry

Interchangeable pin array inserts are composed of seven stainless steel cylindrical pins press fit into threaded aluminum inserts, one of which is installed on the upper wall of the test section. Pin array inserts have a pin diameter $d = 2.5\text{ mm}$, pin spacing $l = 10\text{ mm}$ center-to-center, and pin height $h = 2.5\text{ cm}$, 1 cm , and 0.5 cm . In addition to quartz panoramic side walls, rectangular fused silica windows 2 inches in the spanwise direction and 4 inches in the streamwise direction are flush mounted on both the upper and lower test section walls downstream of the pin array inserts to provide optical access to the wake region. Illustrations of the test section are provided in Figure 11.

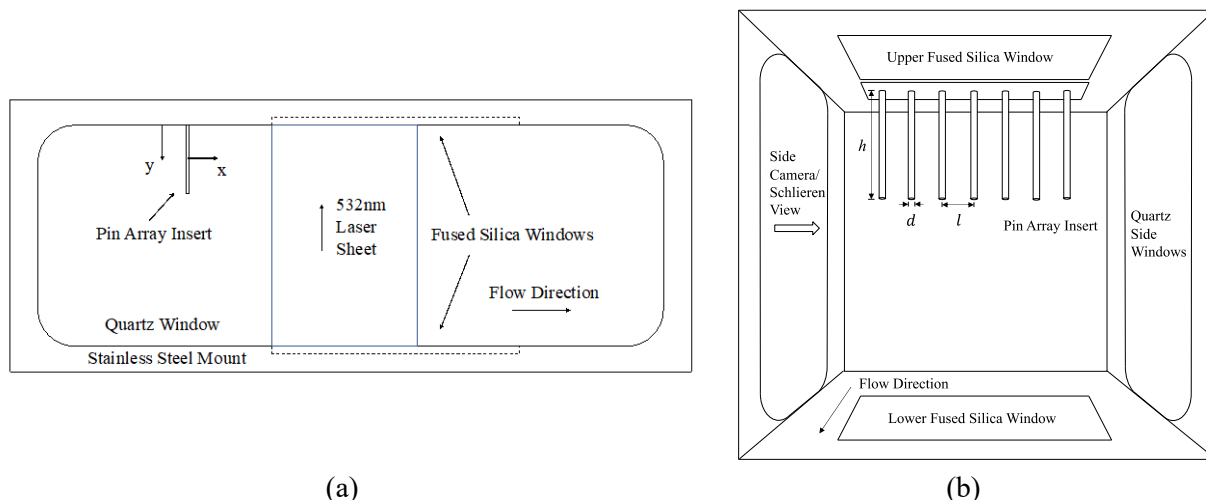


Figure 11. Illustrations of (a) test section side view and (b) perspective view of test section interior

Schlieren Technique

The schlieren system is a conventional refractor-based system. The schlieren light source consists of a high-current broadband white light emitting Diodes (LED) (Luminus Devices CFT-90-WCS-X11-VB600) powered by a pulsed LED driver (PicoLAS GmbH LDP-V 240-100 V3.3) with pulse width 20ns-10 μ s at 40-240A. While the LED is rated for 27A continuous, in pulsed operation it may be used with up to 200A without damage. The light source is focused using a 50mm f=32mm aspheric condenser lens (Thorlabs ACL50832U-A) and a 50mm f=350mm achromatic doublet (Edmund Optics 49-289-INK) and collimated and refocused using two 120mm f/8.33 refractors (Celestron Omni XLT 120). Imaging is performed with a high-speed CMOS camera (Vision Research Phantom v2512) fitted with a Nikon 200mm f/4 AI-s lens. Two schlieren techniques are utilized: a traditional knife edge method and a central dot method. A knife edge method is sensitive to density gradients in one direction, while a central dot method, performed by placing a small black dot on a fused silica plate, is sensitive to density gradients in two directions. Schlieren images in this study use an optical pulse width of 200ns and diode current of 80A.

Acetone PLIF

Bulk seeding with acetone of the SBR-50 working gas is performed by adding pressurized liquid acetone to a pure N₂ stream via liquid atomizer. The mixture is first passed through a static mixer with internal baffles and then a small cell with sapphire windows. Acetone concentration is measured by UV absorbance using a 2 mW 280nm UV LED with collimation and focusing optics and a Gallium Phosphide photodiode combined with a pressure transducer and a resistance temperature detector (RTD). Acetone is seeded at 2-6% by volume.

Laser excitation is performed using the fourth harmonic of an Neodymium-doped Yttrium Aluminum Garnet (Nd:YAG) laser (Quanta-Ray DCR-4) with 10ns pulse width and 10 Hz repetition rate. After frequency doubling from 1064nm to 532nm and again from 532nm to 266nm, the pulse energy is approximately 70 mJ/pulse. Sheet forming optics are then used to produce a 25mm wide 266nm laser sheet that is approximately 200 μ m thick at the sheet waist within the test section. The laser sheet forming arrangement is illustrated in Figure 12.

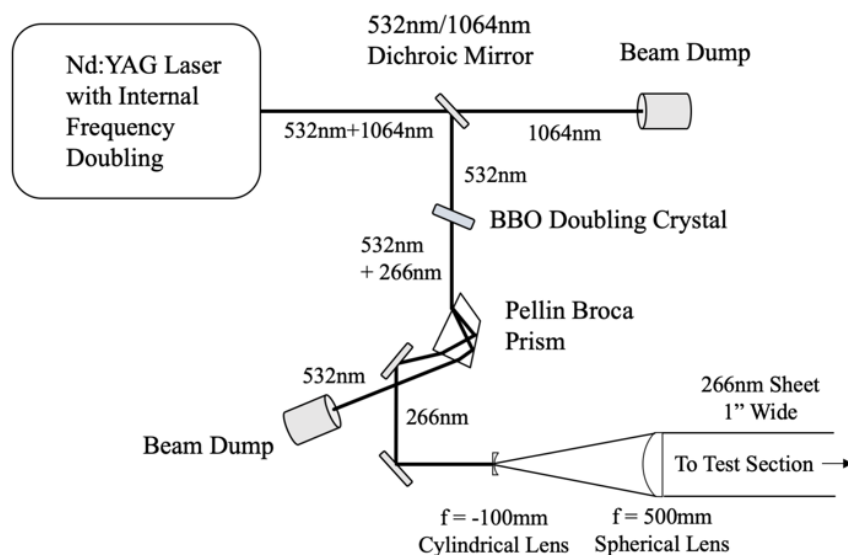


Figure 12. Laser sheet forming arrangement

Mie Scattering

Mie scattering is the elastic scattering of light from particles whose diameters may be smaller or larger than the wavelength of the light. The flow of the SBR-50 is seeded by lowering the stagnation temperature of the acetone seeded flow until the acetone condenses, forming acetone nano/micro-droplets. Since the intensity of Mie scattering is much greater than the intensity of acetone fluorescence, laser sheet forming for Mie scattering omits the second frequency doubling and uses an $f = -50\text{mm}$ cylindrical lens instead of an $f = -100\text{mm}$ lens to form a 50mm 532nm sheet rather than the 25mm 266nm sheet illustrated in Figure 39.

Optical Setup using Shack-Hartmann Wavefront sensor (SHWFS)

Another way to study the density field is to collect spatially-temporally resolved wavefront data, as the wavefronts are proportional to the line integrals of the density [32, 33]. A schematic of the optical set-up is presented in Figure 13(a). To collect the wavefronts downstream of the pin arrays, the 532 nm laser beam from a CW Nd:YAG laser was first expanded to 25 mm using a beam expander and then passed through a beam splitter cube. From the beam splitter, the beam was expanded to 50 mm using a pair of lenses. Using steering mirrors, the beam was sent through the test section 50 mm downstream of the pin array either in the wall-normal direction through the top and the bottom optical inserts, indicated by a blue box in Figure 13(b), or along the spanwise direction through the test section windows, indicated by a green circle in Figure 13(b). After passing through the test section, the beam was reflected back along the same optical path using a large flat return mirror. This so-called double path setup doubles the optical signal. The beam splitter cube reflected the return laser beam sideways and, after passing through a pair of re-imaging lenses, the beam was sent to the SHWFS. The sensor consisted of a Vision Research Phantom v1611 high-speed camera with a mounted lenslet array. The lenslet array had a pitch of 0.3 mm and a focal length of 38.2 mm. Time-resolved two-dimensional wavefronts were collected at two different sampling frequencies and spatial resolutions. One data set was collected at a lower sampling frequency of 39 kHz with the spatial resolution of 62x64 subapertures. The second data set was collected at a higher frequency of 99 kHz with a reduced spatial resolution of 34x38 subapertures.

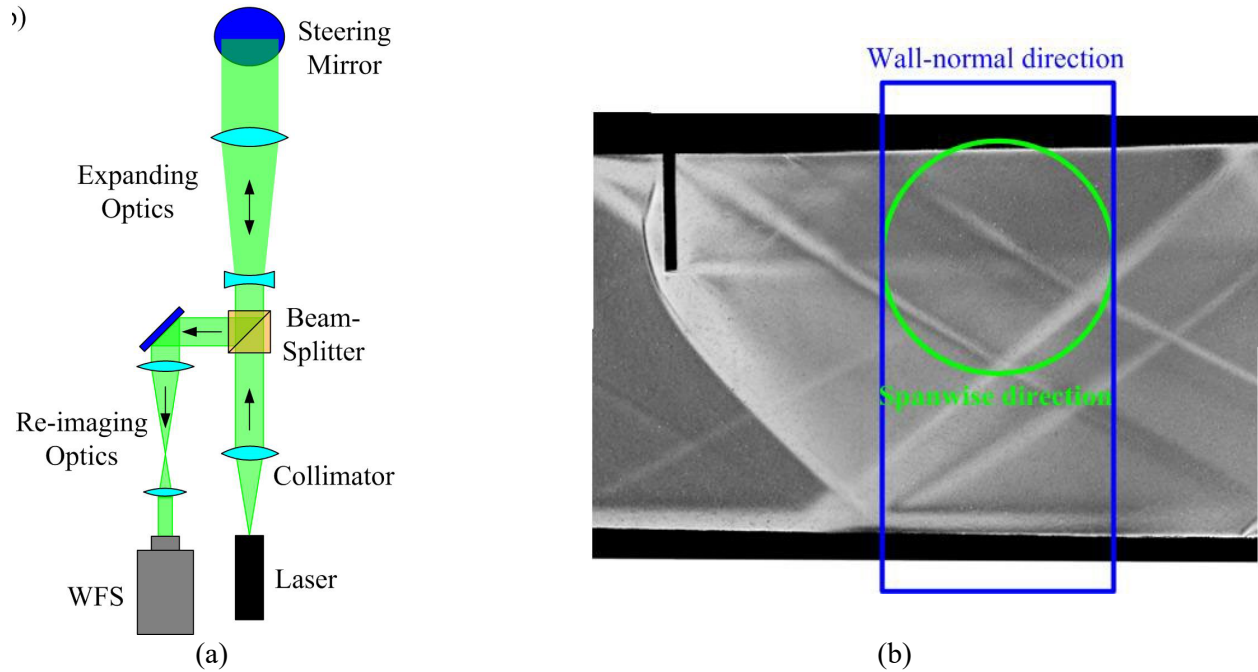


Figure 13. (a) Schematic of optical set-up using SHWFS and (b) laser beam arrangements in the wall-normal (blue box) and in the spanwise (green circle) directions to collect wavefronts. The laser beam was 50 mm in diameter, with the upstream edge 50 mm downstream of the pin array

The SHWFS measures the local deflection angles, which are spatial gradients of the wavefronts. A Southwell method [34] was implemented to reconstruct the time-resolved wavefronts, $OPD(x,y,t)$, from the deflection angles using in-house software. After removing the instantaneous piston and tip/tilt modes from each wavefront, spatial maps of $OPD_{rms}(x,y)$, defined as $OPD_{rms}(x,y) = \sqrt{\overline{OPD^2(x,y,t)}}$, were computed for each dataset. Here an overbar denotes time averaging.

For the data set along the spanwise direction, the dispersion analysis was also used to estimate the convective velocities at different distances from the wall. In [9,35,36], the dispersion analysis of the deflection angles was demonstrated to be effective in characterizing convecting optical disturbances. The dispersion analysis uses time-resolved streamwise deflection angles in several consecutive streamwise points, $\theta_x(x,t)$ to numerically compute a two-dimensional autospectral density function of the deflection angles, $S_\theta(f,k_x)$, using the standard procedure [37]. A stacking approach [36] was used to de-alias the spectra in the frequency domain. If the flow structures convect with a constant speed, the spectrum will have a single branch with a fixed slope. The convecting velocity, U_C , both the direction and magnitude, can be computed from the branch slope as $U_C = 2\pi f/k_x$.

Topic 3: Experimental studies of the aero-optical jitter of the hemisphere-on-cylinder turret at various amounts of protrusion

Aero-Optical Jitter Studies

Wind Tunnel Testing

Wind tunnel tests were performed at the University of Notre Dame's White Field Mach 0.6 wind tunnel facility. This facility has a 0.91 by 0.91 m (3 by 3 ft) test section capable of producing Mach numbers up to approximately 0.6. The facility is particularly useful for these experiments since the

dynamic pressures in the tunnel are close to the dynamic pressures seen in real transonic flight environments. Four different protrusion distances into the freestream flow were tested: $H=0.08$ m (3 in), 0.15 m (6 in), 0.19 m (7.63 in), and 0.27 m (10.5 in). For protrusion distances greater than the radius of the turret, the cylindrical mount also protruded into the flow. These so called “hemisphere on cylinder” configurations have also been previously researched. Figure 14 illustrates the four configurations (partial hemisphere, hemisphere, hemisphere on partial cylinder, and hemisphere on full cylinder) mounted in the wind tunnel. Notice that for the two “hemisphere on cylinder” configurations, the interface between the hemisphere and cylindrical base is covered with a plate to avoid complicated cavity flow phenomena. For all configurations, Mach numbers 0.3, 0.4, and 0.5 are tested.

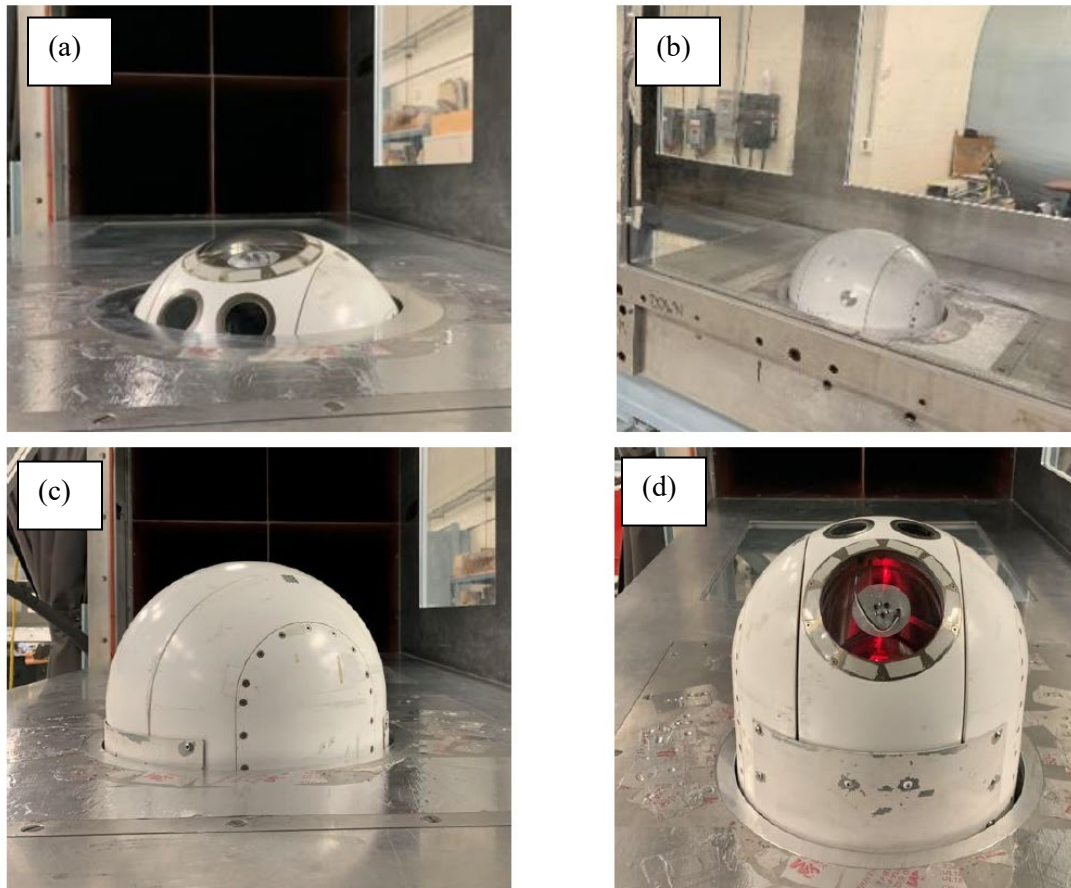


Figure 14. (a) Partial hemisphere configuration. (b) Hemisphere configuration. (c) Hemisphere on partial cylinder configuration. (d) Hemisphere on full cylinder configuration

OIRU Beam

For these tests, the mechanical contamination induced jitter is measured a few ways. Firstly, an OIRU is mounted on an optical bench outside the turret. The benefit of the OIRU is that the outputted beam is inertially stabilized, meaning any bench or lab vibrations up to a certain bandwidth are rejected from the outgoing beam. The OIRU beam passes through a 50/50 beam splitter and then enters the turret parallel to the optical axis of the system. Rather than exiting the turret through the viewing aperture, the OIRU beam is reflected off a mirror installed on the back of the secondary mirror of the telescope. As such, the return beam then follows the same path back out of the turret. The beam is turned by the same 50/50 beam

splitter and is then focused by a 250 mm lens onto a Phantom v1611 high speed camera. The camera collected images at 30 kHz for 30 seconds with a spatial resolution of 128 by 128 pixels each 28 μm in height and width. By knowing the focal length of the last lens and the pixel size of the camera, a centroid can be extracted in order to compute x-, y-, and subsequently radial jitter as a function of time. For each Mach number and turret configuration, azimuthal angles $\beta=0, 30, 60, 75, 90, 105, 120,$ and 150° relative to the incoming freestream were also tested. Figure 15 shows the optical setup for these measurements outside the turret.

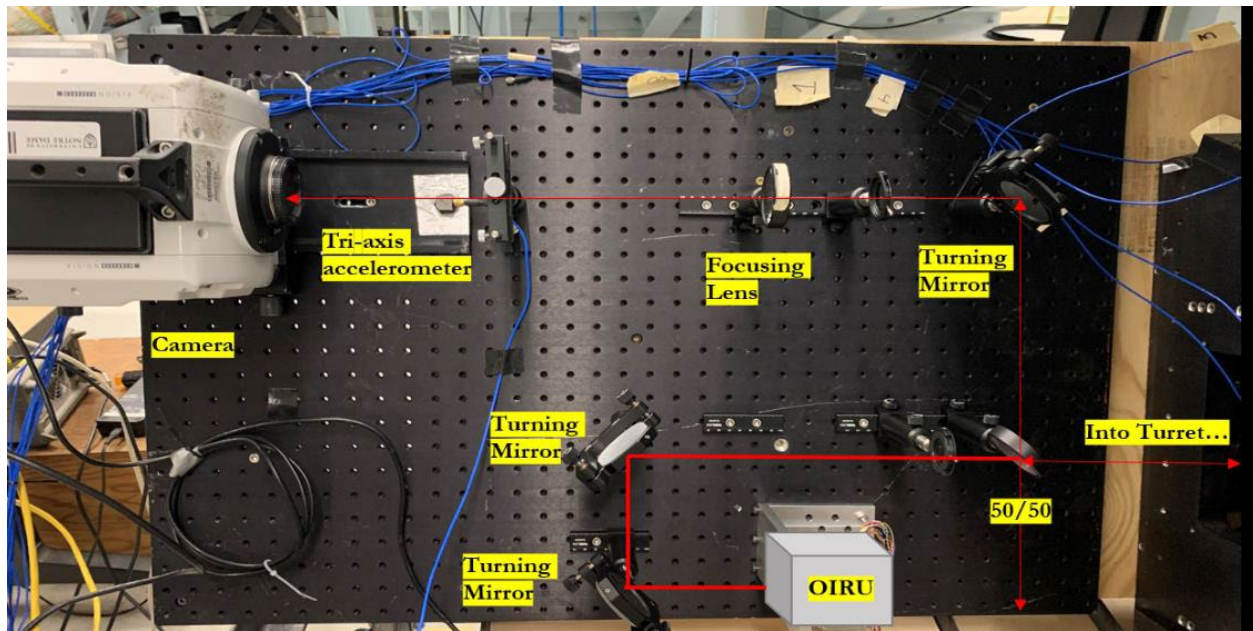


Figure 15. Optical setup for the OIRU beam outside of the wind tunnel and turret

Reflector Mounted Laser Diode

The second method of data collection is by using a blue laser diode installed in the reflector mirror mounted on the back of the secondary mirror (the same mirror the OIRU beam is reflected off). A close-up of this reflector mirror can be seen in Figure 16. Despite this beam not being inertially stabilized like the OIRU beam, the jitter measurements collected using the blue laser diode only pass through the optical path of the turret once. For these measurements using the reflector mounted laser diode, the camera collected images at 20 kHz for 12 seconds with a spatial resolution of 256 by 256 pixels. These measurements are compared with the jitter imposed onto the OIRU source. Again, for each Mach number and turret configuration, azimuthal angles $\beta=0, 30, 60, 75, 90, 105, 120,$ and 150° relative to the incoming freestream were also tested. The optical bench setup outside the turret for the blue laser diode can be seen in Figure 17.

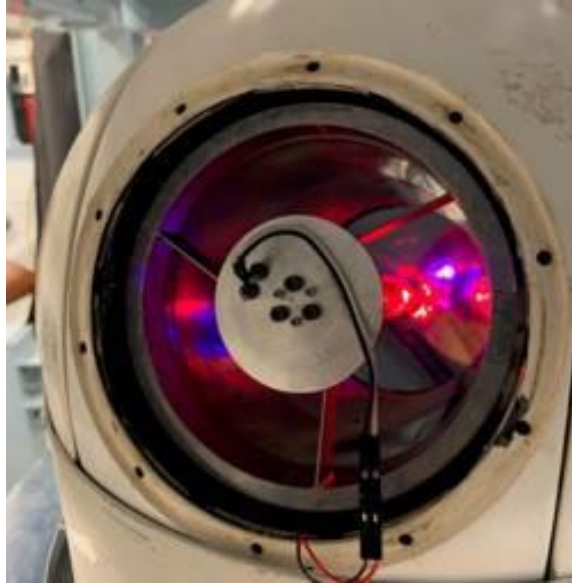


Figure 16. Reflector mounted on the back of the secondary mirror inside the turret telescope

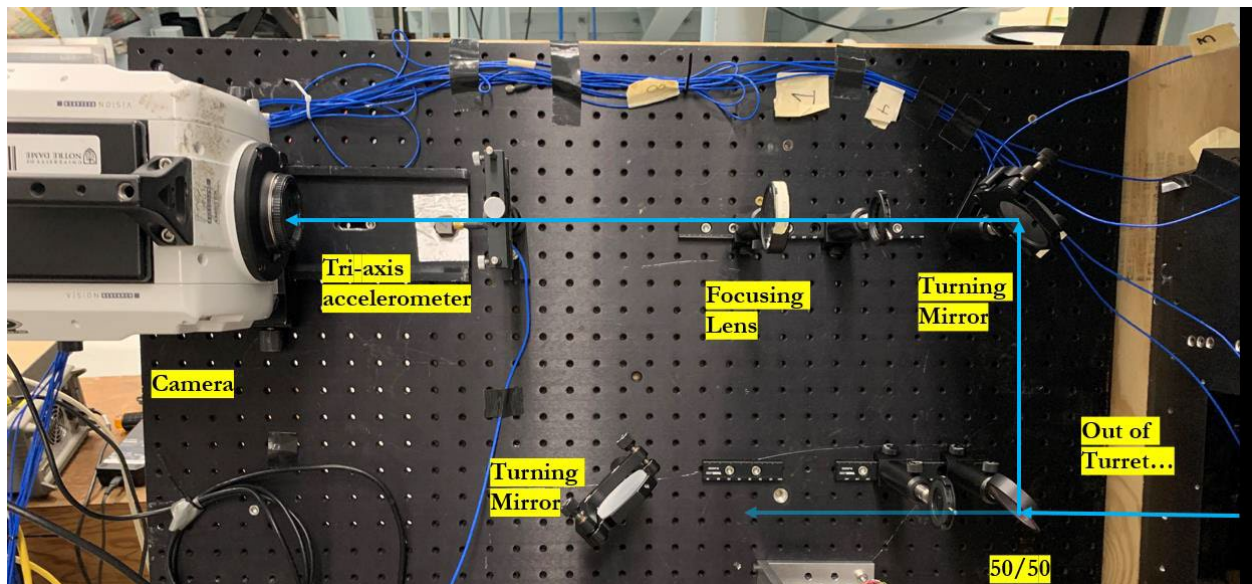


Figure 17. Optical setup for the blue laser diode outside of the wind tunnel and turret

Bench Measurements

In addition to the measurements involving the OIRU beam and the reflector mounted laser diode, bench measurements were also collected. For these bench measurements, the OIRU beam was used and turned towards the camera before entering the turret. The jitter that was imposed onto this beam was from optical components that were exclusively on the optical bench. These measurements gave a baseline estimate of what jitter comes from the optical bench vibration versus the aero-mechanical forcing on the turret itself. Azimuthal angles of $\beta=0, 90$, and 150° were tested for these bench measurements.

Accelerometer Measurements

For all the measurements described above (OIRU beam, reflector mounted laser diode, and bench measurements), simultaneous accelerometer measurements were also recorded. For these tests, 6 accelerometers were used: 1 tri-axis and 5 single axis. The tri-axis accelerometer was placed on the mounting bracket of the high-speed camera used to collect jitter measurements, as seen in Figs. 15 and 17. Three single axis accelerometers were placed in directions pointing with respect to x, y, and z on the turret collar which presses up against the wind tunnel. The last two accelerometers were placed on the mounting stands for two turning mirrors located inside the turret. Accelerometers were sampled at 30 kHz for the OIRU beam and bench measurements and then 20 kHz for the reflector mounted laser diode measurements. All accelerometers were collected simultaneous to the highspeed camera. The voltage measurements collected using the accelerometers are converted to accelerations using company provided calibrations. Accelerations are then converted to displacements by using a simple midpoint rule twice.

AAOL-BC Flight Testing

AAOL-BC is an airborne laboratory, retrofitted to accommodate equipment to perform optical experiments [35, 38, 39, 40]. For these tests, the same turret used for wind tunnel tests and described above was installed in the aircraft. Two flights campaigns were conducted where the turret was flown in the “hemisphere” and “hemisphere on full cylinder” configurations. Figure 18 shows the two turret configurations mounted in the aircraft. Similar to the wind tunnel tests, two laser sources were used to measure the aero-mechanical imposed jitter. Instead of using the OIRU for these flights tests, a 532 nm continuous laser was used and rigidly mounted to the optical bench in the aircraft. An OIRU was not used since the pitch, yaw, and roll of the aircraft exceeds the rejection capability of the unit. There was consideration for an inertial feedback loop to the OIRU but in that case, the measuring device would also need a stabilization platform. Ultimately, the assumption was made that the jitter contribution associated with using a non-stabilized platform is much smaller than the jitter imposed onto the beam due to the aero-mechanical forcing on the turret, which is why the 532 nm continuous laser was used. The same reflector mounted laser diode that was used during the wind tunnel tests was also used for these flight campaigns. Instead now, a kinematic mount was designed and implemented to give the reflector mounted laser diode its own steering capability separate from the mounting of the reflector itself. This mount can be seen in Figure 19. The utility of this approach is that it allows for both beams to be scored onto the camera simultaneously. Therefore, for these flight tests, the rigidly mounted 532 nm continuous laser, the reflector mounted laser diode, and the accelerometers were all collected simultaneously.

Figure 20(a) shows the inside of the aircraft with the equipment and turret installed. Figure 20(b) shows the optical setup used on the inside of the aircraft. The camera collected images at 30 kHz for 30 seconds with a spatial resolution of 128 by 128 pixels. For both the hemisphere and the hemisphere on full cylinder configurations, Mach numbers 0.3, 0.4, 0.5, and 0.6 were tested as well as azimuthal angles $\beta = 60, 75, 90, 105, 120, \text{ and } 150^\circ$. Mach numbers 0.3, 0.4, and 0.5 were tested at 3,050 m (~10,000 ft) and Mach numbers 0.5 and 0.6 were tested at 6,700 m (~22,000 ft). Mach 0.5 measurements were collected at both altitudes to have overlap in data at the same Mach number but different dynamic pressures. As mentioned above, simultaneous accelerometer measurements were also collected. For these flight tests, 10 accelerometers were used (1 tri-axis and 9 single axis). The tri-axis accelerometer was mounted on the camera mounting bracket. Two single axis accelerometers were mounted on the laser mounting platform. Two single axis accelerometers were mounted in the turret on the mounting mechanisms for the two turning mirrors in the same locations as the wind tunnel experiments. One accelerometer was placed in the middle of the optical bench. Two accelerometers were placed on the top and side of where the turret collar presses up to the aircraft door and two were placed on the top and side of the turret collar itself. All accelerometers were sampled at 60 kHz for the full duration of camera measurements.



(a)



(b)

Figure 18. (a) Hemisphere configuration mounted in AAOL-BC aircraft. (b) Hemisphere on full cylinder configuration mounted on AAOL-BC aircraft

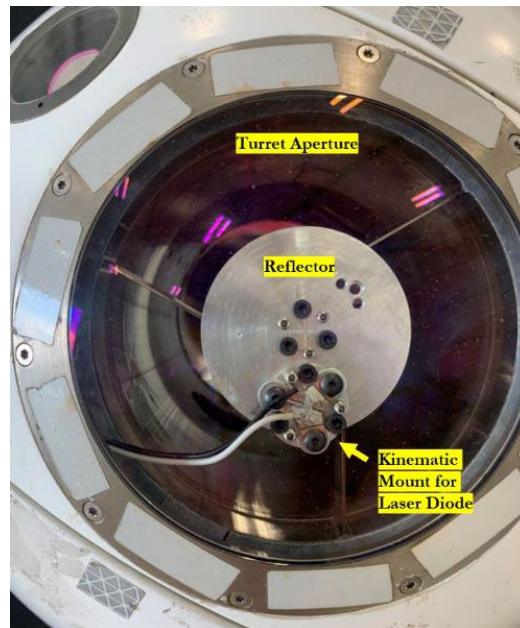


Figure 19. Kinematic mount for laser diode attached to reflector

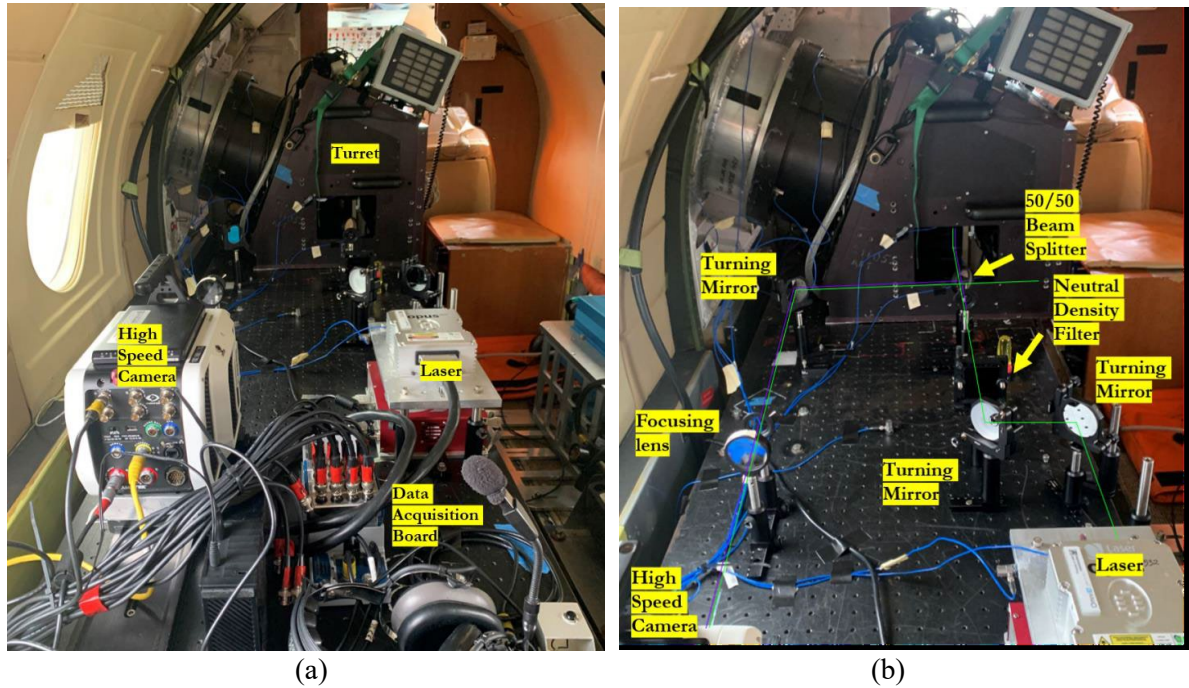


Figure 20. (a) Inside of AAOL-BC aircraft with experiment hardware (b) Optical setup inside AAOL-BC aircraft

Data Reduction and Analysis

A simple centroiding algorithm, such as a first moment scheme, works great for an image with a single measurement beam on the camera like the wind-tunnel testing data had. However, when multiple beams are present, as was the case with the AAOL-BC flight data, other approaches need to be taken. In order to handle multiple beams, a MATLAB function called *regionprops* was employed. This function starts by looking at the mask of pixels that exceed a user defined intensity threshold. Then, the algorithm determines regions of associated pixels. Once a relevant set of regions is determined, the function looks at the pixel values in that region and computes a centroid based on the first moment method. Additional statistics such as spot major and minor dimensions, orientation, equivalent diameter, and the mean and max intensity were recorded to track a given beam throughout the time series. In order to have the capability of handling intermittent image noise, a mean image was computed and run through the same function to determine the general area that each beam encompasses. For each frame, the beam that was closest to a mean beam location and within some user defined minimum distance, was assigned to that beam's data array. This ensures that the same beam is constantly referenced throughout the test point.

Once the camera images are converted into usable data by extracting a centroid of the beams in each frame, knowing the pixel size and focal length of the focusing lens allows the x- and y-jitter imposed onto the beam to be extracted as a function of time. The x- and y-jitter time series were converted into a radial, or total jitter time series, $\sigma_T(t) = \sqrt{\sigma_x^2(t) + \sigma_y^2(t)}$.

Studies of the surface pressure fields on and around turret with different amount of protrusion

Experimental setup for surface pressure measurements

In addition to aero-jitter measurements, surface pressure measurements of various hemispherical turret geometries were collected in a wind tunnel at varying Mach numbers. The turret used in the experiments had a diameter of $D=0.30$ m (12 in). Turret geometries of four different protrusion distances, H , into the freestream flow were tested. These different protrusions were $H=0.07$ m (2.75 in), 0.15 m (6 in), 0.19 m (7.5 in), and 0.27 m (10.5 in) and are referred to as “partial hemisphere,” “hemisphere,” “hemisphere on partial cylinder,” and “hemisphere on full cylinder,” respectively. For all configurations, Mach numbers 0.3, 0.4, and 0.5 are tested, and tunnel temperature, static and total pressures are also recorded.

PC-PSP was applied to the hemispherical pressure turret and the cylinder it sits on, as well as the wind tunnel mounting plate downstream of the turret centerline. The PC-PSP was applied with a thickness of approximately 100 μm . Greater details on the PSP and application process can be found in [18, 41]. The turret and associated components were mounted onto a raisable table allowing the turret to be lifted and lowered with ease. Eight UV lights were installed, four on either side of the test section in order to illuminate the turret during testing. The UV lights were aimed through quartz window inserts to minimize reflection losses. Two high speed Phantom cameras, v1611 and v2512, were used to simultaneously image each side of the turret. These cameras were time synced with each other, as well as the fast response pressure transducers also installed on the setup. The cameras collected images at 3 kHz. Filters were also placed in front of each camera to ensure that only the PSP signal was measured. An image of the experimental setup can be seen in Figure 21.

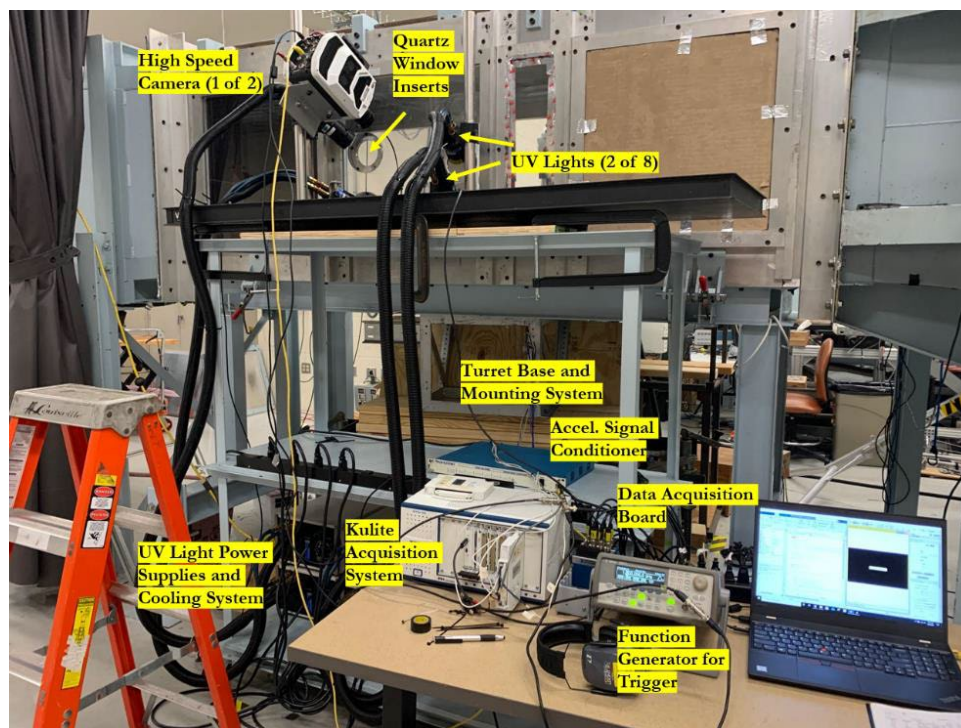


Figure 21. Experimental setup on outward side of the test section

In addition to PSP image measurements, simultaneous surface mounted pressure transducer measurements are also collected in order to perform the in-situ PSP calibration. Four Kulite XT-140 pressure transducers were installed on the hemispherical turret. This type of pressure transducer was selected for its high sampling capability and suitable pressure range. The four Kulites were placed on the top, back, and one on each side of the turret in the spanwise direction and each sensor was referenced to the ambient lab conditions. The locations of these Kulites mounted on the turret surface can be seen in

Figure 22. These fast response pressure transducers were sampled at 30 kHz and as mentioned before, were time synced with camera measurements. An image of the hemisphere on full cylinder configuration illuminated in the wind tunnel can be seen in Figure 23.

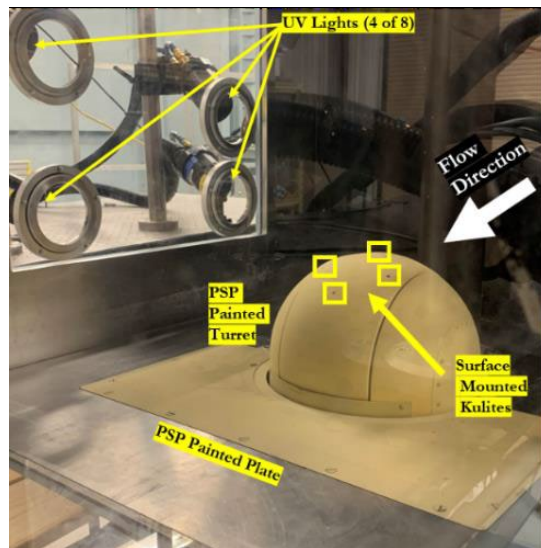


Figure 22. Kulite locations on turret mounted in wind tunnel

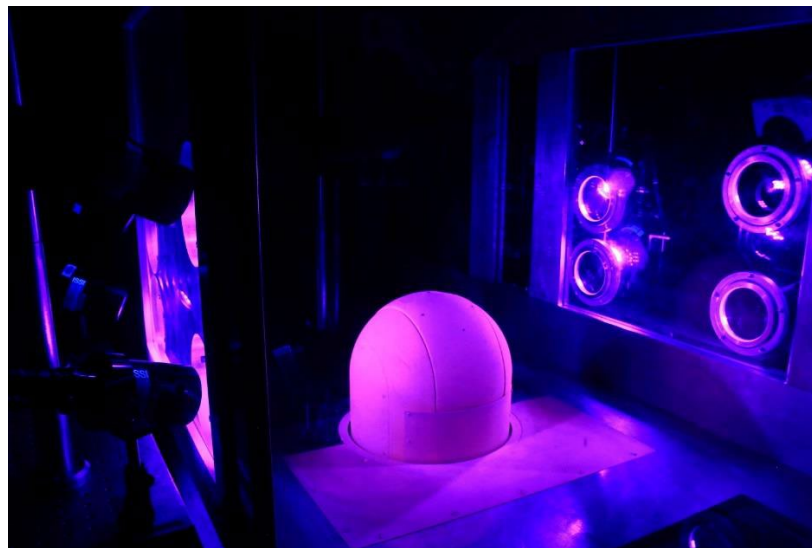


Figure 23. Hemisphere on full cylinder painted with PSP and illuminated with UV lights in the wind tunnel facility

Data Reduction and Processing

Intensity variations, I , of the PSP are related to instantaneous local static pressure fluctuations, P , by the Stern-Volmer equation, $\frac{I_{REF}}{I} = A + B \frac{P}{P_{REF}}$. Here, I_{REF} is an intensity reference image, which for these experiments was an average of no flow images of the turret with the UV lights on for each configuration. The variables A and B are experimentally determined constants and P_{REF} was the ambient lab pressure. The constants A and B are found by performing a calibration using the Kulite pressure measurements. Using the intensity fluctuations in proximity to each Kulite for varying Mach numbers, a calibration curve

is generated. This was done for both cameras and all turret configurations. A linear curve fit is applied to the data and the calibration constants represent the slope and offset of this fit. These calibration equations allow the collected intensity images to be converted into pressure fields.

The PSP measurements were collected by way of two high speed cameras collecting synchronized images of both sides of the turret in the wind tunnel. Ultimately, it is desirable to study the full three-dimensional surface pressure field of the turret. Since cameras collect two-dimensional images, a perspective matrix transformation (PMT) technique is employed to project the two-dimensional image measurements into a three-dimensional intensity field [42,43]. The PMT establishes a relationship between a three-dimensional physical space point and an image point.

Once the PMT matrix is calculated for both cameras, an associated pixel location can be extracted for a given three-dimensional point within the field of interest. After projecting physical space into camera space, the intensity values of interest can be extracted for each camera. In order to reduce noise in the reconstructed pressure field, the intensity is averaged over a region of adjacent pixels. It is also beneficial to have one full field view of the object rather than two separate pressure measurements from both cameras. To address this problem, a blending algorithm was written which takes the intensity fields from both cameras and combines them into one continuous three-dimensional intensity field. After doing so, the intensity field can be converted in pressure using the in-situ calibration constants described above. Since each turret geometry protrudes into the wind tunnel a different amount, the pressure measurements are also corrected to account for varying tunnel blockage by maintaining a constant mass flow rate through the test section.

POD [24] is a modal analysis technique that decomposes a data matrix into an optimal basis set of orthogonal spatial modes in order of increasing to decreasing energy. Since POD modes are identified and organized in order of decreasing energy, it helps identifying what the dominant, or most energetic flow features of a particular environment are. Since these modes are orthogonal in space, a much lower order data set containing most of the energy can easily be reconstructed. In this project, POD is used to decompose the measured PSP pressure fields, $p(s,t)$, into orthogonal spatial modes, $\phi_n(s)$, and temporal

coefficients, $a_n(t)$, $p(s,t) \approx \sum_{n=1}^N a_n(t)\phi_n(s)$. The modes are found by solving the eigenvalue problem,

$$\int_S R(s,s')\phi_n(s')ds' = \lambda_n\phi_n(s), \text{ where } R(s,s') \text{ is the two-point correlation matrix defined as,}$$

$R(s,s') = \overline{p(s,t)p(s',t)}$. Each mode has associated temporal coefficients. These temporal coefficients are found by taking the inner product of the mode of interest with the pressure matrix, $a_n(t) = \int_S p(s,t)\phi_n(s)ds$. Finally, the energy contained within each mode is given by its eigenvalue,

which can be computed from the temporal coefficients as $\lambda_n = \overline{a_n^2(t)}$.

Since the introduction of this modal analysis technique, variations of traditional POD approaches have also started to arise. Some of these variations include Spectral Proper Orthogonal Decomposition (SPOD), Temporal POD (TPOD), and JPOD [25,44]. For the experiments conducted here, JPOD has some particularly useful qualities. The advantage of JPOD is that changes in data due to varying experimental parameters can be more easily identified. For example, in the experiments presented here, four different turret geometries were used. JPOD works by averaging correlation matrices corresponding

to data collected from the different parameters, $R_{\text{Joint}}(s,s') = \frac{1}{M} \sum_{\text{Params}}^M R(s,s',\text{Param})$. JPOD modes,

$\Phi_n(s)$, are computed the same way as for the traditional POD shown above. In order to see how much a specific parameter is represented within each mode, the JPOD modes are projected into the instantaneous

pressure field associated with that parameter, $a_n(t; Param) = \int_S p(s, t) \Phi_n(s) ds$. The resultant energy associated with each mode for a given parameter is given by $\Lambda_n(Param) = \overline{a_n^2(t; Param)}$.

By design, this set of spatial JPOD modes is the same for all cases. When the individual data sets for each case are projected onto these spatial JPOD modes, only the temporal coefficients and the corresponding energies will be different. Thus, the differences among cases will be reflected only in the temporal coefficients and the energy distributions, making it easier to compare the cases.

To implement JPOD analysis, all pressure fields for all parameters should have the same spatial coordinates. The mesh in the wake region was rectangular with grid steps of 7.6 mm (0.3 in), while the dome had a spherical mesh with grid steps of 3° in both azimuthal and elevation directions. Mesh points were not included at the locations of the unsteady pressure sensors since the wall-mounted sensors themselves were not painted. Mesh points were not included in the region where the turret body meets the tunnel wall as the transition could not be clearly defined in the images. The individual regions, used for POD analysis, and the common spatial region, used in JPOD analysis, are indicated in Figure 24 as purple and yellow regions, respectively.

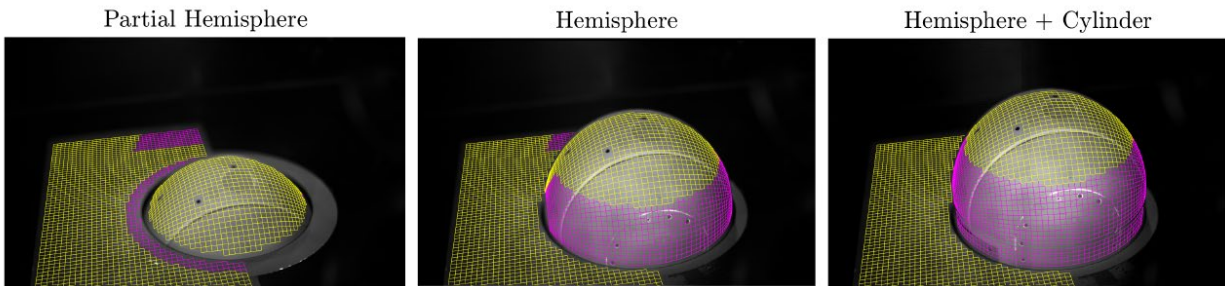


Figure 24. Mesh used to collect data which has been overlayed on top of an example image. The region in yellow is the common region used for JPOD. The purple and yellow regions together were used for POD. Flow goes from right to left

Topic 4: Focused Malley probe as spatially localized aero-optical sensor

Aperture-varying experiments were performed using the 4"x4" transonic in-draft wind tunnel at the Hessert Research Laboratory at the University of Notre Dame. The wind tunnel test section has optical quality glass installed on the sides where the laser beam was transmitted through. A small-aperture, ~1mm, 532 nm YAG:Nd laser beam was expanded to a 1-inch beam using a collimator, as shown in Figure 25. Additional lenses and a variable aperture iris were used to expand or contract the beam to diameters of 0.25, 0.50, 0.75, 1.00, and 1.50 inches. After expanding or contracting the beam to a certain diameter, it was transmitted through the tunnel test section in the span-wise direction. After passing through two boundary layers on the test section walls, the beam was diverted to pass back below the tunnel using a set of mirrors and a 1.5 meter focal length lens was used to converge the beam to a point on a duo-lateral optical PSD. A cardboard tube and an additional iris were used in front of the PSD to reduce the amount of stray glowing laser light reaching the sensor.

The time-resolved overall beam jitter for different beam diameters and flow speeds was collected by recording the instantaneous beam positions of the focused beam on the PSD. To collect data with the smallest beam diameter, all lenses except for the last focusing lens were removed and the laser beam with a diameter of 0.04 in, or ~1mm, was transmitted through the test section. This data set will be referred as the local beam jitter, and the datasets for other beam diameters will be called global beam jitter.

The PSD was attached to a two-direction translation stage for calibration in the X (streamwise) and Y (spanwise) directions. This translation stage was itself affixed to a translation stage in the Z direction, shown in Figure 25, in order to find the exact focus location of the beam. Because the beam got slightly rotated when being directed below the tunnel using the set of mirrors, the PSD was rotated at an angle of

12.5 degrees so that jitter caused by fluctuations in the horizontal or stream-wise direction in the test section would remain in the horizontal direction when directed onto the PSD.

A variable intensity 2 Watt 532 nm Nd:YAG laser was used to ensure the intensity of the light on the PSD was sufficient across all aperture diameters. The tunnel was run at Mach numbers of 0.4, 0.5, and 0.6, verified by a static pressure port, and the only structures in the flow affecting the beam jitter were assumed to be structures in the boundary layers created by the tunnel walls. Results for only the Mach 0.4 case are reported in this report, as other Mach numbers provided similar results.

Beam displacements in both the horizontal and the vertical directions were recorded using a dual-lateral PSD as mentioned previously. Sum and difference voltages for each direction were collected at a frequency of 150 kHz over a sampling time of 30 seconds. The difference voltages that were collected from the sensor were normalized by the sum voltages in order to eliminate any laser intensity dependent fluctuations from the data. Calibration was performed using a translation stage so that coefficients relating voltage readings to the physical beam displacement near the center of the PSD could be determined. The beam displacement readings from PSD, $(\Delta x, \Delta y)$, were then divided by the focal length of the final focusing lens, $f = 1.5$ m, in order to find the angular displacement otherwise referred to as the jitter of the beam in both directions, $(\theta_x, \theta_y) = (\Delta x, \Delta y)/f$. The mean of the beam jitter was removed, and the jitter power spectra were computed using $\left| \hat{\theta}_G(f; Ap) \right|^2$ block averaging scheme such that the final frequency

resolution was 20Hz for all power spectra data. The local jitter power spectra will be denoted as $\left| \hat{\theta}(f) \right|^2$.

At the measurement location, the boundary layer thickness, δ , was 15.6 mm, giving the following values for the beam aperture to boundary thickness ratios: $Ap/\delta = 0.4, 0.8, 1.2, 1.6$ and 2.4 . The temperature in the lab remained constant at 22.6°C throughout the experiments, and it was used to determine the free stream velocity for a known Mach number.

The Focused Malley probe experiments were conducted at the same facilities. Then, the beam was split using a beam splitter, with the split beam directed using a mirror so that both beams converge on the first lens with a small difference in incident angle of approximately 1.3°, as shown in Figure 26. Additional turning mirrors, not shown, were used to allow the setup to fit on the breadboard while achieving a small difference in incident beam angle. This small angle created two focal points of separation $S = 5.15$ mm apart when the beams were converged using the 225 mm focal length lens. The small region around these focal points where the beam apertures are small is the local focused measurement region of the sensor, and this measurement region can be translated to various locations within the wind tunnel. The test section used had a 3.175 mm diameter cylinder mounted vertically in the center to create additional localized optical distortions in the tunnel. A 150 mm focal length lens was used after the tunnel to re-converge the beams to a Phantom v1611 high speed camera. Varying the position of this second lens simultaneously varies the final focusing distance 'L', defined in Figure 27, as well as the spot separation distance on the camera sensor. Closer spots on the camera sensor allow for a higher sampling frequency. A neutral density filter was used to reduce the intensity of laser light going into the camera.

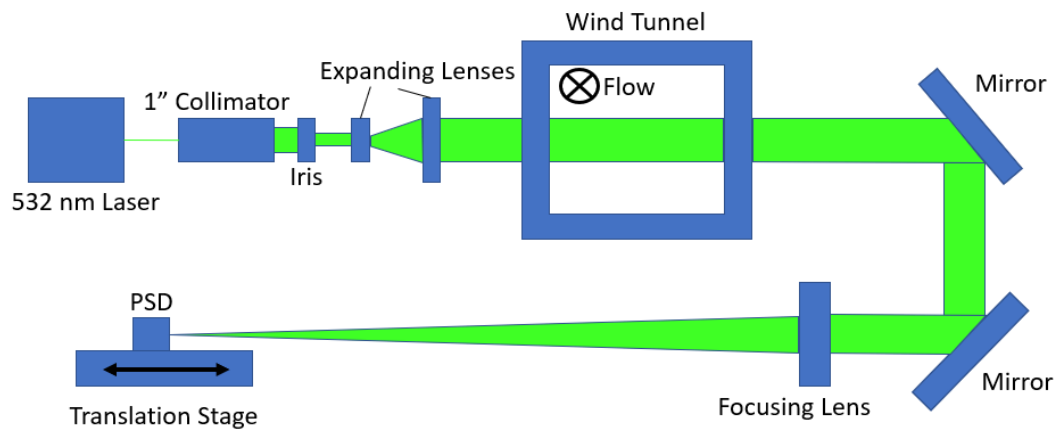
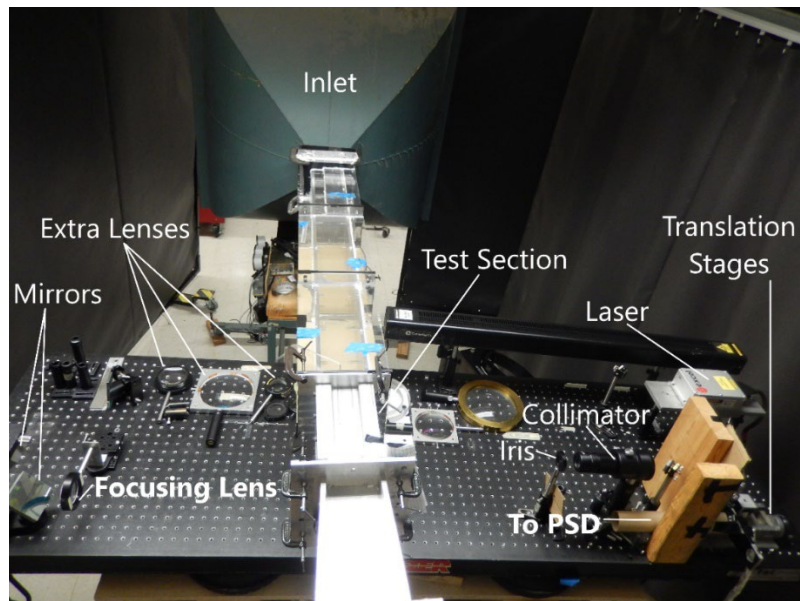


Figure 25. A picture (top) and a schematic (bottom) of the experimental set-up for variable beam diameter experiments

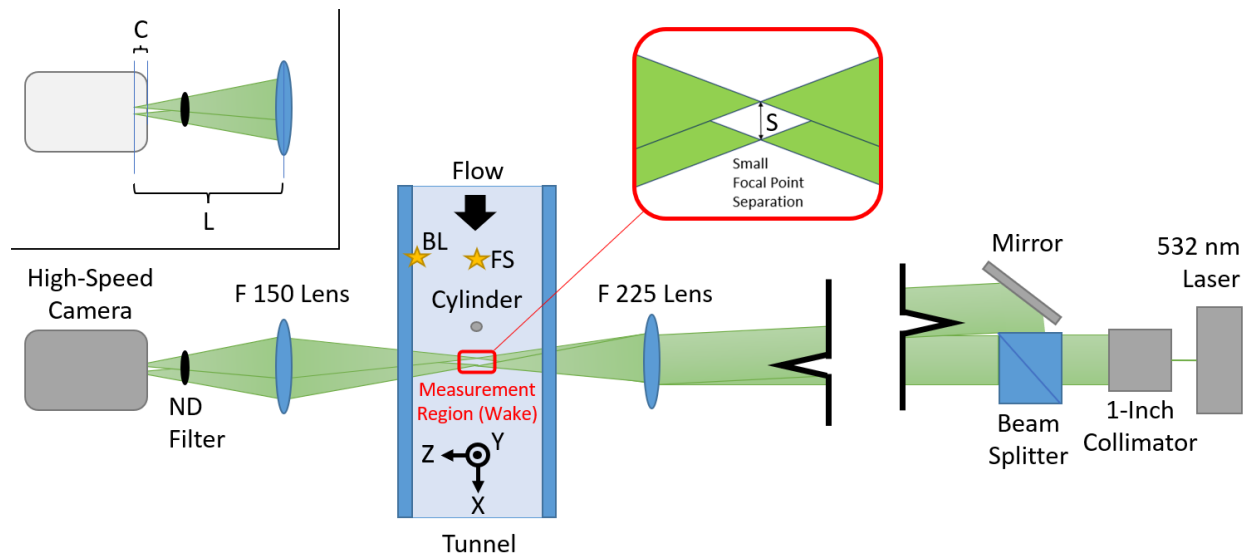


Figure 26. Top-view schematic of experimental set-up for cylinder wake measurements with the focused Malley probe

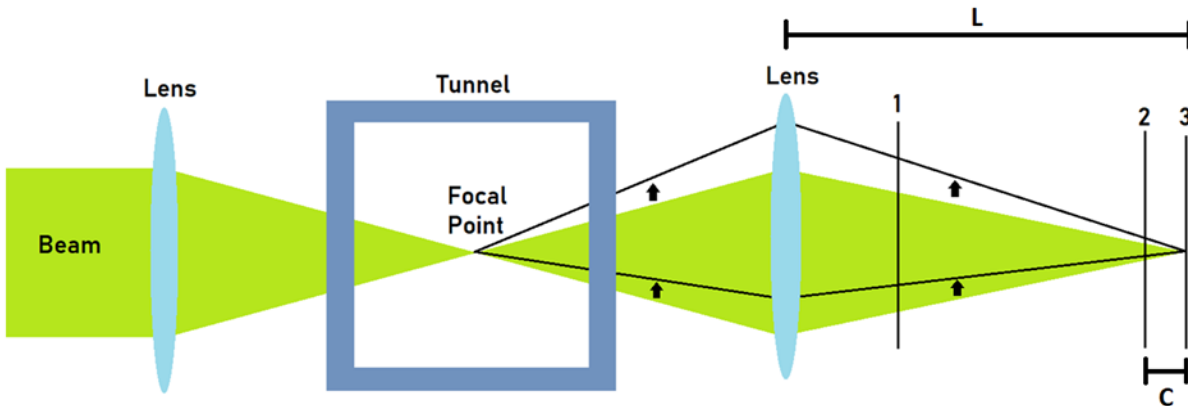


Figure 27. Conceptual schematics of a focused jitter probe

Looking back at Figure 27, it is important to note that due to reimaging, deflections at the focal point will result in zero beam shift at position 3, so a sensor cannot be placed here to measure deflections. For this reason, in order to perform focused jitter measurements, the sensor must measure the beam displacement some distance away from the focal point, such as position 2, but not so far away that the beam would be so large that a high-speed camera could not measure it at high frequency, such as would be the case with position 1. The distance the camera is placed away from the focal point, denoted as C , can be modified as a fraction of the total distance to the focusing lens, denoted as L in Figure 27 and Figure 26, and this fraction is referred to as the C/L ratio. Clearly, the beam displacement magnitude is proportional to C/L ratio, so larger values of C/L result in a stronger signal. On the other hand, the beam size is also proportional to the C/L ratio, resulting in a larger image size and, consequently, a smaller sampling frequency. A parametric analysis was performed [45], and it was demonstrated that the values of C/L between 15% and 25% are optimal to achieve both a strong signal and sufficient sampling frequency in order to properly resolve the localized jitter spectrum.

Experiments were conducted by placing the measurement region at three different locations within the test section at a Mach number of 0.44, to measure the signals from the wake of the cylinder, the free stream, and the boundary layer. The first set of experiments, illustrated in Figure 26, were conducted with the focal points approximately 5.5 cylinder diameters downstream of the cylinder in the wake region, and the other two sets of experiments were performed with the focal points approximately 9.5 cylinder diameters upstream of the cylinder, with the second set focused on the free stream flow in the center of the tunnel, and the third set focused on the left turbulent boundary layer, with the focal points roughly one third the boundary layer thickness of 15.6 mm away from the tunnel wall. The location of the measurement region for the free stream is denoted as 'FS' and the location of the measurement region for the boundary layer is denoted as 'BL' in Figure 26. The cylinder formed a turbulent wake with vortex shedding at a theoretical frequency of $St_D = 0.2$ [46] or 9.55 kHz. Experiments were performed with C/L ratios of 5% and 20% for all focal point locations, with additional measurements performed with C/L ratios of 10% and 15% in the wake of the cylinder. The final distance 'L' was 405 mm, or in one case 425 mm, for a ratio of 20%, 285 mm for 15%, and 250 mm for both 10% and 5%. The complete test matrix for all experiments conducted using the focused Malley probe is shown in Table 2.

Table 2. Test Matrix for Focused Malley Probe Experiments

Case Number	Measurement Location	C/L Ratio	Sampling Frequency (kHz)	Final Distance L (mm)
1	Cylinder's Wake	20%	110	425
2	Cylinder's Wake	20%	150	405
3	Cylinder's Wake	15%	220	285
4	Cylinder's Wake	10%	320	250
5	Cylinder's Wake	5%	720	250
6	Cylinder's Wake	5%	150	250
7	Free Stream	20%	150	405
8	Free Stream	5%	720	250
9	Free Stream	5%	150	250
10	Boundary Layer	20%	150	405
11	Boundary Layer	5%	720	250
12	Boundary Layer	5%	150	250

Data Reduction for Focused Malley probe

Beam displacement data was recorded using a Phantom v1611 high speed camera. The beams were converged to small diameter spots on the camera from which the displacements could be directly extracted, taking care to avoid the attenuation at the exact focal point. The camera was placed at various distances away from the final lens in order to determine the effect of this distance on the spot quality and spectral quality. Assuming a small angle approximation, the beam displacement readings, x , illustrated in Figure 28, were divided by the distance C in order to find the beam angular displacement a_1 , otherwise referred to as the global beam jitter, at the sensor location. Small angle approximations were then used to determine a scale factor to convert the angular displacement a_1 at the sensor location to the angular displacement a_2 at the measurement location, or the pair of focal points inside the tunnel. If the final focusing distance after the second lens is defined as L_1 and the distance between the measurement location focal points inside the tunnel and the second lens is defined as L_2 , then using the equal deflection distance at the second lens h , this scale factor to convert sensor-location angular deflections to measurement-location angular deflections is equal to L_1/L_2 . Because L_1 is directly measured during the experiment and the second-lens focal length of 150 mm is known, L_2 can be determined from the thin lens equation.

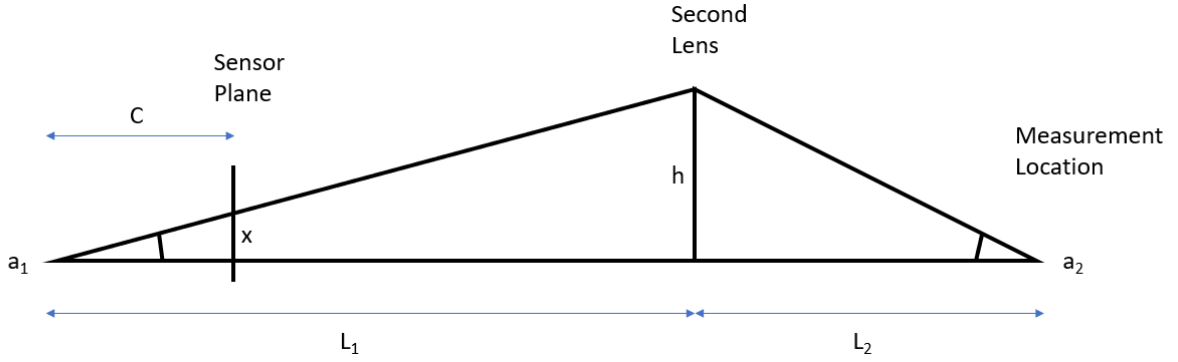


Figure 28. Schematic for Calculation of Scale Factor for Deflection Angles

Obtaining reliable beam displacement data with the focused jitter probe requires an extra step of processing which is not required with the traditional Malley probe. All existing aero-optical measurement techniques using lasers typically rely on focusing the beam down to a small point to measure the overall centroid position of that point, and this act of focusing to a point tends to get rid of the effects of any intensity variations within the beam itself that do not affect the overall centroid motion.

The intensity-based method for determining the centroid of the beam, which is the standard for aero-optical measurements, consists of taking a weighted average centroid of the image, calculated by the equation below, based on the intensity of each pixel at each instant in time. In this equation, p represents the pixel, x_p is the x-location, or y-location, depending on the direction chosen, of the pixel on the sensor, I_p is the intensity of the pixel, and N is the total number of pixels,

$$x_{centroid}(t) = \frac{\sum_{p=1}^N x_p I_p}{\sum_{p=1}^N I_p} \quad (16)$$

However, with larger spots, as is the case with the focused Malley probe or focused jitter probe, intensity variations inside the spot due to diffraction patterns from dust and other optical imperfections tend to affect the measurement, so additional processing must be done in order to determine the best way to capture the overall motion of the spot. Reference [45] provides more discussion on the need for applying a thresholding algorithm to each image before computing the centroid. This threshold value should be chosen individually for each of the two spots in each data set in order to minimize the number of dark pixels within the spot and bright pixels outside of the spot. A mask is applied to each spot to compute the centroids of the left and right spots individually. Once the threshold is applied to each spot, the same centroiding algorithm from the equation above is applied to compute the spot centroid at each instant in time. Examples of the unthresholded spots for the simultaneous measurement of the upstream and downstream beams for the focused Malley probe for C/L ratios of 20% and 5% are shown below in Figure 29 and Figure 30, respectively. Due to their inability to perform image thresholding, position sensitive devices (PSDs) cannot be used for the focused Malley probe because of their sensitivity to the spatial intensity variation. For this reason, a high-speed camera must be used to capture the full images for post-processing.



Figure 29. Unthresholded inverted-color upstream and downstream spot patterns for focused Malley probe at a C/L ratio of 20%



Figure 30. Unthresholded inverted-color upstream and downstream spot patterns for focused Malley probe at a C/L ratio of 5%

Similar to the conventional Malley probe data analysis [10], the cross-correlation spectral analysis was implemented to compute the time delay between the two beams. After converting the beams' displacements into the global angular deflections or jitter at the measurement region, the mean of each global beam jitter was removed, and the jitter power spectra were computed using a standard block averaging Fourier transform. The cross spectral density, $S(f)$, between the two beams was computed using standard block averaging Fourier transforms with a Hanning window and 500 blocks. The phase of the cross spectral density function was then computed, and the phase was unwrapped to compute the linear fit. For a quality data set, the unwrapped phase plot should show an identifiable slope related to the time delay, τ , of the convecting optical structures by the equation below.

$$\tau = \frac{1}{2\pi} \frac{d}{df} \text{phase}[S(f)] \quad (17)$$

In order to determine the slope, linear regions of the unwrapped phase plots were visually identified, and linear fits were performed over the appropriate frequency ranges. Some data sets showed linear slopes as expected, while others showed no meaningful signal and were corrupted by noise, as discussed later on. The R^2 value of the linear fit was determined to gauge the quality of the correlation and the fit, and is given by the equation below.

$$R^2 = 1 - \frac{\sum_i (\text{phase}(f)_i - \text{fit}(f)_i)^2}{\sum_i (\text{phase}(f)_i - \overline{\text{phase}(f)})^2} \quad (18)$$

Once the time delay is known, it can be used along with the known separation between the two beams at the measurement location, defined as 's' in Figure 26, which is 5.15 mm for these experiments, to compute the local convective velocity U_C according to the equation $U_C = s/\tau$. The ambient temperature can then be used to determine the speed of sound, and the free stream speed was estimated to be $U_\infty = 152$ m/s for these experiments from the known Mach number of $M = 0.44$, measured by using a Pitot probe installed in the test section upstream of the cylinder. The freestream speed can then be used to determine the ratio U_C/U_∞ .

4.0 RESULTS AND DISCUSSION

Below results and discussions are provided for each topic.

Topic 1: Aerodynamic response of the spanwise oscillating turret: experiments and modeling

Results of Experimental Work

Oscillating Turret Motion

Time series of the turret position in the spanwise direction for the oscillating case were extracted, as discussed before, and auto-correlation spectral densities at $M = 0.4$, 0.5 and 0.6 are presented in Figure 31. The spectra for the oscillating turret reveals the presence of a single strong peak at a frequency of 87 Hz. This value is close to the theoretical main resonant frequency of 89.4 Hz, predicted by the oscillating turret model. In addition to the dominant peak, the first and the second harmonics at 174 Hz and 260 Hz, respectively, with much smaller levels of spectral energy are also present in the spectra, indicating a small degree of non-linear effects in the turret response. A range of low frequencies, centered around 15 Hz, are also present in the spectra, and, as it will be shown later in this report, they are related to the intermittent nature of the turret motion.

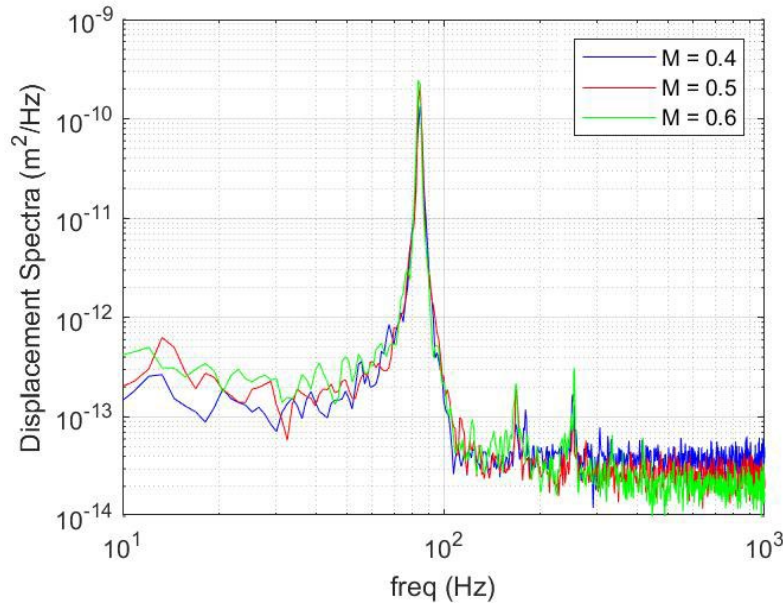


Figure 31. Auto-correlation spectral densities of turret spanwise displacement for the oscillating case at $M = 0.4$, 0.5 and 0.6

The time series of the extracted turret position for the oscillating case at $M = 0.5$ are presented in Figure 32 as a thin blue line. The time series show intermittent bursts up to 0.5 mm in amplitude with durations of few hundred of D/U_∞ . Note that the turret motion relative to the turret diameter is small, $|z_{\text{turret}}|/D < 2\%$. The amplitude of Morlet wavelet transform of the edge motion was extracted at the 87 Hz main resonant frequency and is presented in Figure 32 as a thick red line, outlining the bursts in the turret position. Similar intermittency of the turret spanwise motion were observed at other test Mach numbers. As the source of the turret oscillations is the spanwise unsteady forcing, this behavior confirms the intermittent nature of the unsteady spanwise forcing, acting on the turret. We will provide additional analysis of the related intermittent forcing later in this report.

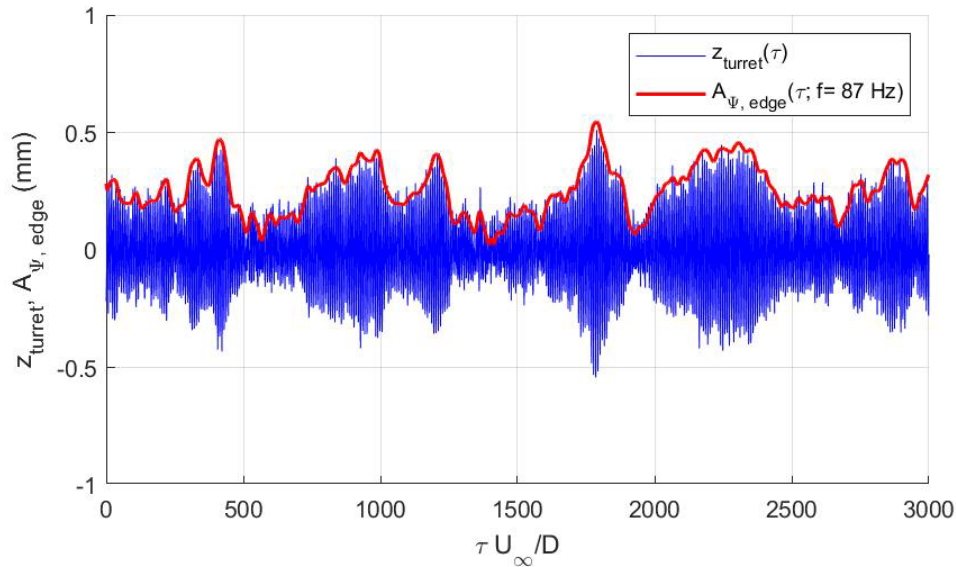


Figure 32. Time series of the turret spanwise motion, z_{turret} , (thin red line) and amplitude of Morlet wavelet transform at the main resonant frequency, $A_{\Psi}(\tau; f = 87 \text{ Hz})$ (thick red line) for the oscillating case at $M = 0.5$

Unsteady Pressure Fields

The spatial distribution of the temporal root-mean-squared pressure coefficients, $C_{p,rms}(x, y)$, for the oscillating and stationary turret cases at $M = 0.4, 0.5$, and 0.6 are presented in Figure 33. The unsteady pressure fields for both cases are approximately symmetric in the spanwise direction, indicating a symmetric wake. The unsteady neckless vortex, formed in front of the turret, is responsible for the increase in $C_{p,rms}$ in this region. The unsteady separation over the turret results in the increase in the pressure fluctuations, visible as a narrow region aligned in the spanwise direction on top of the turret. Finally, an inherently unsteady re-attachment line downstream of the turret creates a crescent-shaped region of large pressure fluctuations downstream of $x/R = 1.35$. Overall, the spatial map of the fluctuating pressure is very similar to ones previously observed in other studies of the pressure fields on and around hemispheres at subsonic speeds [31, 47, 48].

For the oscillating turret, the source of the turret motion is the unsteady force acting on the turret. As it requires energy to move the turret, the overall turbulent energy in the wake should decrease. Indeed, as it can be seen in Figure 33, there is a noticeable difference between the pressure fields for the oscillating and stationary cases, as the oscillating turret does weaken the turbulent wake, as well as increases its streamwise extent. To demonstrate this extent of the unsteady pressure region, the locations of the maxima of the fluctuating pressure field in the wake for both cases at different Mach numbers are indicated by star symbols in Figure 33; the streamwise locations of the maxima in $C_{p,rms}$ are also presented in Table 3. The location of the maximum pressure variation in the wake moves farther downstream from the turret with the increased Mach number and these locations are shifted even farther downstream for the oscillating case, compared to the stationary case, for all measured Mach numbers.

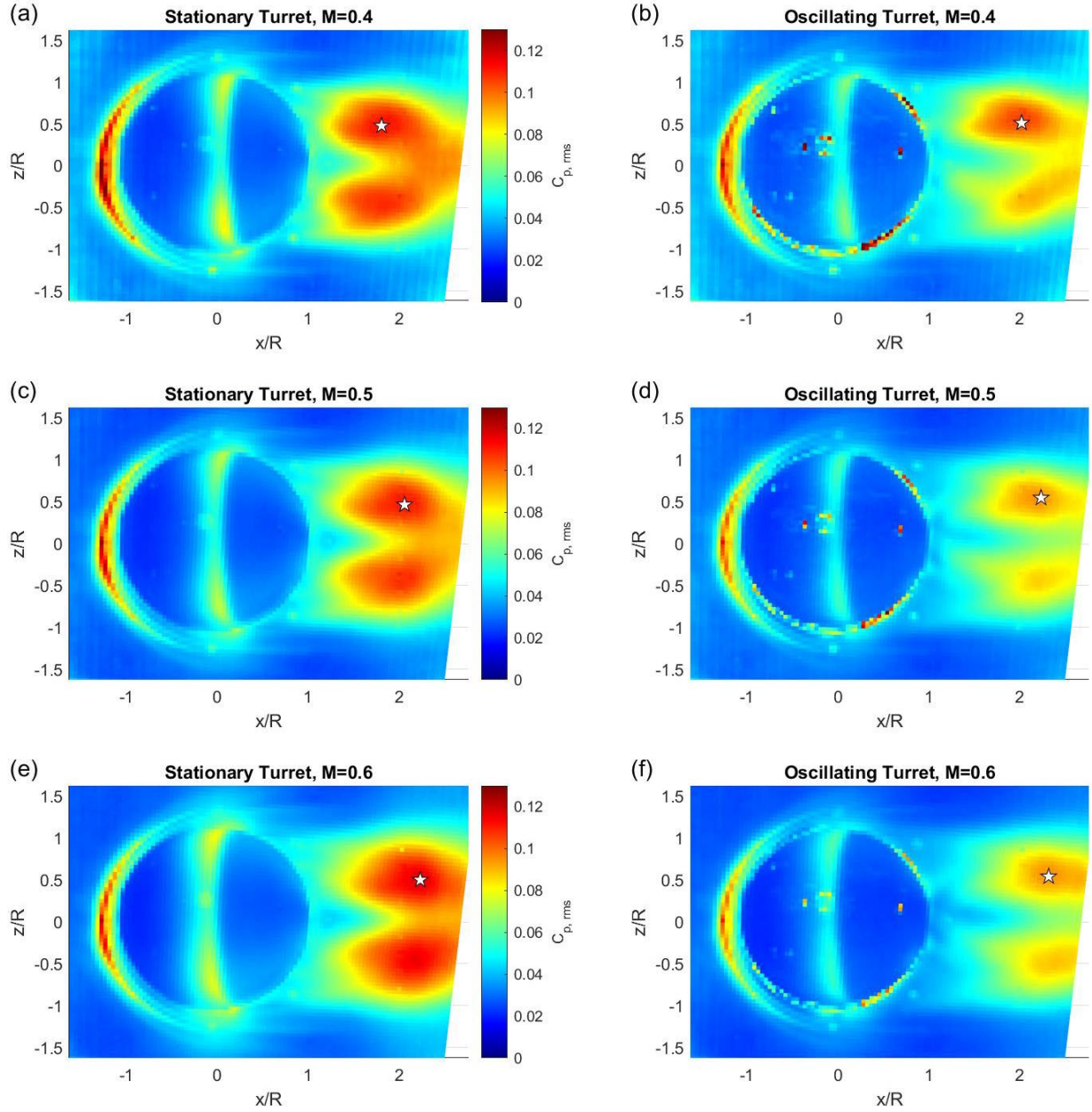


Figure 33. Spatial distributions of $C_{p,rms}(x, y)$ for (a,c,e) the stationary turret case and for (b,d,f) the oscillating turret case for (a,b) $M = 0.4$, (c,d) $M = 0.5$ and (e,f) $M = 0.6$. The locations of the maximum $C_{p,rms}$ in the wake are indicated by a star

Table 3. Streamwise locations of the maxima of $C_{p, rms}$ in the wake of the turret for different cases and Mach numbers

M	0.4	0.5	0.6
$x_{\max}/R$, Stationary Turret	1.81	2.06	2.23
$x_{\max}/R$, Oscillating Turret	2.02	2.24	2.32

A threshold of 0.3 mm, corresponding to the time-averaged value of the wavelet amplitude of the edge motion in Figure 32, was used to identify time intervals where the turret exhibits a strong oscillatory behavior and when it is mostly stationary. Using this threshold, unsteady pressure fields for the oscillating case during time intervals above the threshold were separated into a strong oscillating regime, and the pressure fields during time intervals below the threshold were separated into the mostly stationary state. The corresponding conditionally averaged spatial maps of $C_{p, rms}$ were computed and are presented in Figure 34 for $M = 0.5$. There is a very little change in the wake response during the mostly stationary and the strong oscillating regimes. The threshold value was varied between 0.1 and 0.4 mm and the resulting spatial pressure maps were found to be nearly independent of the amplitude threshold. Similar results were observed for other measured Mach numbers and therefore are not shown here. This behavior suggests that the wake pressure field for the oscillating turret does not respond quickly enough to intermittent changes in turret motion. In other words, when the oscillating turret becomes primarily stationary during short intervals of time, for instance, between $500 \leq tD/U_\infty \leq 750$ in Figure 32, the wake pressure field does not appear to respond to these changes.

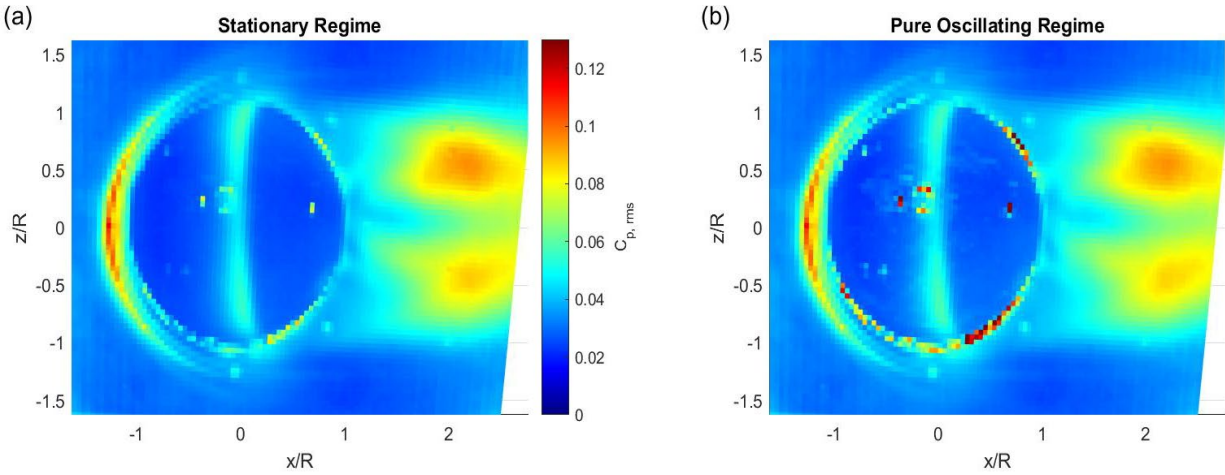


Figure 34. Conditionally averaged $C_{p, rms}(x, y)$ during (a) the mostly stationary state and (b) the strong oscillating regime for the oscillating turret case at $M = 0.5$

As it was mentioned in the Introduction, the dominant frequency range of the anti-symmetric wake motion is $St_D = f_{\text{peak}}D/U_\infty = 0.1\text{--}0.2$, which corresponds to a typical time scale of $T_{\text{wake}} = 1/f_{\text{peak}} = 5\text{--}10 D/U_\infty$. Thus, the durations of the strong turret oscillations of $100\text{--}200 D/U_\infty$, observed in Figure 32, would correspond to $10\text{--}40 T_{\text{wake}}$. No visible changes in the conditionally-averaged pressure fields during the primarily stationary and the strong oscillating regimes, shown in in Figure 34, indicates that the wake downstream of the turret needs longer than ~ 20 wake time scales to adjust to a changing environment.

Convective Velocity Fields

To quantify the surface topology of the wake, unsteady pressure fields were used to compute the convective velocities, $(U(x,y), V(x,y))$, in the wake of the turret, using Eq. (13). Resultant U- and V-fields for the stationary case at $M = 0.5$ are presented in Figure 35(a,b). The U-component is spanwise symmetric and positive in two regions: in front of the turret and downstream of it. The first region is associated with the footprint of the necklace vortex in the front of the turret, while the second region indicates vortical turbulent structures, formed in the turbulent wake and convecting downstream. The streamwise velocity of these wake structures reaches $0.14U_\infty$ at $x/R = 2$; similar velocity magnitudes of $\sim 0.2U_\infty$ were reported in [49]. The recirculating region immediately adjacent to aft of the turret is characterized by the negative streamwise velocity, indicated as a blue region in Figure 35(a). The location of the saddle point, indicative of the streamwise size of the recirculating region, and defined as a zero-crossing of the streamwise velocity along the centerline $y = 0$, is denoted as an open circle in Figure 35(a,c).

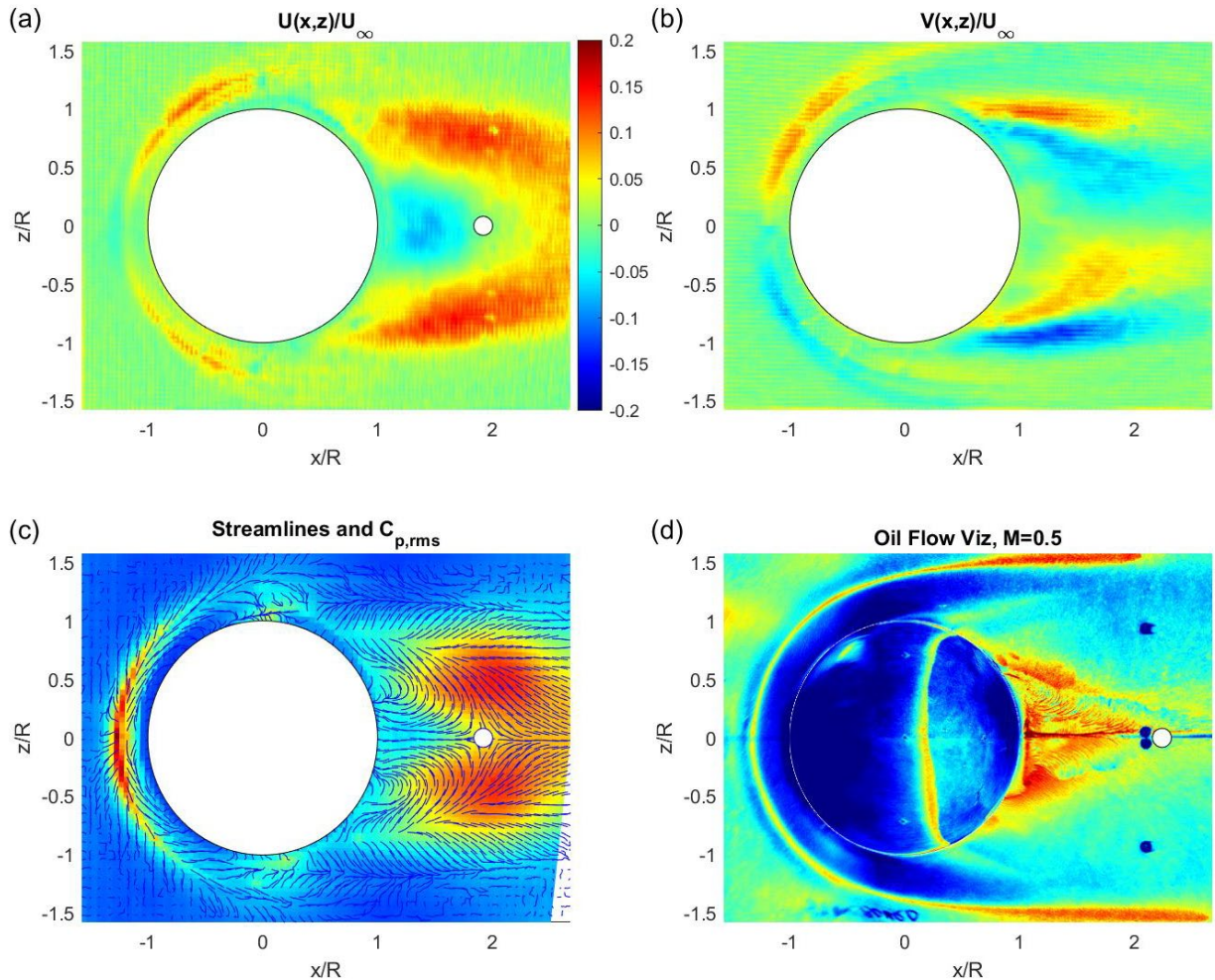


Figure 35. Normalized convective (a) streamwise velocity (b) spanwise velocity and (c) streamlines with superimposed $C_{p,rms}$ field from Figure 10(c), for the stationary turret at $M = 0.5$ (d) Oil flow visualization of the wake topology around the hemisphere at $M = 0.5$, adapted from [50]. Locations of the saddle points along the re-attachment line are indicated by open circles in (a, c, d)

The spanwise V-velocity, shown in Figure 35(b), is anti-symmetric in the z -direction and essentially non-zero in the same regions, where the U-component is positive. At both sides of the wake region, the

V-velocity changes a sign, indicating a divergent flow in the spanwise direction and marking the boundary of the recirculating region. This region is clearly observed in the streamline pattern downstream of the turret in Figure 35(c). The spatial distribution of the fluctuating field, $C_{p,rms}$ from Figure 33(c) is also plotted along with the streamline pattern. One region of the increased pressure fluctuations is associated with the unsteady necklace vortex upstream of the turret. Other regions are located along and downstream of the boundary of the recirculating region, associated with the unsteady re-attachment line. Interestingly, the pressure fluctuations are relatively small inside the recirculating region itself. Finally, small increases in the fluctuating pressure are located on both sides of the turret near the flow separation at $x/R = 0$ and are related to vortical structures, observed in [50] to form at the hemisphere-floor junction. Similar velocity fields were observed at other tested Mach numbers.

Detailed studies of the surface flow topology around a fixed hemisphere using oil flow visualization was conducted [50] and the example of the surface oil streak pattern for $M = 0.5$ is presented in Figure 35(d). Clearly, the streak pattern is very similar to the streamline pattern for the stationary case in Figure 35(c), computed using the unsteady pressure fields. The location of the necklace vortex in front of the turret is properly measured by both techniques. The location of the saddle point, found to be at $2.2R$ downstream of the turret and indicated by an open circle in Figure 35(d), is close to the location of $1.92R$, found using the convective velocity field. Also, vortical structures inside the recirculating region at $(x/R, z/R) = (1.2, \pm 0.5)$ can be seen in both patterns. Thus, spatio-temporally resolved pressure fields can also be used to extract and to study the topology of the surface flow around the turret and other geometries.

To study the changes in the surface topology due to the oscillating turret, streamline patterns for both the stationary and the oscillating cases at different Mach numbers are presented in Figure 36. Since the streamline patterns were found to be spanwise symmetric, only a half of the pattern is plotted in each subfigure. The locations of the saddle points for the stationary and the oscillating cases are indicated by open circles and filled squares, respectively. For the stationary case, the location of the saddle point moves farther downstream with increasing Mach number, from $x/R = 1.88$ at $M = 0.4$ to $x/R = 2.05$ at $M = 0.6$. A similar increase in size of the recirculating region was observed using oil-flow visualization in [50]. The trend is also consistent with the downstream shift of the location of the maximum $C_{p,rms}$, shown in Figure 33. For the oscillating case, the saddle point is always farther away from the turret, compared to the stationary turret case. The largest shift was observed at $M = 0.5$, where the saddle point moves from $x/R = 1.92$ to $x/R = 2.3$. Again, the results are consistent with the similar trends in the location of the maximum $C_{p,rms}$, shown in Figure 33.

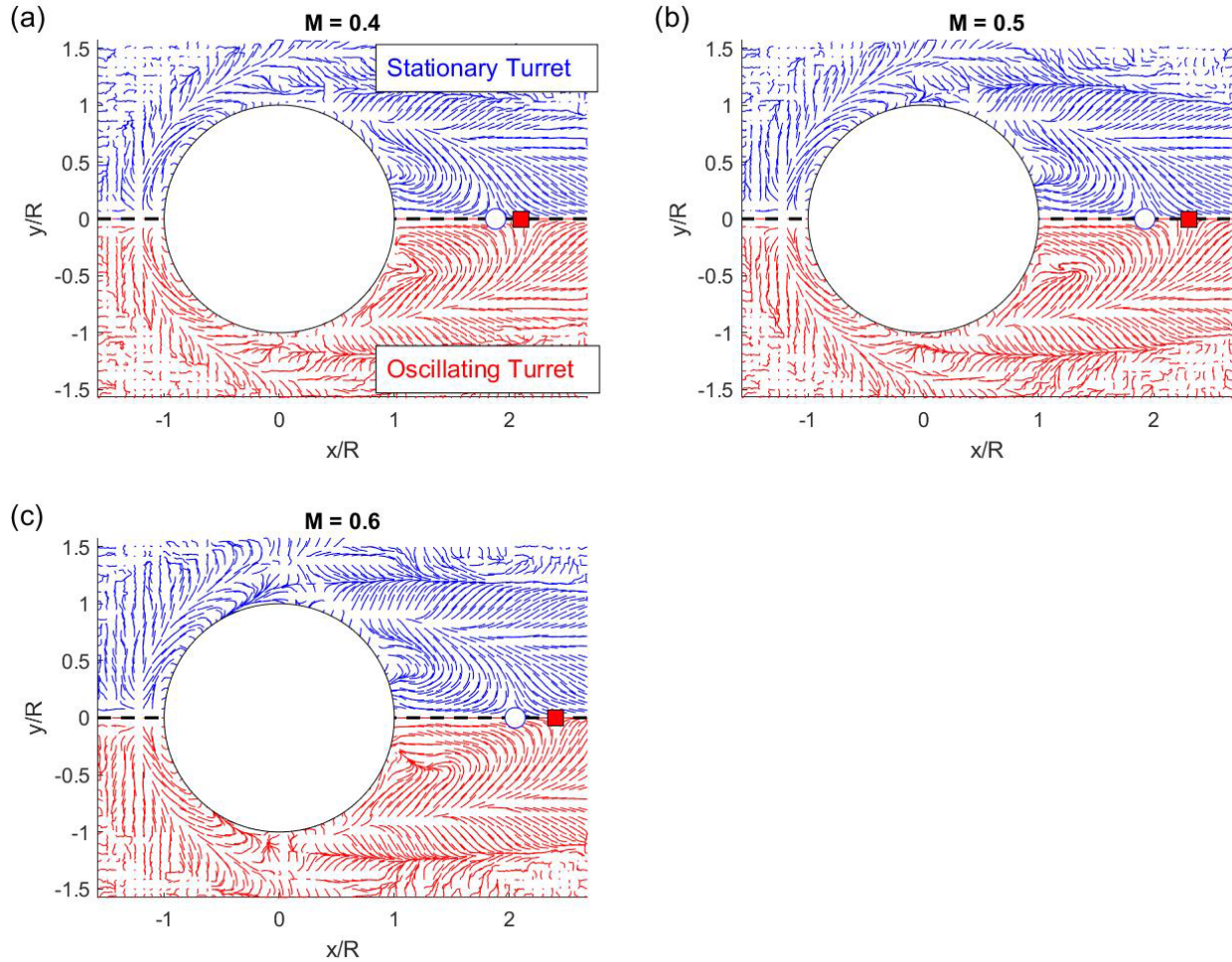


Figure 36. Streamline patterns for the stationary (upper half in blue) and the oscillating (lower half in red) cases at $M =$ (a) 0.4, (b) 0.5 and (c) 0.6. The locations of the saddle points for the stationary and the oscillating cases are indicated by open circles and filled squares, respectively

JPOD Analysis of Unsteady Pressure Fields in the Wake

The pressure data in the wake of the turret for the stationary and the oscillating cases for $M = 0.5$ were used to perform JPOD analysis. The first six JPOD spatial modes are presented in Figure 37. The first dominant mode, as well as the third and the fifth modes are symmetric in the spanwise direction, while modes # 2, # 4 and #6 are anti-symmetric in the spanwise direction. In previous studies of the unsteady pressure fields in the wake around hemispherical turrets [31, 48, 51], the spanwise symmetric modes were associated with the global symmetric separation over the turret, while the spanwise-anti-symmetric modes were attributed to the anti-symmetric vortex shedding.

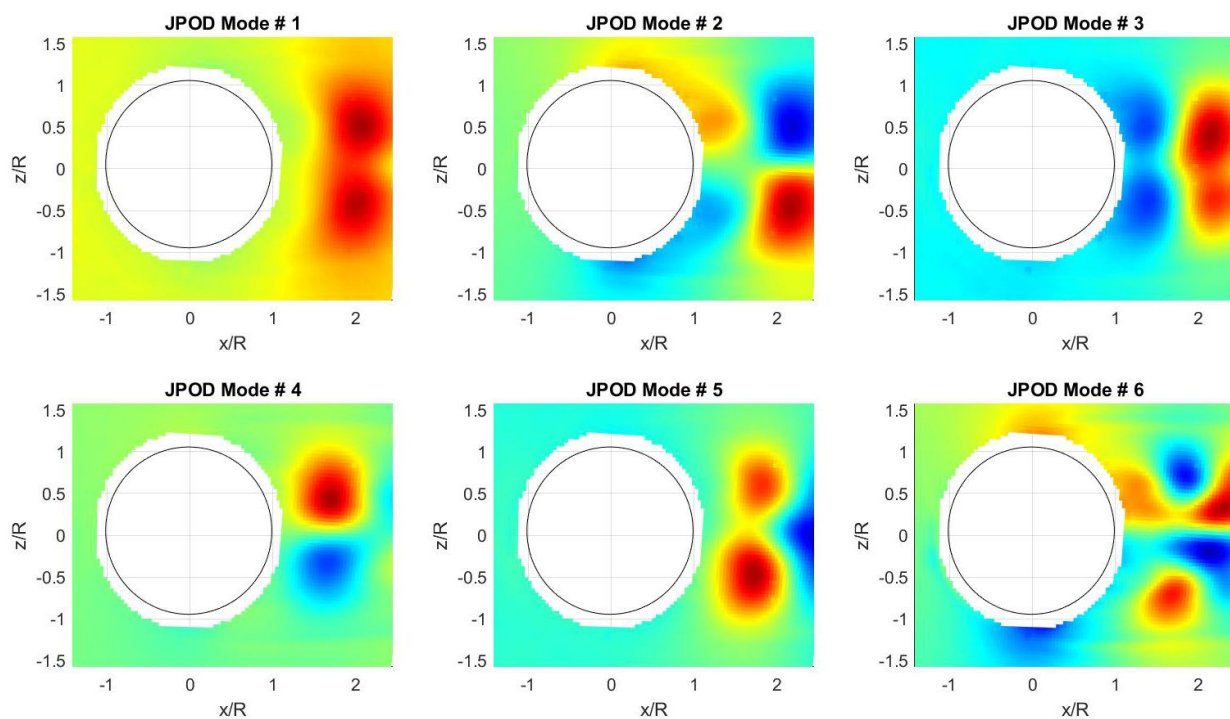


Figure 37. First six dominant JPOD spatial modes for $M = 0.5$. The turret outline is denoted by a black circle

The relative individual and cumulative energies of the first 100 JPOD modes for the oscillating and stationary cases at $M = 0.5$, normalized by the total energy for the stationary case, are presented in Figure 38. The first JPOD mode contains about 20% of the total energy for both the stationary and the oscillating cases, and the first six modes contribute about a half of the unsteady pressure energy in the wake region. The cumulative energies for the oscillating case are lower than the cumulative energies for the stationary case, consistent with the smaller $C_{p, rms}$ values in the wake observed in Figure 33. Further comparing the mode energies of the stationary and the oscillating cases, energies of anti-symmetric modes # 2 and # 4 are significantly reduced by a factor of two, indicating the oscillating turret primarily suppresses the global anti-symmetric shedding.

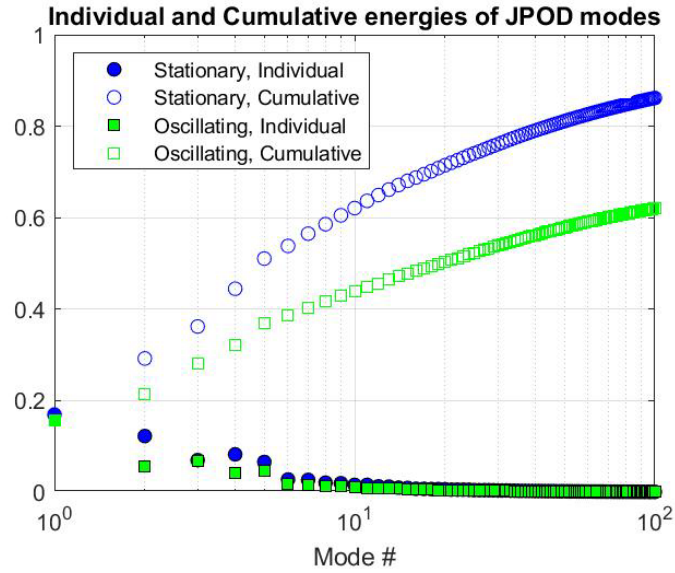


Figure 38. JPOD cumulative and individual energies, for the oscillating and stationary cases at $M = 0.5$, normalized by the total energy for the stationary case

The spectra of the temporal coefficients, normalized by the square of the dynamic pressure, for the stationary turret case at $M = 0.4, 0.5$ and 0.6 are presented in Figure 39. The frequency was normalized by the turret diameter and the freestream velocity, $St_D = fD / U_\infty$. All modal spectra collapse over the range of the measured Mach numbers, demonstrating a self-similar behavior of the wake. The spanwise-symmetric modes # 1, # 3, and #5 have most of their energy contained in low frequencies. Modes #1 and #3 also exhibit a relative small peak in their spectra around $St_D = 0.35$. This peak is inside the range of $St_D = 0.2 - 0.5$, associated with the symmetric vortex shedding in [52]. The anti-symmetric motion, represented by JPOD modes #2, # 4 and #6, have distinct peaks in their spectra at approximately $St_D = 0.17$, and this peak is independent of the Mach number. This peak was also observed in previous studies by [25] and [31] and also was found to be approximately constant for a range of Mach numbers between 0.35 and 0.66. As discussed in the Introduction, this peak is associated with the anti-symmetric vortex shedding [49, 52].

A comparison between spectra of the temporal coefficients for the stationary and oscillating cases at $M = 0.5$ is presented in Figure 40. The normalized spectra of the spanwise symmetric mode, Mode #1, as well as other symmetric modes # 3 and #5, are largely unchanged between the stationary and the oscillating cases. In contrast, the peaks in the spectra of the anti-symmetric motion, represented by JPOD modes #2, #4 and #6, are significantly suppressed for the oscillating case, compared to the stationary case. In addition, the peaks in the spectra of these anti-symmetric modes are shifted toward the main oscillating

turret frequency of 87 Hz, indicated as vertical dashed lines in Figure 40. A very similar peak suppression was observed for $M = 0.4$ and 0.6 and therefore is not shown. This behavior provides a strong evidence that the resulting mechanical motion of the turret driven by the unsteady turbulent flow reduces the overall energy of the global anti-symmetric shedding, while keeping the dynamics of the global symmetric wake motion mostly unchanged.

As discussed in [53], the consistent reduction in wake pressure energy is logical from an energy conservation standpoint. When the total energy of the flow, which remains constant throughout the control volume of the test section, is partially converted into work being done in order to move the turret back and forth in the spanwise direction, less energy is available in the turbulent wake to form convective structures and to create anti-symmetric and symmetric motion behavior that is readily observed for the stationary turret. This analysis provides useful information that will aid in developing a comprehensive understanding of the flow downstream of a hemispherical spanwise-oscillating turret.

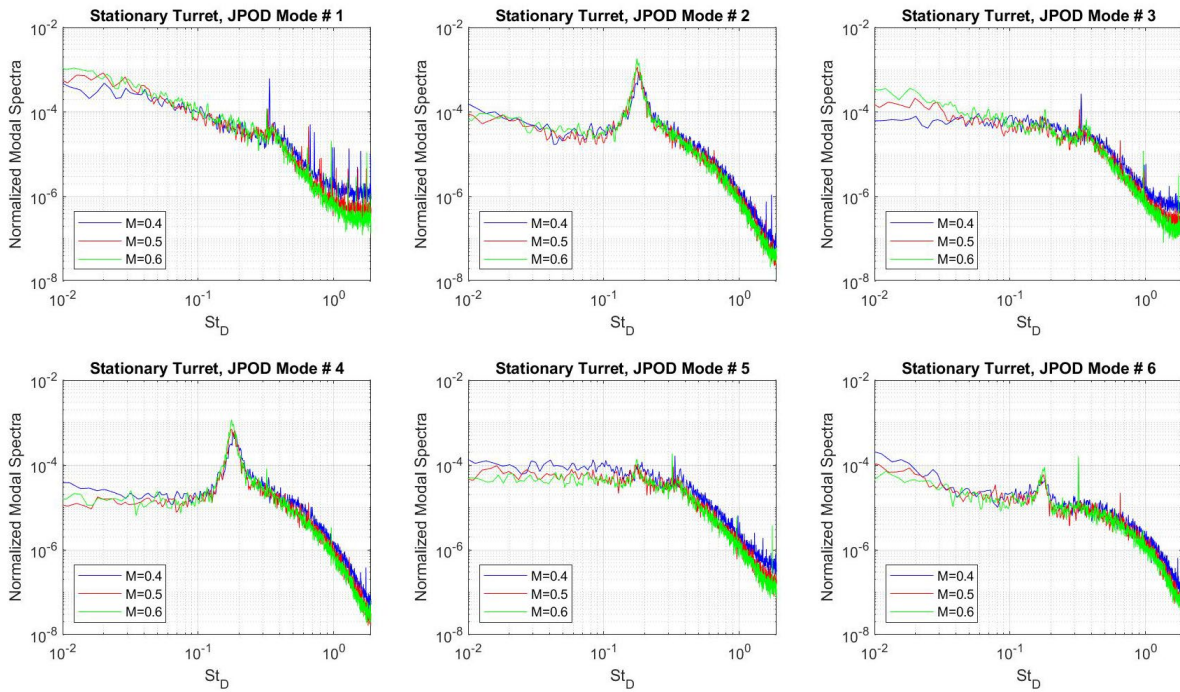


Figure 39. JPOD temporal coefficient normalized spectra corresponding to the first six dominant JPOD modes for the stationary turret case at $M = 0.4, 0.5$ and 0.6

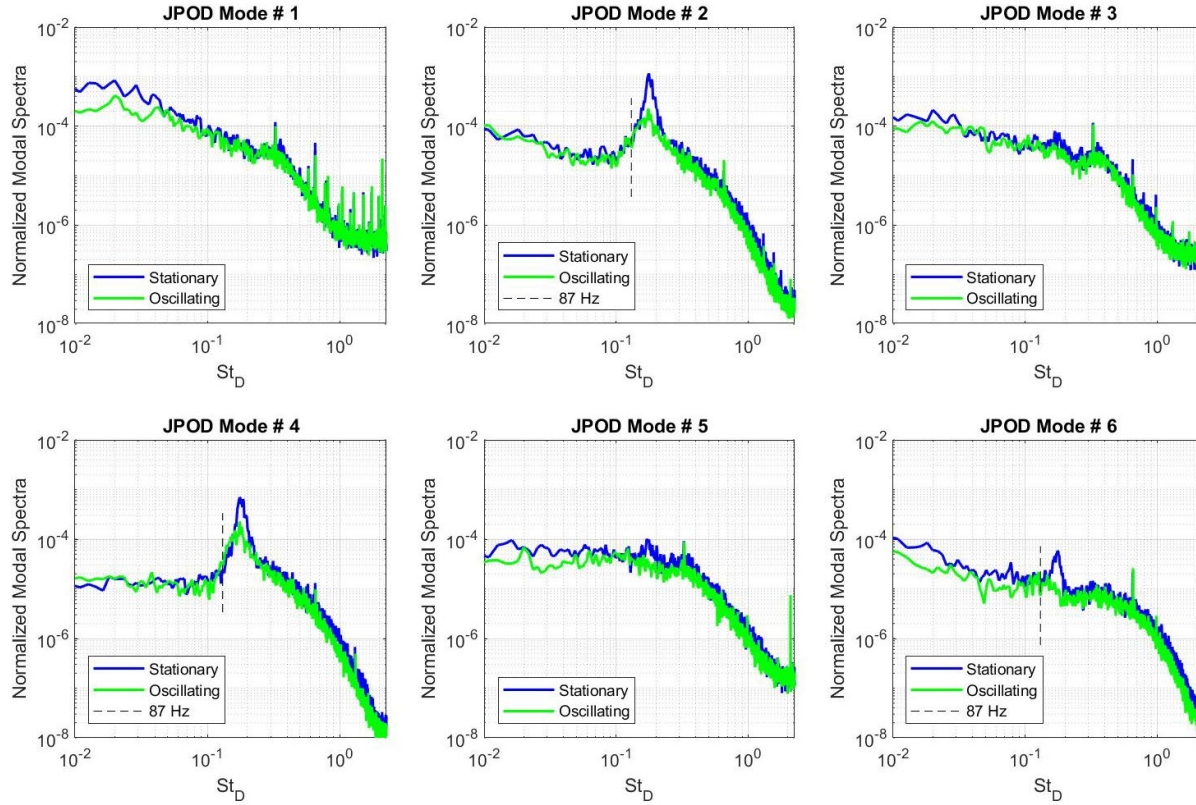


Figure 40. JPOD temporal coefficient normalized spectra corresponding to the first six dominant JPOD modes for the stationary and the oscillating turret cases at $M = 0.5$. The main oscillating frequency of 87 Hz is indicated as a vertical dashed line

Analysis of Unsteady Forces Acting on Turret

The computed normalized coefficients of unsteady force components are presented in Figure 41 for the oscillating and stationary cases at $M = 0.4, 0.5$, and 0.6 . The highest magnitude of the fluctuating force on the turret occurs in the spanwise z -direction for both cases. The coefficient of force is over 50% higher in the z -direction than in the wall-normal y -direction and between three and four times higher than the streamwise x -direction for both turret configurations at all three Mach numbers. The computed force coefficients for the stationary turret agree reasonably well with the values, obtained on a hemisphere-on-cylinder turret at $M = 0.5$ in [51, 54] and presented in Figure 41 as filled stars. The differences in actual force coefficients are attributed to different turret geometries.

Generally, the coefficients either weakly increase or stay approximately constant with the increasing Mach number. The force coefficients for the oscillating case are smaller than the coefficients for the stationary case for z -coefficients and, in lesser degree, for y -coefficients. The drag-related x -coefficients are virtually unchanged by the oscillating turret. One way to explain these trends is to recall that the oscillating turret responds to the unsteady pressure acting on it. Let us say the pressure is higher on one side compared to the opposite site. The oscillating turret will start moving in the spanwise direction and the resulted work produced by the flow will reduce the pressure and, consequently, the z -force, acting on the oscillating turret. Since the turret cannot move in the streamwise direction, the turret motion does not affect the streamwise force.

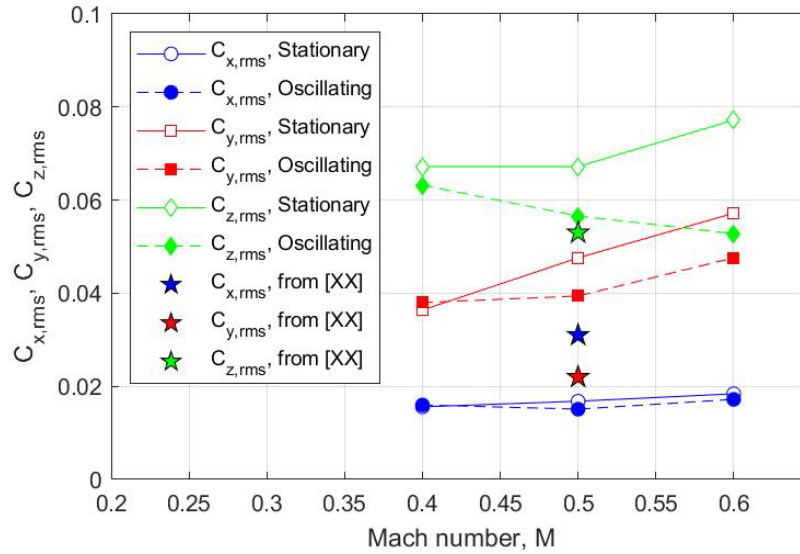


Figure 41. The coefficients of different force components for various Mach numbers and both the stationary (open symbols) and the oscillating (filled symbols) turrets. Results for the hemisphere-on-cylinder turret for $M = 0.5$ from [54] are presented as star symbols for comparison

Spectra of the spanwise z -component of the unsteady force on the oscillating and stationary cases are presented as a function of the normalized frequency at $M = 0.4, 0.5$ and 0.6 in Figure 42. For the stationary case, see Figure 42(a), the spectrum of z -force has a broad peak at the same normalized frequency of $St_D = 0.17$, the location of this spectral peak is independent of the Mach number. In contrast, the dominant peak, present in the z -force for the oscillating turret, see Figure 42(b), coincides with 87 Hz resonant frequency, indicated as vertical dashed lines. There is a second weaker peak in the spectrum located at the normalized frequency of $St_D = 0.17$, and it appears to be significantly dampened with respect to the stationary case at all Mach numbers. The analysis of spectra for other force components were not significantly affected by the oscillating turret, see [17] for details.

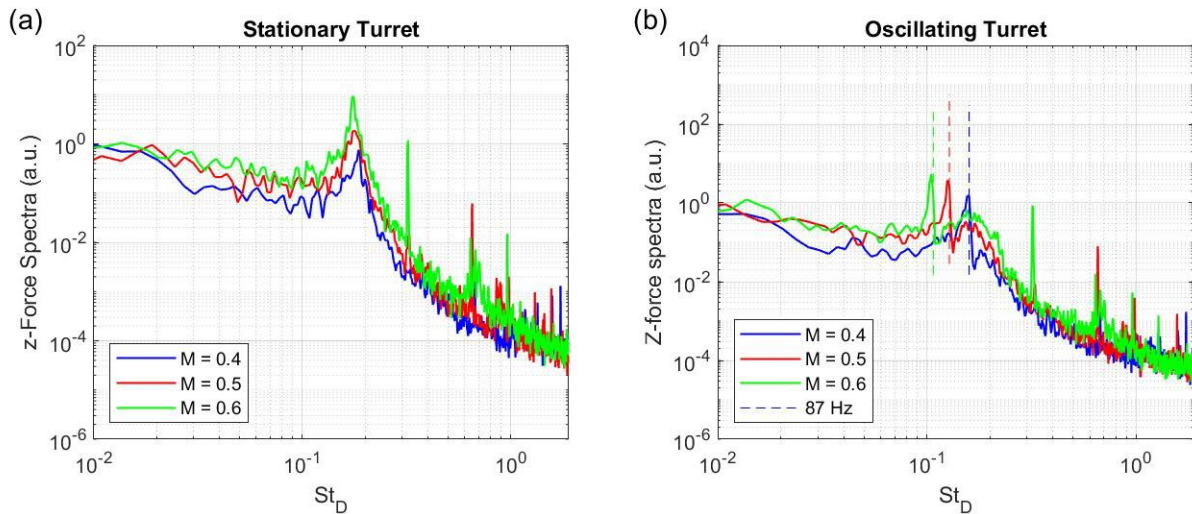


Figure 42. Spectra of z -component of fluctuating force for (a) the stationary turret, and (b) the oscillating turret, at $M = 0.4, 0.5$ and 0.6 . In plot (b), the main oscillating frequency of 87 Hz is indicated as colored vertical dashed lines

To investigate the intermittent nature of the spanwise z-force, a Morlet wavelet analysis was applied to the time series of the spanwise force coefficient for the stationary and the oscillating cases at $M = 0.5$. A map of wavelet amplitude for the stationary case as a function of the normalized frequency and normalized time is shown in Figure 43(a). The force amplitude is clearly intermittent, with a typical burst durations of 20-40 D/U_∞ ; similar time durations of the wake coherence around the hemisphere were observed in [49]. Most of the force bursts occur at the range of $St_D = 0.1 - 0.25$, so some of the bursts would coincide with the natural resonant frequency of 87 Hz, indicated in Figure 43(a) as a horizontal dashed white line. When it happens, the oscillating turret will responds to these force bursts by amplifying the turret motion. When the force burst either shifts away from the resonant 87 Hz or decreases in amplitude, the turret motion is dampened. For this reason, the observed bursts in the force are very similar to the bursts in the turret motion observed in Figure 32.

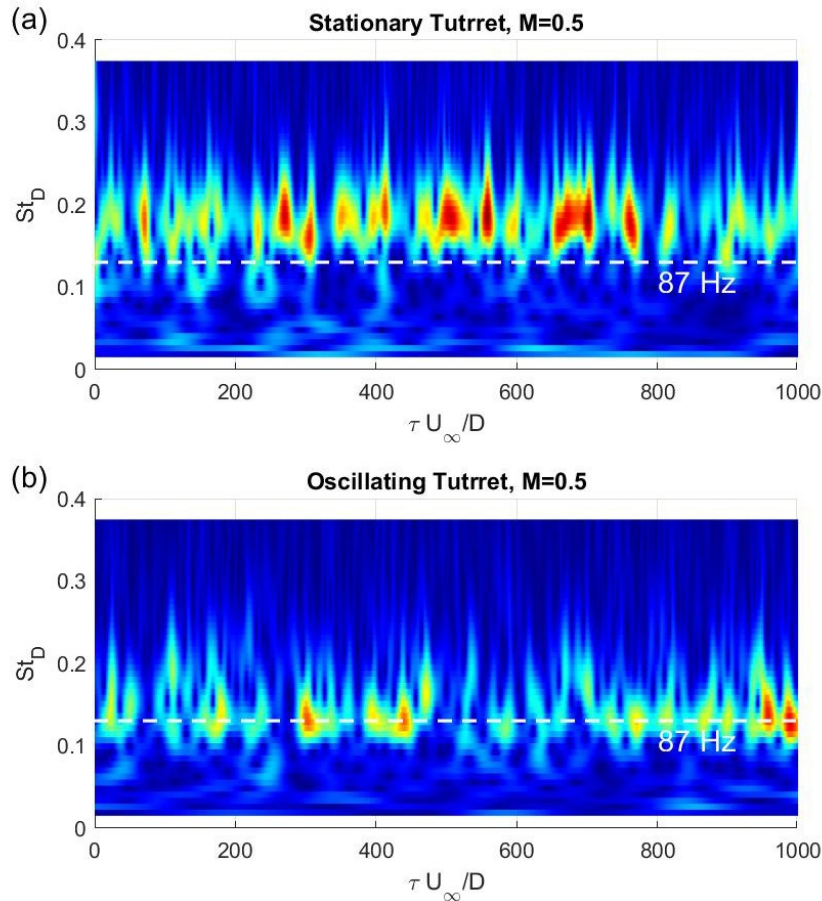


Figure 43. Amplitude of Morlet wavelet transform of the spanwise fluctuating force for (a) stationary turret and (b) oscillating turret cases at $M = 0.5$. The main oscillating frequency of 87 Hz as marked by a dashed white line

As it was demonstrated in Figure 42, due to aero-elastic interaction, the turret motion will modify the spectrum of the spanwise force by suppressing the natural peak at $St_D \sim 0.17$ and enhancing the spectral energy at the fixed resonant frequency of 87 Hz. This effect can be observed in the wavelet map for the oscillating case in Figure 43(b), where most of the force bursts now occur near 87 Hz. The durations of the bursts appear to be unchanged, while the frequency and the amplitudes of the burst occurrences are reduced, compared to the stationary case. These less frequent and less energetic bursts result in the overall reduced values of the spanwise force coefficients, reported in Figure 41.

Finally, using the computed unsteady force in the z-direction, F_z , and the resulting turret position, z_{turret} , it is possible to extract the spectral transfer function between these quantities as a ratio of Fourier transforms, $G(f) = FT\{F_z\} / FT\{z_{\text{turret}}\}$, and to compare it with the theoretical transfer function, Eq. (8). The amplitude and the phase of the experimentally calculated transfer function, normalized by the steady value of the transfer function, G_{steady} , are presented in Figure 44, along with the theoretical model from Eq. (8). These results agree quite well with the linear second-order model up to 150 Hz, including the location and the amplitude of the resonant peak, as well as the phase jump, verifying that the turret motion can be approximately modeled as a linear second-order underdamped system. Above 150 Hz, the experimental transfer function deviates from the linear model. One reason for it is possible non-linear effects of these high frequencies; similar non-linear effects were observed in the spectra of the turret position in Figure 31. Another reason is that the spectrum of the turret position, presented in Figure 31 is essentially flat for frequency above 100 Hz due to the noise related to accuracy of the optical technique to extract the turret position.

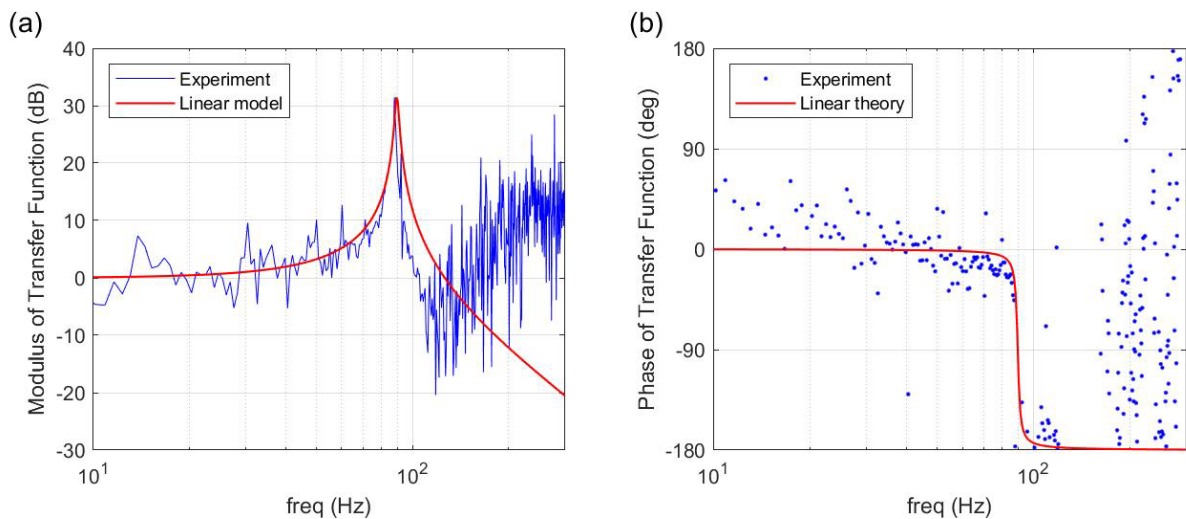


Figure 44. (a) Amplitude and (b) phase of experimentally-measured harmonic normalized transfer function, $G(f)/G_{\text{steady}}$, between the unsteady z-force and the resulted turret z-displacement at $M = 0.5$. The theoretical linear model from Eq. (8) is also shown for comparison

Results of the Numerical Simulations

Rigid Turret

The following section details the baseline simulation for the rigid turret. The steady state solution is computed and the unsteady time stepping is continued from that initial solution. Every 25th time step the flow field is written out for post-processing. The steady state restart is also saved and used as initial condition for the flexible cases described below. Figure 45 shows a representative image of the flow field. The flow image shows an iso-surface of the Q-criterion colored by pressure. The typical flow features are observed behind the turret. The incoming boundary layer on the tunnel floor rolls up at the base of the turret and generates a necklace vortex which convects around the side of the turret. The flow then attaches to the front surface of the turret and accelerates to the top of the turret due to the favorable pressure gradient. As the flow approaches elevation angles beyond 90 deg the flow is exposed to an adverse pressure gradient and separates forming a highly unsteady shear layer. The massively separated flow structures convect downstream, interacting and merging in a highly unsteady fashion. Importantly, it was observed that the separation line over the hemisphere is highly unsteady with cross-stream 'tilting' and up-and downstream fluctuations.

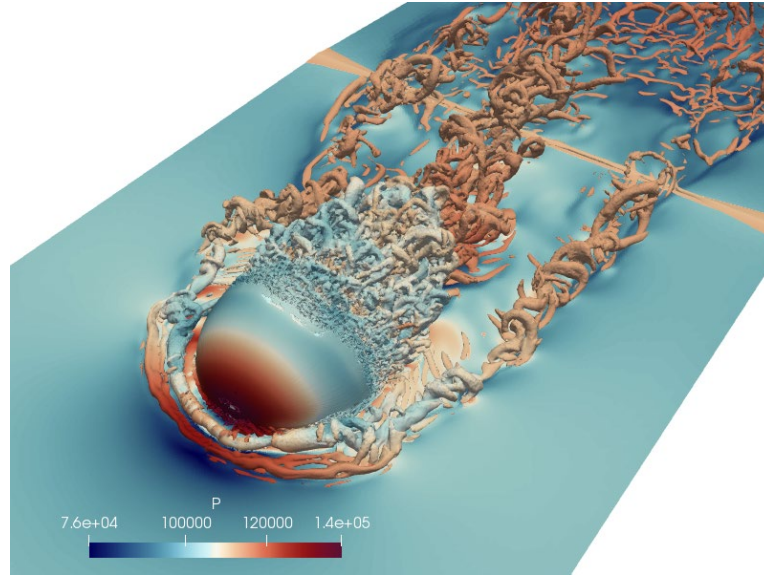


Figure 45. Flow still/animation of an iso-surface of the Q-criterion colored by pressure

As evidenced by the time-accurate visualization, the separation characteristics are highly unsteady; therefore, to understand the statistical behavior of the flow features, the mean and standard deviation of the surface pressure was computed and plotted in Figure 46. The mean pressure coefficient ($\bar{C}_p$) shows the stagnation pressure in the front of the turret and a suction peak over the top of the turret. The $\bar{C}_p$ distribution also shows lower pressure where the necklace vortex approaches the floor of the wind tunnel. The fluctuating component of the pressure coefficient, C'_p , indicates areas of significant unsteadiness. The front of the necklace vortex is highly unsteady which is also apparent from the animation above. Secondary and even tertiary vortices are present at times which tend to merge and interact in a sporadic fashion; the pressure variation in Figure 46(b) is indicative of this behavior. On the downwind side of the turret, the largest pressure variations are observed just downstream of the separation location, commensurate with the highly energetic vortices developing in the separated shear layer. The other 'band' of large C'_p likely is due to the large scale motion of the separation line in time.

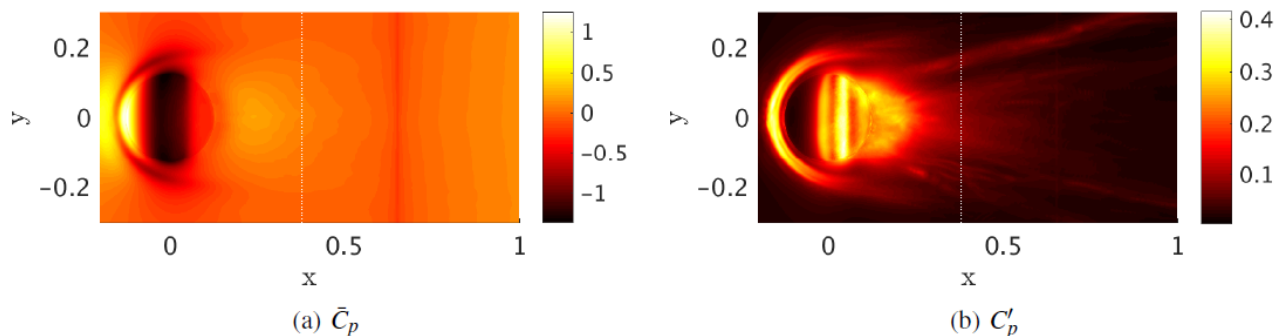


Figure 46. Mean and standard deviation of the surface pressure distribution. x,y in m

To understand the temporal behavior of the pressure footprint, the surface pressure was extracted in the wake of the turret. Specifically, the pressure was sampled one diameter downstream of the turret across the entire wind tunnel floor. This line is representative of pressure taps which will be installed in the wind tunnel as well. This line is represented in Figure 46 as a white dotted line. Figure 47(a) shows the temporal evolution of the pressure at this line. The x-axis is the cross-stream position normalized by the turret diameter, and the y-axis is the non-dimensional time, $\tau = t V/D$. Effectively, the flow can be thought of as moving upward in this figure. The surface is colored by the pressure coefficient. As shown, there are periods of time during which the wake exhibits hot spots (high or low pressure regions) during which large vortical structures convect over this location one diameter downstream of the turret. Secondly, it is apparent that the wake naturally wanders in the cross-stream direction. This may be attributed to changes in the angularity of the separated shear layer over the turret. From this time sequence, it is hard to determine any dominant frequencies or spatial wavelengths. Figure 47(b) shows the mean and variance of the pressure coefficient along this line. This figure shows that the primary fluctuations lie in the center of the wake, with additional peaks at the location of the necklace vortices.

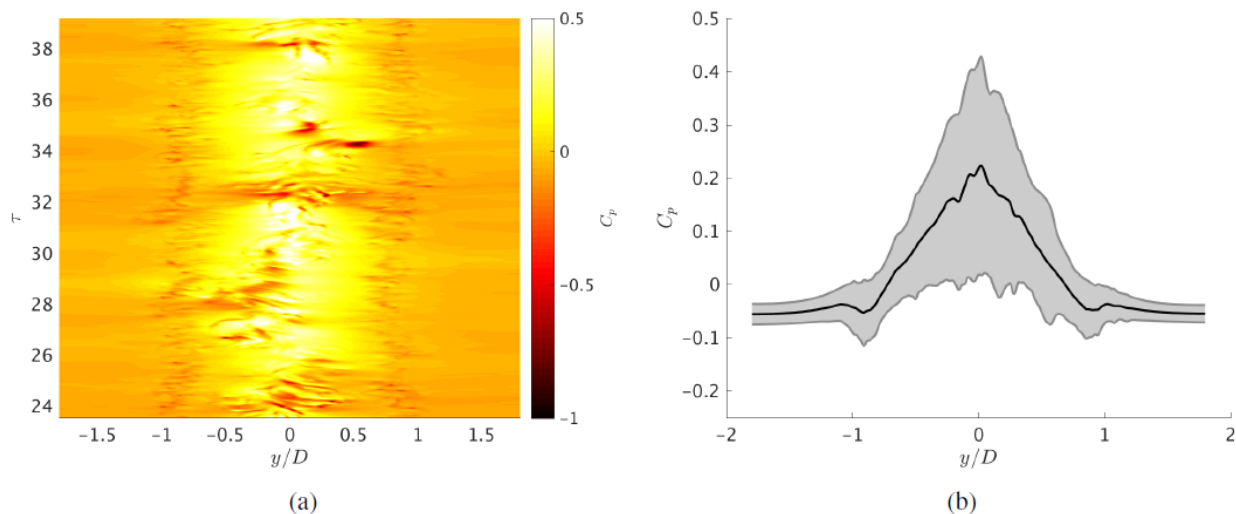


Figure 47. Convective pressure distribution of the wake line and mean and variance across the pressure wake line taken at one diameter downstream

To visualize the unsteadiness of the surface pressure, the time accurate flow was analyzed and a few different physical features or states were identified. The flow seems to assume a random sequence of these states. What triggers a specific state or transition from one to the other is still under investigation. The identified states are shown in Figure 48. The first, Figure 48(a), shows a delayed, but very well defined separation line. This is exhibited by a very large gradient in the surface pressure C_p . In this case the near wake is symmetric about the center plane and the hemisphere is experiencing zero side force, a large lift increase and drag reduction. The second case identified shows the opposite: the separation location moves upstream which looks to be caused by an accumulation of upstream traveling pressure waves from wake structures. In this state, the wake also appears to be symmetric and two large vortices perpendicular to the floor are shed which can be observed by low pressure regions just behind the turret. This state exhibits high drag, small lift, and no side force. The third and fourth modes are complements of each other and are capture the skewing of the wake in the cross-stream directions. Figure 48(c) and Figure 48(d) depict time steps when these modes are active. The presence of these modes is characterized by a

large side force in either direction and results in a highly skewed wake. Depending upon the direction of skew, a single vortex is shed and convects perpendicularly to the separation line.

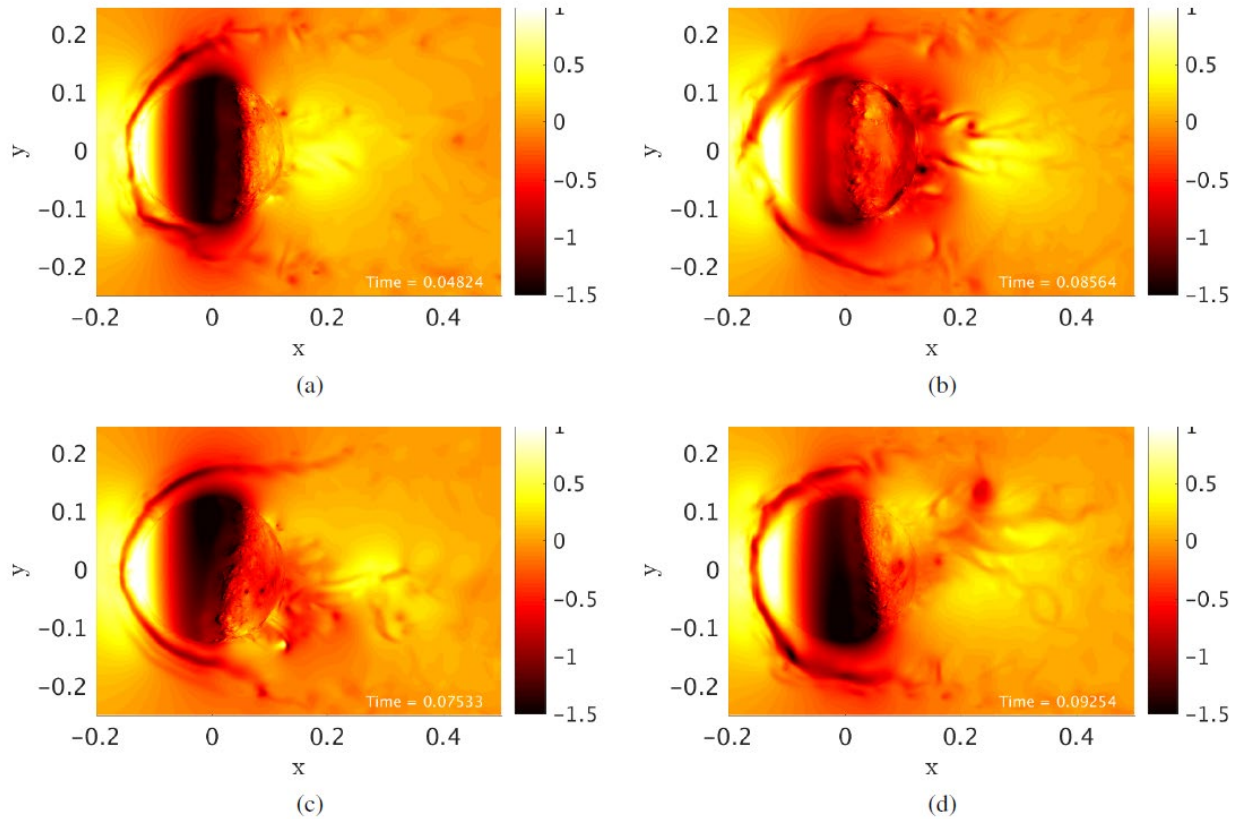


Figure 48. Individual snapshots of surface pressure distribution showing the identified flow states on the hemisphere

Flexible Turret

With a basic understanding of the flow features occurring around the rigid hemisphere, the structural model as discussed previously was introduced. To achieve the FSI coupling, at each time step in the simulation, the fluid forces on the turret are transmitted through the Simulia co-simulation engine to Abaqus which then computes the resulting deformation and provides it to Loci/CHEM. Loci/CHEM has an internal mesh deformation algorithm which then moves the surface grid and propagates the deformation into the volume grid. As an important note, the tunnel walls, inlet and outlet boundaries are not allowed to deform. Since the turret is essentially sliding along the tunnel floor, the floor grid must deform, but the motion must be restricted to in-plane motion. Because the floor is non-planar, a separate grid must be specified to restrain the deformation to a non-planar condition. The FSI coupling was tested on a coarse mesh for a very weak cross stream spring to ensure the coupling algorithm was working properly. Figure 49 shows this test setup. Figure 49(a) shows the maximum extent of the deformation in one direction and Figure 49(b) shows the maximum extent of the deformation in the opposite direction. It is easy to see that the turret moves approximately half of the diameter, validating the coupling and mesh deformation framework.

Once the FSI framework was tested and validated, the fine mesh was coupled to the linear MDK structural model. The simulation was restarted from a rigid solution continued for a period of time. The differences between the rigid and flexible turret simulations can then be analyzed to understand what the

effects of the fluid-structure interaction are. These simulations were extremely expensive, as the structural solver and mesh deformation algorithm take a significant amount of time when compared to the CFD-only solution. Therefore, only a single FSI simulation was performed to date. The run took nearly 8 days on 1024 cores before the job reached the maximum wall clock time limit and terminated. Approximately 10,000 iterations (0.05 seconds), providing 4.8 Terabytes of flow data, were captured.

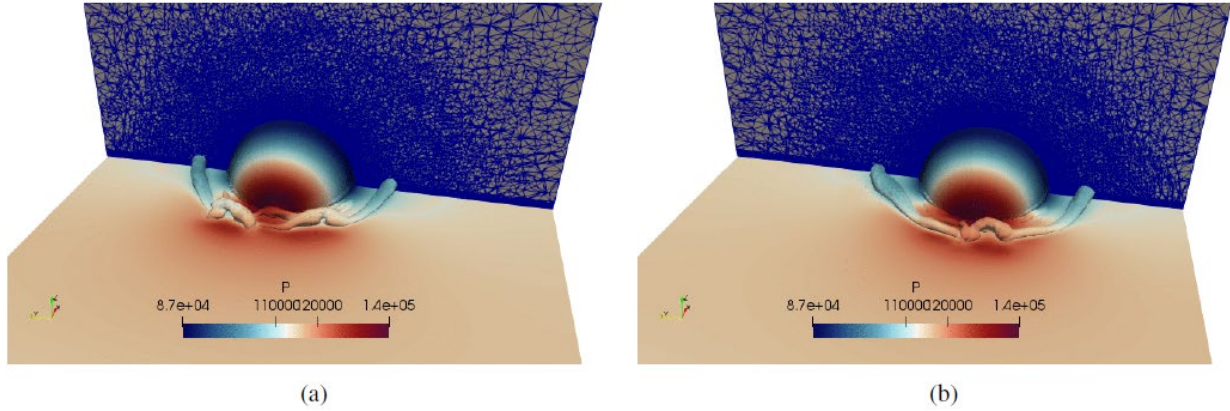


Figure 49. FSI test setup with coarse mesh and weak spring

Figure 50 shows the aerodynamic forces for both the rigid and flexible cases. It is important to note that the flexible simulation started from the rigid solution. The force coefficient data began to diverge from the rigid data after approximately two flow through times (t) (i.e. 0.011 sec) before differences in the aerodynamic forces became apparent. However, the lift and drag force magnitudes remained similar to the rigid results; as expected, the side force changed the most in comparison to the rigid case. This was because the single structural DoF is the deformation in the cross-stream (i.e. side force) direction. Interestingly, the side force magnitude tends to be reduced due to the turret motion. However, this may be due to the limited time history of the simulation.

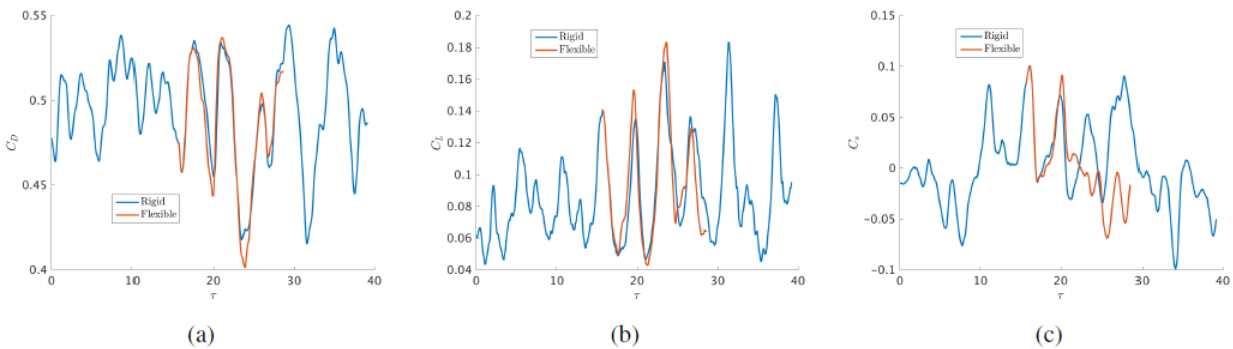


Figure 50. Aerodynamic forces of the rigid and flexible turrets

Based on the earlier wind tunnel measurements of the side force and linear beam dynamics, the magnitude of deformation was predicted to be approximately 0.2 to 0.5 mm with a frequency of 115 Hz. The deformation obtained from the simulation is plotted in Figure 51. As shown, the magnitude matches the prediction. In addition, the frequency was estimated from the limited time history as 113.8 Hz, which closely matches the predicted eigenfrequency of the beam-turret system. These results indicate that the flow does indeed excite the first bending mode of structure, as designed.

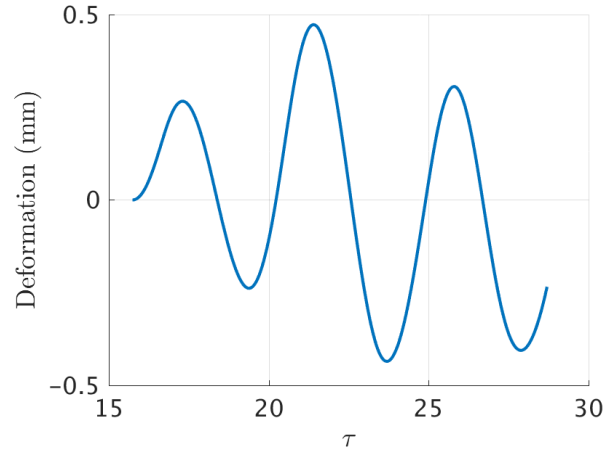


Figure 51. Deformation magnitude of the flexible turret

To answer the question of how this deformation influences the flow structures, the mean and standard deviation of the surface pressure was computed and plotted in Figure 52. The mean pressure coefficient ($\bar{C}_p$) shows the stagnation pressure in the front of the turret and a suction peak over the top of the turret, as expected. The $\bar{C}_p$ distribution also shows lower pressure where the necklace vortex approaches the floor of the wind tunnel. The fluctuating component of the pressure coefficient, C'_p , indicates areas of significant unsteadiness.

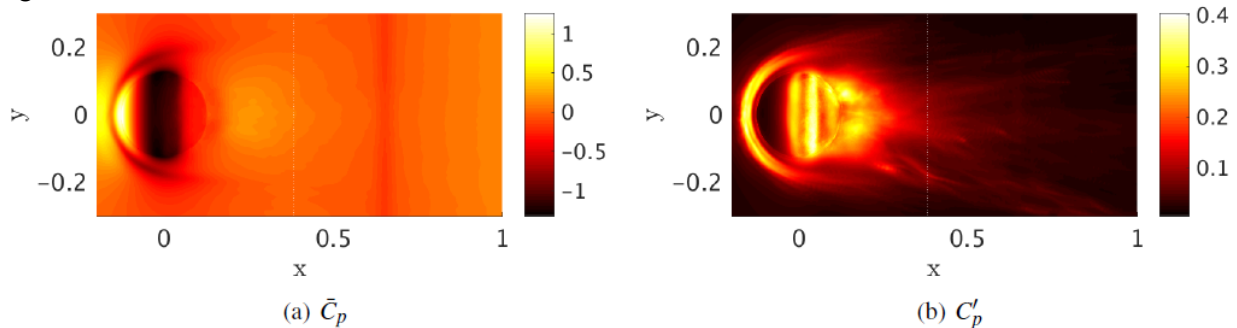


Figure 52. Mean and standard deviation of the surface pressure distribution for the flexible turret

The regions of unsteady pressure variations are very similar to the rigid case. The front of the necklace vortex is highly unsteady due to secondary/tertiary vortices merging and interacting in a sporadic fashion. On the downwind side of the turret, the largest pressure variations are observed just downstream of the separation location, commensurate with the highly energetic vortices developing in the separated shear layer. The other 'band' of large C'_p , as in the rigid turret case, is likely due to the large scale motion of the separation line in time.

To understand the effect of the turret motion on the flow structures, the unsteady pressure is sampled at the wake line across the floor of the wind tunnel, as in the rigid simulation. The temporal behavior is analyzed on this line. Figure 53(a) shows the pressure across this wake line over time. The results show a dominant convective frequency and wavelength is indeed present. This frequency appears to be approximately 4 convective times (i.e. about 95 Hz) which is commensurate with the structural oscillation

in Figure 51 and a Strouhal number of 0.0144. The statistical properties on this wake line (Figure 53(b)) are similar to the rigid case where the majority of the fluctuations lie upon the wake centerline.

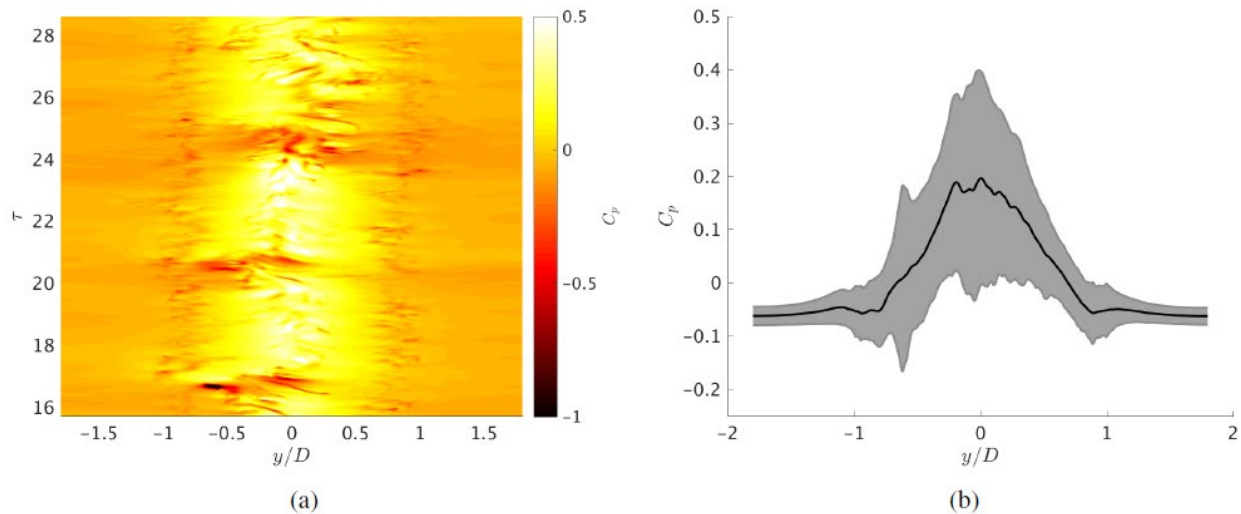


Figure 53. Convective pressure distribution of the wake line and mean and variance across the pressure wake line taken at one diameter downstream for the flexible turret

The time accurate pressure field is shown in Figure 54. Similar states are seen when compared to the rigid case. Arguably, the number of skewed wake states where the separation line angles to the left occurs fewer times than in the rigid case. This may indicate that now that the turret is able to absorb some of the cross-stream energy fluctuations, perhaps the wake becomes more symmetric. Most of the modes seen in the animation exhibit large scale streamwise motions as opposed to asymmetric behavior.

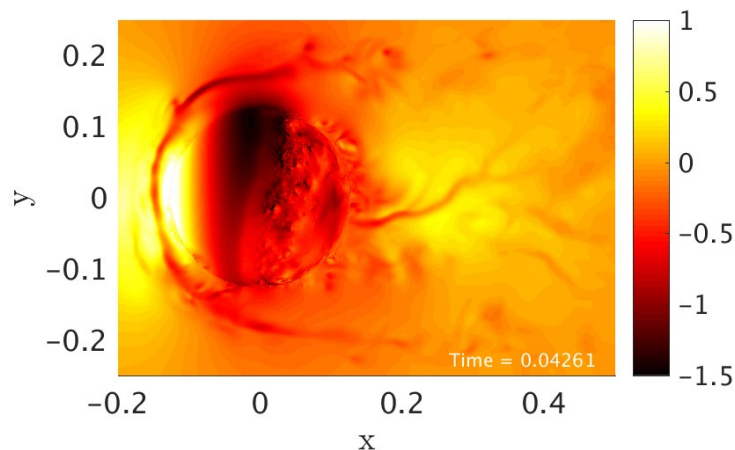


Figure 54. Flow still/animation of the turret and tunnel floor pressure distribution of the flexible turret

Comparison between the rigid and flexible simulations

From the results presented above, there are apparent differences in the flow features between the rigid and flexible simulation, but they are still difficult to distinguish. The simulations only capture approximately 40 convective flow through times (0.11 seconds), so establishing statistically significant quantifications is challenging. The following section discusses qualitatively the variations in the flow features due to the flexibility of the turret. To further quantify the specifics of the influence of deformation, the simulations would need to be carried out for a much longer time frame.

Figure 55 shows the pressure plots on the line one diameter downstream of the turret. Figure 55(a) shows the rigid simulation and Figure 55(b) shows the flexible case for the same time sequence. Both cases exhibit similar frequencies and structures for the first 2-3 convective flow times. Not until $t = 20$ the most apparent difference, a very large negative pressure fluctuation, indicates that a strong vortex was shed. This is also commensurate with the peak in the turret displacement shown above. While the frequencies are similar between the cases, the fluctuating pressure magnitudes seem to increase due to the deformation. Also, the wake appears to meander less which supports the previous hypothesis that the asymmetric modes are less energetic.

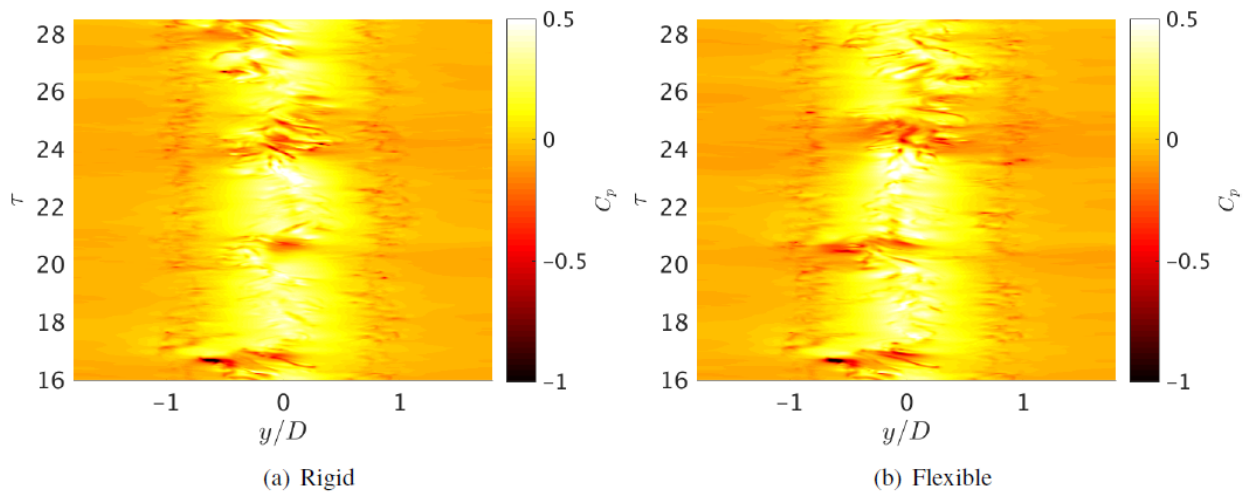


Figure 55. Convective pressure distribution of the wake line across the pressure wake line taken at one diameter downstream for the rigid and flexible turret

The standard deviation of the pressure fluctuations are compared for the rigid and flexible turrets in Figure 56. The most prominent difference are the distinct structures in the near wake of the turret. The rigid case shows a fairly uniform C_p' distribution in the wake region which indicates a constant switching between the modes identified above. The flexible case shows two vortex cores just aft of the hemisphere. It is postulated that the surge (forward and backward motion) of the separation line becomes more prevalent, thereby increasing the wake symmetry. The corollary is true as well: the asymmetric wake modes (i.e. the skewing of the separation line) are reduced.

This feature is also seen if the two images are spliced together at the centerline of the turret as in Figure 57. The top half shows the flexible case in which a large vortex structure is present just aft of the turret, and the bottom half (rigid) shows less spatial consistency of pressure fluctuation. Also, the first band on the top of the turret, which was attributed to large scale motion of the separation line, is in a slightly different position for the flexible turret. The separation is slightly further upstream than in the rigid case. This would also suggest that for this dataset the flexible case has more pronounced forward and aft fluctuation of the separation line.

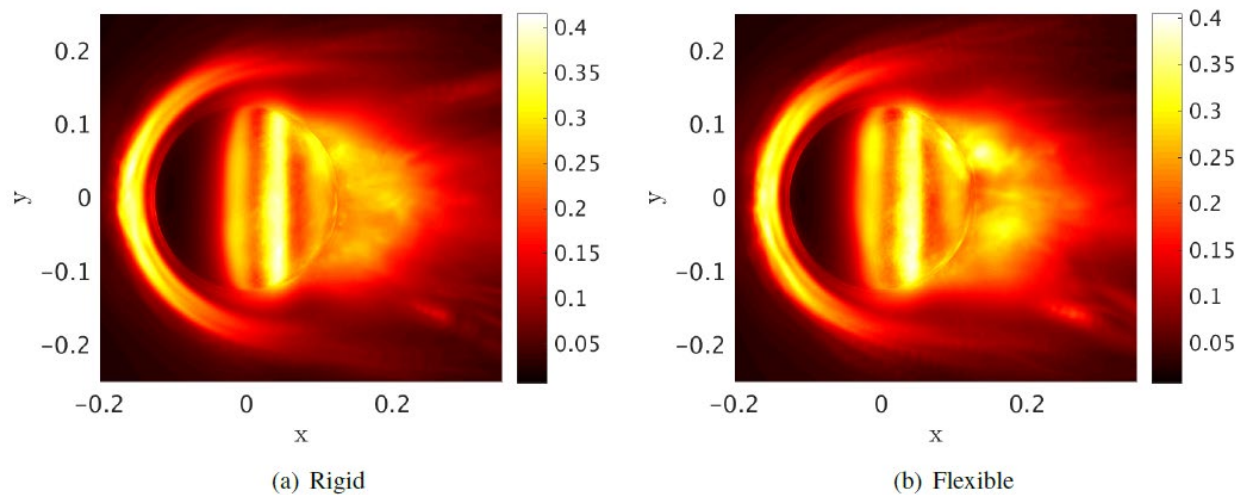


Figure 56. Pressure variance for both flexible and rigid turret simulations

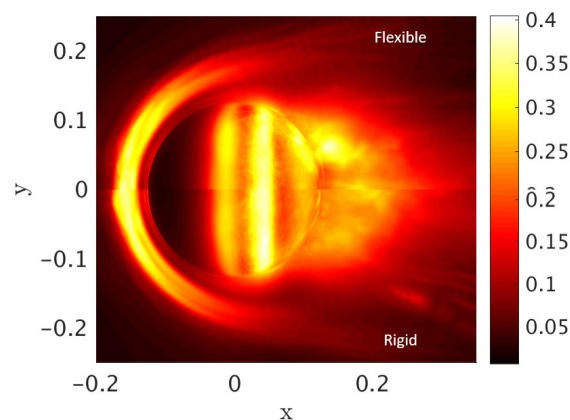


Figure 57. Pressure variance for both flexible and rigid turret simulations

Topic 2: Experimental studies in supersonic flow and related aero-optical effects to validate numerical codes

Results and Discussion

Overall flow structure

In general, the shock structure near a wall-normal circular cylinder is composed of a forward separation shock (1) which joins a separated normal bow shock (2) and a rearward shock (3) closer to the base of the cylinder at the triple point to form the classic lambda shock structure. This structure is well-visualized in the experimental composite schlieren images in Figure 58, which use a central dot method. A subsonic separation region (4) is formed beneath the lambda shock base, while the bow shock (5) curves around the tip of the cylindrical pin to form a nearly straight oblique shock (6) that reflects off the opposite wall. An oblique shock (7) is formed near the downstream base of the pin by the reattachment of the boundary layer. A shear layer (8) is formed at the pin tips, which propagates downstream.

Detailed views of the 25mm pin array are given in the Schlieren images of Figure 59, which uses a vertical knife edge method. Visible in these images are the lambda shock structure upstream of the pin

array, a bow shock which curves around the pin tips, oblique shock impingement on the boundary layer of the bottom wall, boundary layer separation with expansion fan and reattachment shock, an expansion fan at the pin tips, an oblique shock originating near the pin base due to boundary layer reattachment, flow acceleration through the pin array, and an oblique shock crossing the supersonic region downstream of the pin array.

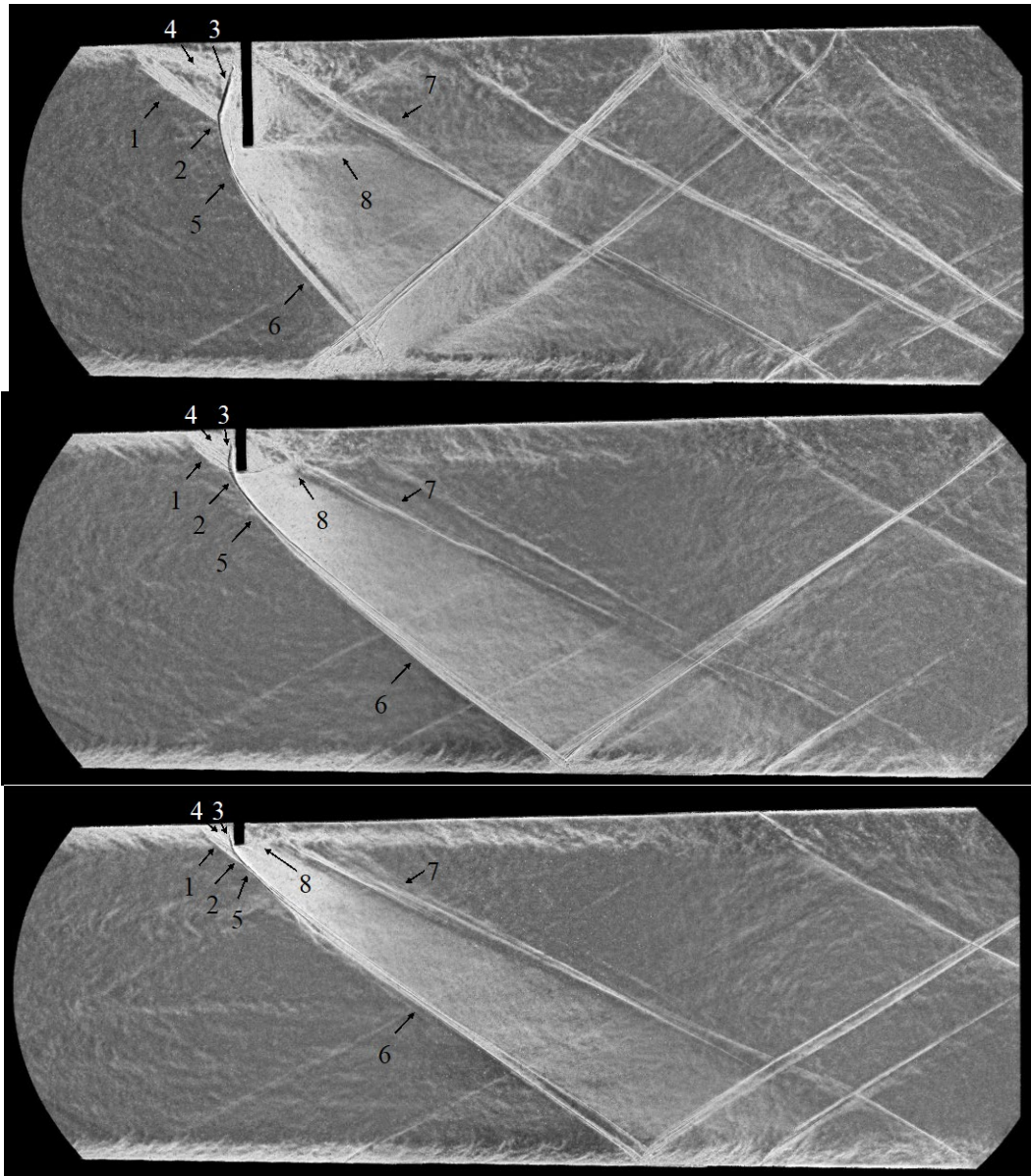
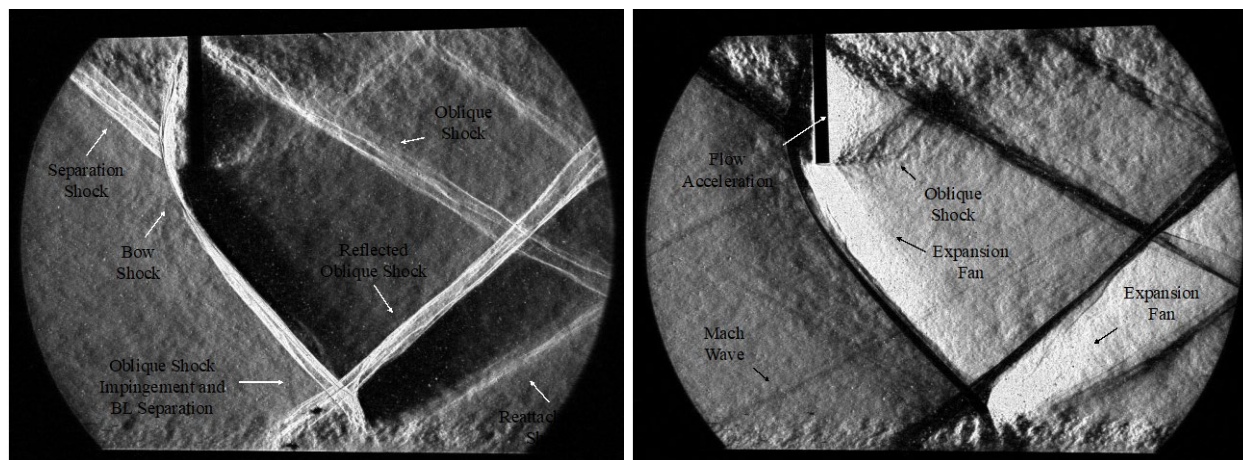


Figure 58. Instantaneous composite schlieren images of (a) 25 mm pins, (b) 10 mm pins, and (c) 5 mm pins



(a) Vertical knife on upstream side

(b) Vertical knife on downstream side

Figure 59. Instantaneous schlieren with vertical knife edge and 200ns optical pulse

The Mach-area relation for $\gamma = 1.4$ flow is

$$\frac{A_*}{A} = \frac{216}{125} M \left(1 + \frac{M^2}{5} \right)^{-3}, \quad (19)$$

where ‘*’ indicates sonic conditions. Using the pin dimensions, the area fraction of the 2-D nozzle formed by adjacent pins is $A_*/A = 3/4$, and the two solutions to the Mach-area relation are $M = 0.50$ and $M = 1.70$. Using normal shock equations and a nominal upstream freestream Mach number of $M = 2$, the flow immediately downstream of the normal shock in front of the pin array is subsonic with a Mach number of approximately $M = 0.58 > 0.50$, indicating that the flow between the pins is sonic and the flow downstream of the pin array is supersonic with a Mach number of approximately $M = 1.7$.

From oblique shock relations, the flow downstream of an oblique shock in Mach 2 flow is sonic at an oblique shock angle of 61.5 degrees. By analyzing the schlieren images of Figure 59, it is found that flow immediately downstream of the bow shock curving around the pin array is subsonic for $y \leq 9\text{mm}$ from the end of the pins in the wall-normal direction. This subsonic flow is reaccelerated to supersonic speed by the expansion fan at the end of the pin tips.

A weak shock wave enters the flow field in the bottom left corner of Figure 59(b), which is created by a small step on bottom wall. Since this step is $25\text{-}50\ \mu\text{m}$ high, this weak shock may be considered a Mach wave with infinitesimal strength. The wave angle of this Mach wave downstream of the oblique shock formed by the bow shock around the pin array is about $\theta = 29$ degrees. Using the relation $\sin \theta = 1/M$ it is found that the Mach number is about $M = 2$, indicating that after the expansion fan emanating from the pin tips, the flow behind the straight oblique shock has returned to approximately the same Mach number as the flow in undisturbed upstream region. However, due to the greater shock strength in the curved bow shock region near the pin array, the Mach number in this region is $M < 2$.

The wave angle of the oblique shock originating from the pin tips and crossing the accelerated flow region directly behind the pin array is about $\theta = 39$ degrees, indicating that the Mach number in this region is $M \geq 1.6$, which is in agreement with the above estimate of $M = 1.7$. However, since this oblique shock has finite strength and the turning angle is not known, the Mach number in this region cannot be precisely calculated.

PLIF

PLIF images were taken using a 25 mm wide 266nm sheet positioned on the centerline of the test section. Stagnation conditions are $P_0 = 2.6$ bar and $T_0 = 425$ K with 6% acetone by volume in N_2 . The upstream edge of the laser sheet is positioned against the upstream edge of the fused silica window and 25 mm from the pin arrays, which are in the upper left-hand side of the images. Since the pin arrays contain an odd number of pins, the laser sheet is positioned directly behind the middle pin. PLIF images are uniformly scaled and presented in Figure 60.

A corner shock is visible in the upper portion of Figure 60(a) originating from the base of the 25mm pin array. The strong oblique shock from the pin array enters the sheet near the bottom wall in Figure 60(a), and the shock wave/boundary layer interaction and reflected oblique shock is especially evident. Since acetone fluorescence intensity is a function primarily of flow density, brighter regions in the PLIF images downstream of shock waves indicate a denser region in the flow. The density of the flow region in Figure 60(a) is greatest immediately downstream of the reflected oblique shock as evident by the very intense fluorescence intensity. The shock-induced separated area near the wall is also visible in Figure 60(a). The corner shock and oblique shock are visible in Figure 60(a) and Figure 60(b), but progressively less so due to the weakening of the shocks with the decreased height of the pins.

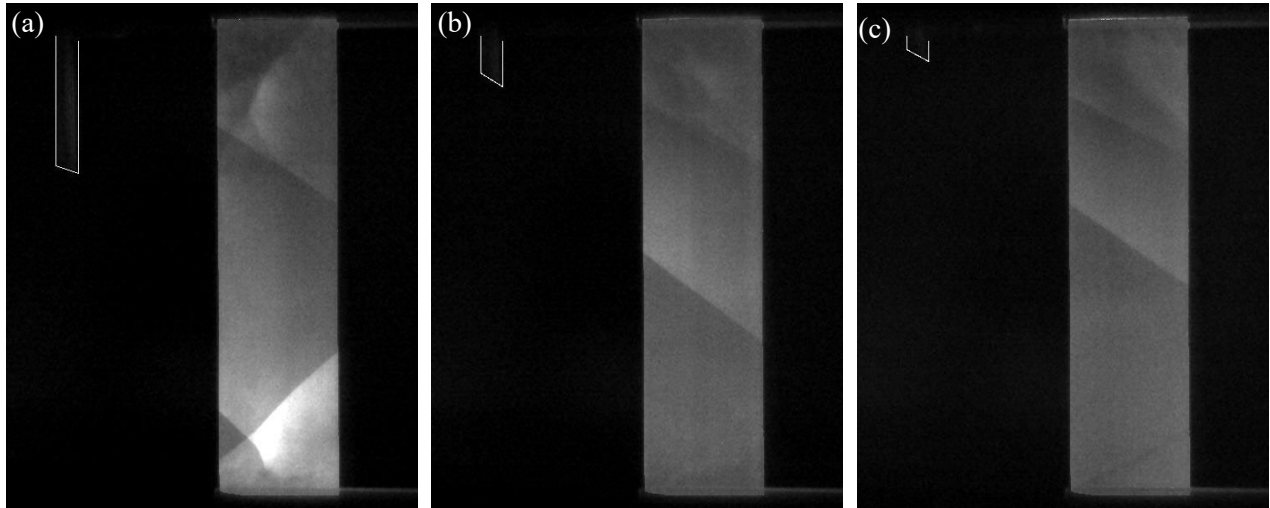


Figure 60. PLIF images behind (a) 25mm pins, (b) 10mm pins, and (c) 5mm pins. Pin array outlined in white

Semi-quantitative density fields presented in Figure 61 are obtained from the PLIF images by extracting the laser sheet image, subtracting the off-plane background to account for sensor dark current and background scattering, and scaling by the average pixel value in the freestream region. The density of the freestream $\rho_\infty = 0.7$ kg/m³ is obtained from isentropic relations with a nominal freestream Mach number of $M = 2$.

The pressure ratio for an oblique shock with wave angle θ and upstream Mach number M for $\gamma = 1.4$ flow is

$$\frac{\rho}{\rho_\infty} = \frac{6M^2 \sin^2 \theta}{M^2 \sin^2 \theta + 5}. \quad (20)$$

The oblique shock entering the bottom left of Figure 60(a) has a wave angle of about $\theta = 45$ degrees, and the resulting density ratio of $\rho/\rho_\infty = 1.7$ is in good agreement with Figure 44(a).

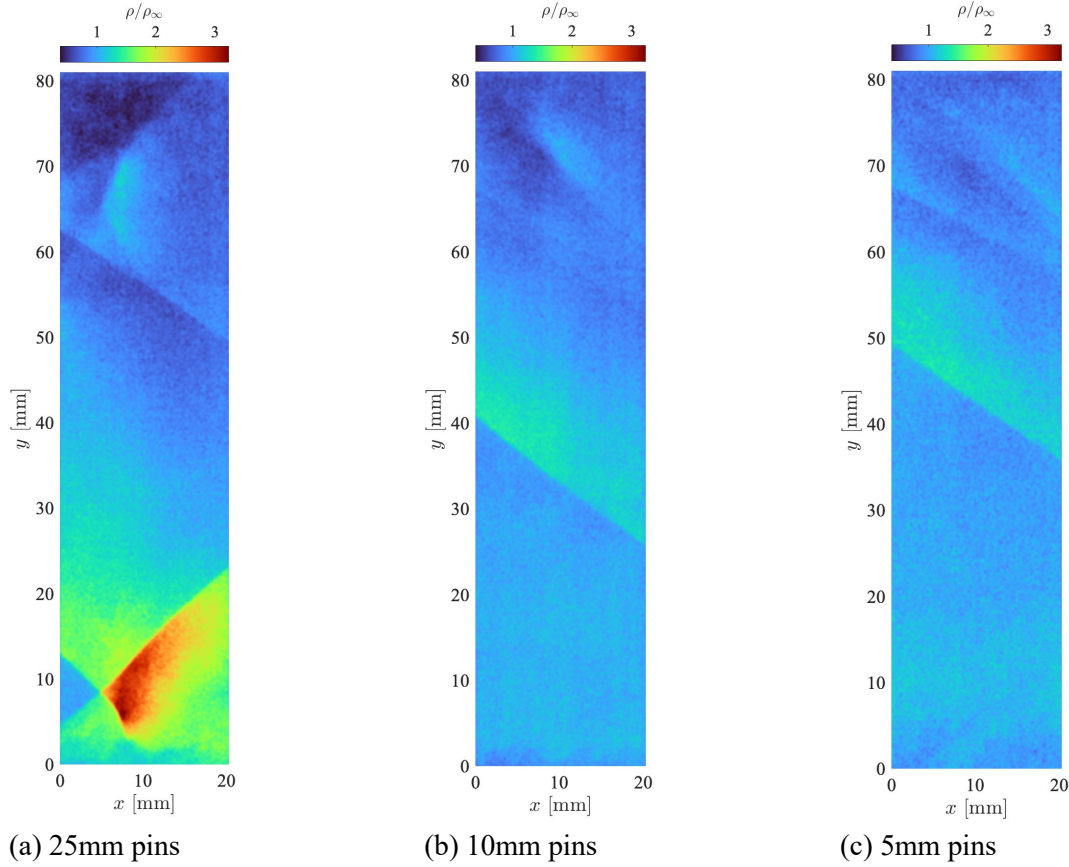


Figure 61. Semi-quantitative density fields from PLIF images

Wavefront measurements using SHWFS

Figure 62 shows the spatial map of OPD_{rms} in the wall-normal direction for the pin array with 25 mm height. For reference, the spatial map is plotted relative to the locations of tunnel side walls and the pin array. One main feature of the spatial map is two thin regions of increased optical distortions, related to shocks, crossing roughly in the middle of the aperture. By tracing back these shocks, it was concluded that these shocks are reflected bow shocks, originated from the first and the last pins. The angle of these shocks is approximately 30 degree relative to the flow direction, suggesting the wall-normal average Mach number of about $M = 2$.

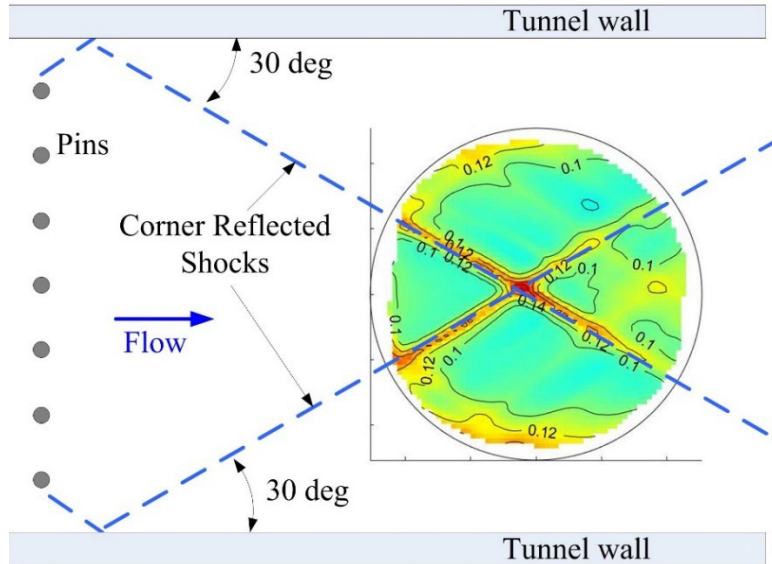


Figure 62. The spatial map of OPDrms (in microns) in the wall-normal direction, relative to the pins' positions and tunnel walls. Pin height is 25 mm

Figure 63 presents the spatial map for the spanwise measurements for 25 mm pins, overlaid with the time-averaged Schlieren image. A series of shocks can be clearly observed both in the middle and near the perimeter of the aperture. These shocks can also be found in Figure 59. The region $y < 10$ mm corresponds to the energized boundary layer at the wall, with the associated increase in density fluctuations. The weak shear layer at approximately $y = 25$ mm, originated from the pins tips, can also be observed.

Three different wall-normal locations were chosen to perform the dispersion analysis and estimate the convective speeds at these locations. One location is $y = 33.6$ mm, which is in the freestream region, well above the pins. The second location is at $y = 15.6$ mm, which is in the wake region downstream of the pin array. The third location was chosen to be inside the wall boundary layer at $y = 4.8$ mm. Figure 64 presents the stacked auto-spectral density functions for these three different wall-normal locations. At the location of $y = 33.6$ mm, which is above the wake introduced by the pin array, the spectrum, see Figure 64(a), exhibits predominantly one branch, indicated by a solid black line, moving supersonically at approximately the freestream speed. In the wake region, see Figure 64(b), this branch is also present. In addition, the spectrum reveals the presence of a range of the subsonic convective speeds, with the maximum speed of approximately 0.4 of the freestream, denoted by the dashed red line. Thus, two types of regions exist in the pin wake region. One of them travel at the supersonic speed, close to the freestream speed, and represent regions between the pins. Another type has a range of slower speeds between 0 and $0.4U_\infty$. Using isentropic relations, the speed of $0.4U_\infty$ corresponds to subsonic Mach number of about $M = 0.6$. These subsonic regions Figure 64(c), the spectra shows the presence of only one branch, convecting at the speed slightly less than the freestream speed.

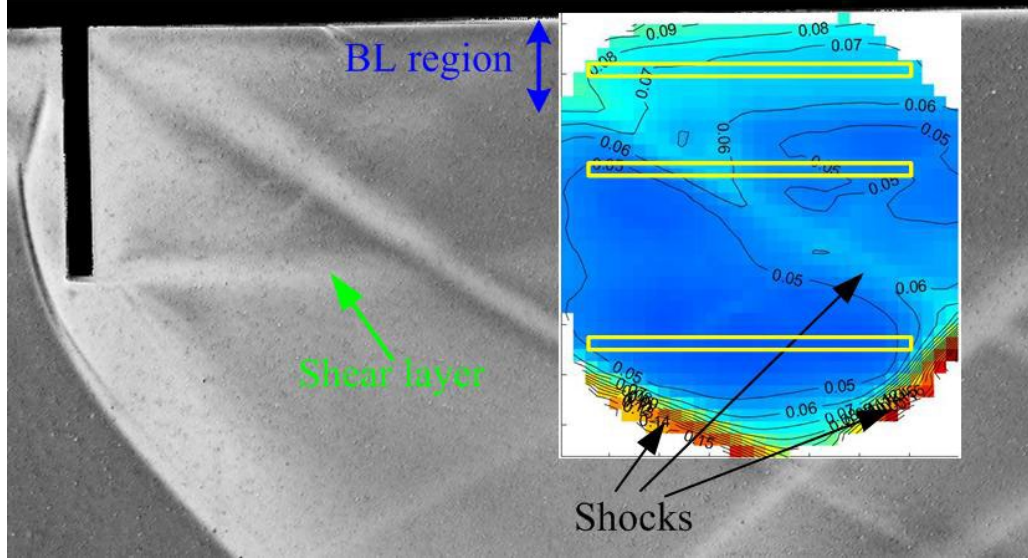


Figure 63. The spatial map of OPD_{rms} (in microns) in the spanwise direction, overlaid with the time-averaged Schlieren image. Locations to perform the dispersion analysis are indicated by yellow boxes. Pin height is 25 mm

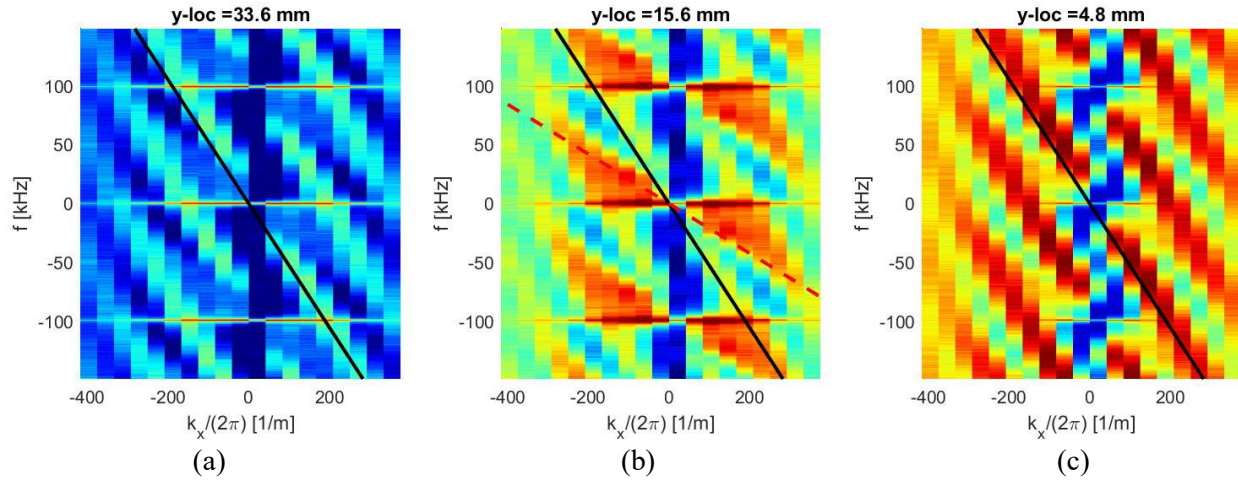


Figure 64. Stacked 2-D spectra of the deflection angles, plotted as $\log_{10}[S_{\theta}(f, k_x)]$, for (a) $y = 33.6$ mm (b) $y = 15.6$ mm and (c) $y = 4.8$ mm. Pin height is 25 mm. A solid black line indicates a convective speed of approximately U_{∞} , a dashed red line in (b) denotes a convective speed of $0.4U_{\infty}$.

Streamwise Features by Mie Scattering

The Mie scattering images in Figure 65 were taken using a 50 mm wide 532nm laser sheet positioned on the centerline of the test section and against the upstream edge of the fused silica window. Stagnation conditions are $P_0 = 2.6$ bar and $T_0 = 300$ K with 2% acetone by volume in N_2 . Similarly to Figure 42, oblique and reflected shocks and a turbulent boundary layer are visible in Figure 48, as well as weak corner shocks in Figure 48(b) and (c).

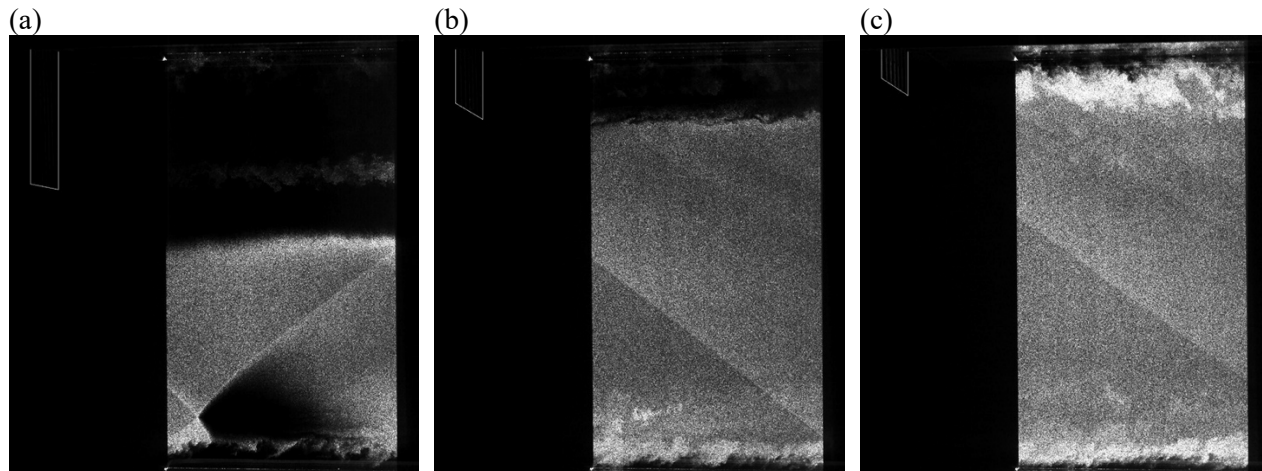


Figure 65. Mie scattering images from (a) 25mm pins, (b) 10mm pins, and (c) 5mm pins. Pin array outlined in white

A notable feature in the images of Figure 65 is the low intensity of scattering directly downstream of the pin arrays. Since stagnation temperature remains unchanged across shocks, the lower Mach number flow directly behind the pin arrays results in increased static temperatures compared to the freestream which prevents acetone recondensation directly behind the pin arrays. Due to low flow velocity in the boundary layer and resulting higher static temperatures, Mie scattering is not present in the boundary layer immediately next to the solid wall. A region devoid of acetone droplets and thus Mie scattering is also present near the bottom wall of Figure 65(a) downstream of the reflected oblique shock due to high gas temperatures in this region.

Two exceptions to this trend of droplet evaporation are in the shear layer downstream of the pin tips in Figure 65(a) and to a certain degree in Figure 65(b), as well as in some structures in the turbulent shear layer near the upper wall. Since both the pin tip shear layer and the turbulent boundary layer on the upper wall must pass through the high-temperature lambda shock region upstream of the pin arrays, some portion of this flow must either experience rapid local expansion and the corresponding re-condensation of acetone droplets or ingest relatively cooler gas from another region in the flow.

When the acetone concentration is increased to 6%, as shown in Figure 66, the shear layer at the pin tips and the boundary layer on the upper wall are more visible. A streamwise periodic structure is observed in the pin tip structures caused by the shedding of the vertical von Kármán vortices illustrated in Figure 1, and the boundary of the shear layer is visible as a bright horizontal strip. The high temperature region downstream of the reflected oblique shock seen in Figure 65 is also present in Figure 66 but is smaller in size, and a narrow dark line propagates downstream of the intersection of the separation and oblique shocks due to localized high temperature at this point.

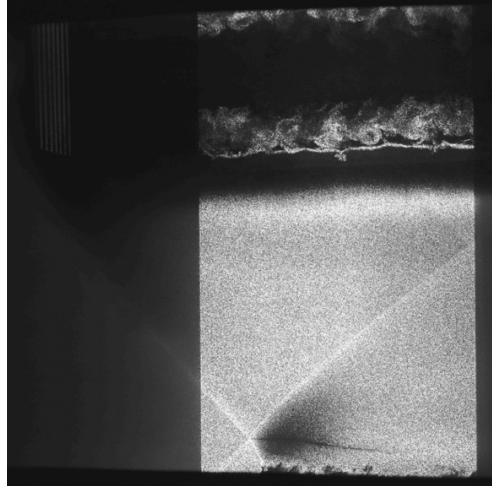


Figure 66. Mie scattering from 25mm pins with 6% acetone. For illustrative purposes, the figure has a nonlinear brightness scaling

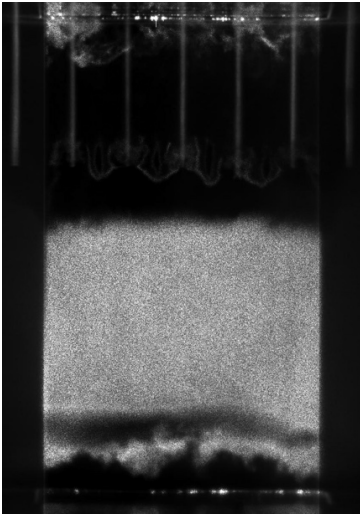
Cross-flow features by Mie scattering

Cross-flow Mie scattering images were taken using the same laser arrangement as streamwise images but with the cylindrical diverging lens rotated 90 degrees. Images were acquired through a fused silica window on the vacuum tank using a Nikon 200mm f/4 lens and a Tokina 400mm f/5.6 lens. The pins are visible in the images due to light scattering off the stainless steel surfaces.

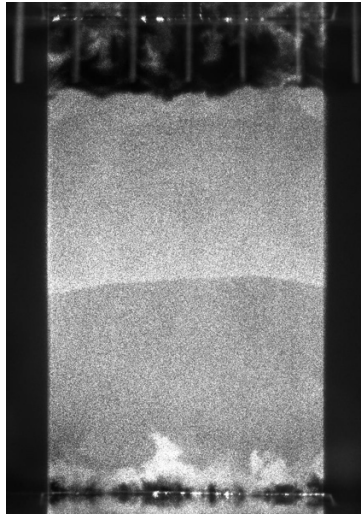
The oblique shock, seen as a diagonal line in Figure 65, is visible as a horizontal line in Figure 67 as it cuts through the plane of the image. The shock is not perfectly two-dimensional, and it curves slightly near the side walls. A turbulent boundary layer is visible on both the upper and lower walls, and large turbulent structures of increased brightness are present which penetrate into the core flow. The physical mechanism responsible for the increased light scattering in these regions is discussed earlier. The nearly droplet-free region behind the pins in Figure 65 are also visible in Figure 67.

The droplet-free region behind the oblique shock impingement in Figure 65(a) is visible as a dark strip near the bottom of Figure 67(a). Large-scale structure is visible in interface between the warmer droplet-free region behind the pins and the cooler droplet-filled region in Figure 67, and the size of the structures is similar to the pin-to-pin spacing. These structures grow in size as the flow moves downstream and the two regions mix together.

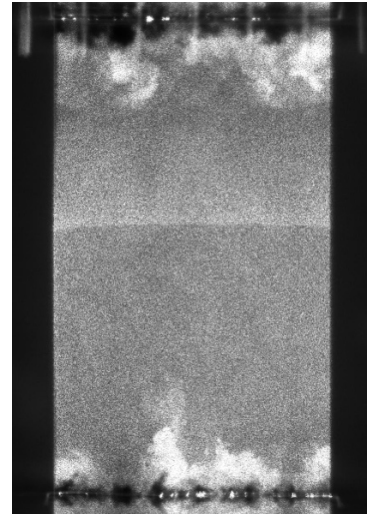
Also visible in Figure 67 are fine-scaled structures near the end of the pin tips. These structures are especially evident for the 25mm pins, which are shown in detail in Figure 68 at 25, 50, and 75 mm downstream with enhanced contrast.



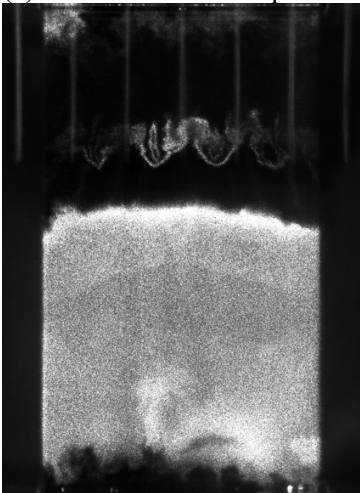
(a) 25mm from 25mm pins



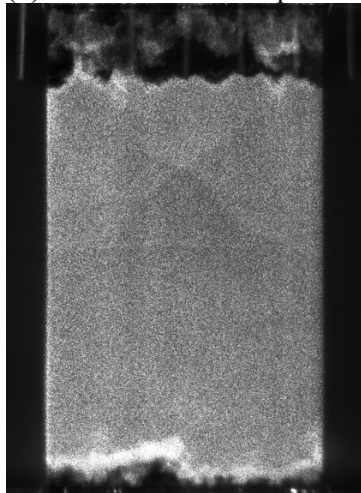
(b) 25mm from 10mm pins



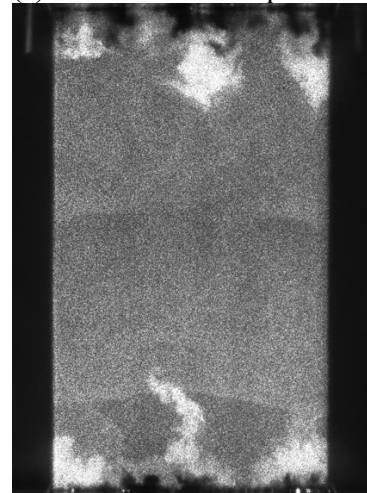
(c) 25mm from 5mm pins



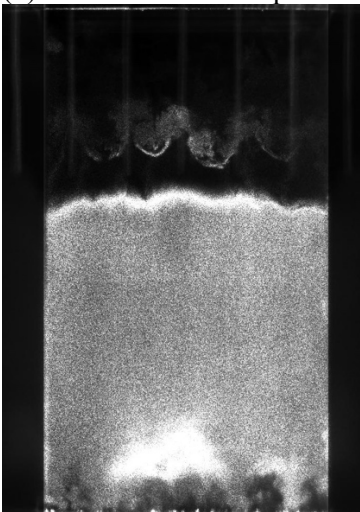
(d) 50mm from 25mm pins



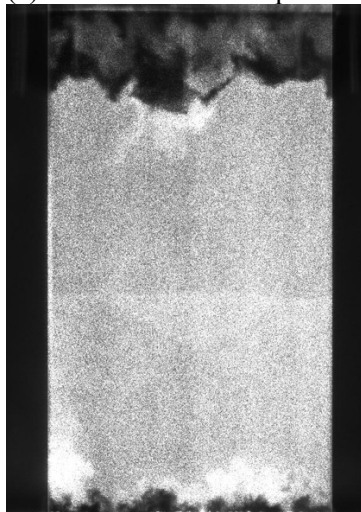
(e) 50mm from 10mm pins



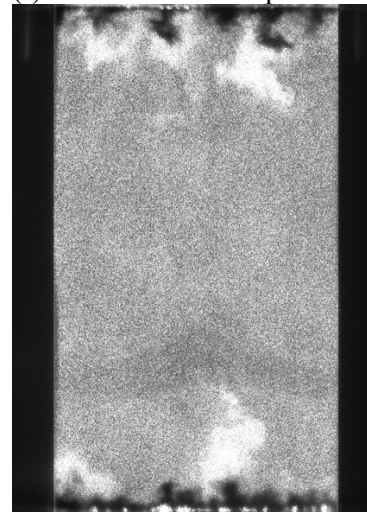
(f) 50mm from 5mm pins



(g) 75mm from 25mm pins



(h) 75mm from 10mm pins



(i) 75mm from 5mm pins

Figure 67. Mie scattering cross-flow images

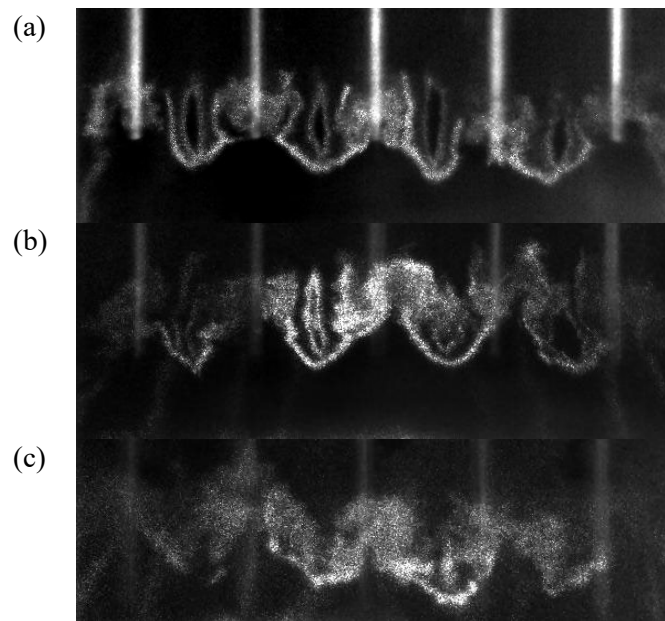


Figure 68. Pin tip structures (a) 25mm, (b) 50mm, and (c) 75mm downstream of 25mm pins with enhanced contrast

Flow field Areas of a Special Interest

Several flow field areas of special interest are shown in Figure 69. In Figure 69(a), structures (1) on either side of the 25mm pin tip are believed to be pin-tip vortices similar to those illustrated in Figure 1(a). The line (2) is the dividing surface between the accelerated flow between the pins and the flow below the pins which passed through the curved bow shock and the expansion fan. The oval structure (3) is hypothesized to be caused by a jet of the relatively high pressure and high temperature gas just downstream of the curved bow shock near the pin tips into the lower pressure region between the pins caused by flow acceleration through the 2-D nozzle created by adjacent pins. This inter-cylinder gas jet is cut off by the end of the expansion region. The interface of the flow between and below the pin tips is further distorted by the pin tip vortices and further gas expansion through the pin array. Once formed, this structure continues propagating downstream as a distinct structure visualized by Mie scattering due to temperature differences in the flow regions. This is schematically illustrated in Figure 70.

The shear layer boundary at the end of the 10mm pins is visualized using Mie scattering in Figure 69(b), and a regular pattern is observed in which the boundary is higher directly beneath the pins than between the pins. This is thought to be related to structure (2) in Figure 69(a) and due to flow expansion through the 2-D nozzle created by adjacent pins.

The wake compression zone is visualized in Figure 69(c) by PLIF. This compression is caused first by the crossing of the reattachment and oblique shocks labeled in Figure 60, which occurs just upstream of the laser sheet. Crossing of the oblique shocks reflected off the side windows shown in Figure 62 result in increased compression at the center of the circled region in Figure 69(c).

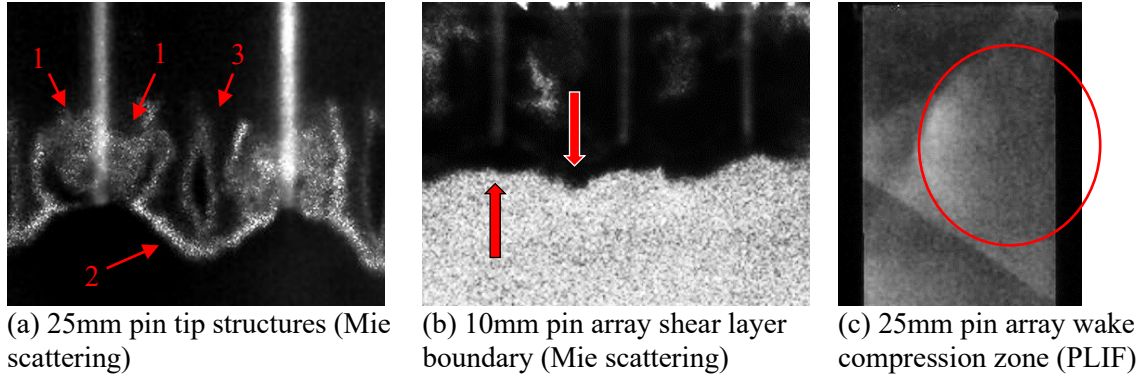
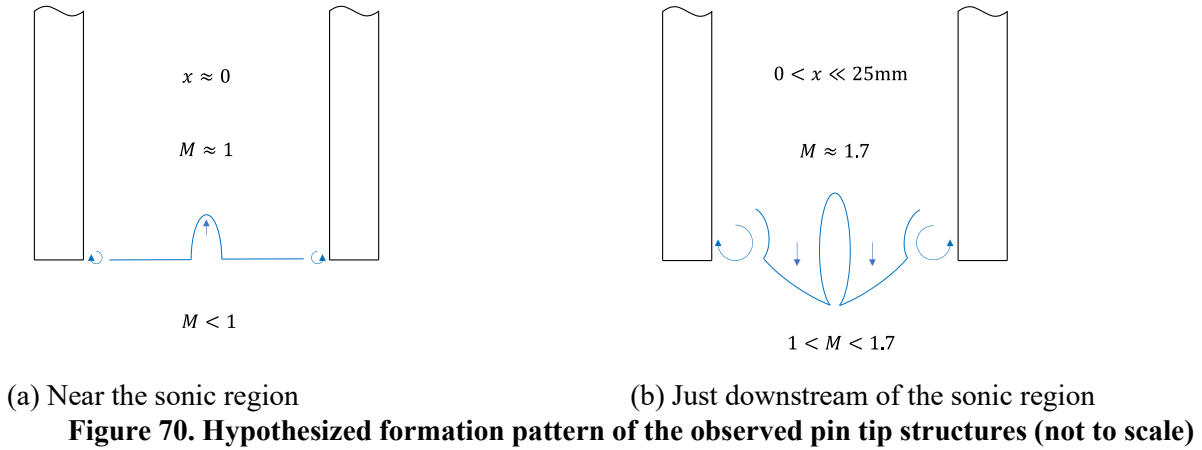


Figure 69. Flow features of special interest



Enhanced Scattering Regions

Apparent in the Mie scattering in Figure 65, Figure 66 and Figure 67 are regions of enhanced laser scattering, resulting in brighter regions of the flow. These regions are generally near an interface between warmer and cooler gas, such as the turbulent boundary layer in Figure 65(c) or at the boundary of the droplet-free region behind the pin tips in Figure 67(g). Since interfaces between warmer and cooler gas are regions with droplet evaporation and re-condensation, droplets in these regions are thought to be smaller and more numerous than in more equilibrated regions of the flow.

When the scattering plane is perpendicular to the direction of the electric vector of polarized light, the intensity of light scattered by a dielectric sphere [55] normalized by the incident light intensity is

$$I = \frac{\lambda^2}{4\pi^2 r^2} |S|^2, \quad (21)$$

where λ is the wavelength of the light, r is the distance to the point of observation, and S is the scattering amplitude function

$$S = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} (a_n \pi_n \cos \theta + b_n \tau_n \cos \theta), \quad (22)$$

where θ is the angle of observation measured from the incident light direction. The angular functions are

$$\pi_n = \frac{P_n^{(1)}(\cos \theta)}{\sin \theta} \quad (23)$$

and

$$\tau_n = \frac{d}{d\theta} P_n^{(1)}(\cos \theta), \quad (24)$$

where $P_n^{(1)}(\cos \theta)$ is the associated Legendre function of the first kind, and a_n and b_n are coefficients given in [55]. For radii $a \lesssim \lambda/10$, the Rayleigh approximation for the scattering amplitude is

$$S = \left(\frac{2\pi a}{\lambda}\right)^3 \left(\frac{m^2-1}{m^2+2}\right), \quad (25)$$

where m is the relative refractive index, which is approximately $m = 1.36$ for acetone.

As shown in Figure 71, the magnitude of the scattering amplitude function squared $|S|^2$ at $\theta = \pi/2$ scaled by the droplet volume $v = (4/3)\pi a^3$ has a maximum at a radius of about $a = 130\text{nm}$. Thus, while scattering from a spherical droplet increases with increasing droplet radius, the scattered light intensity per unit volume of droplets has a maximum at a droplet radius of approximately $a = \lambda/4$. This results in increased light scattering in regions with numerous small droplets. The linear region at small a in Figure 54 corresponds to the Rayleigh scattering regime.

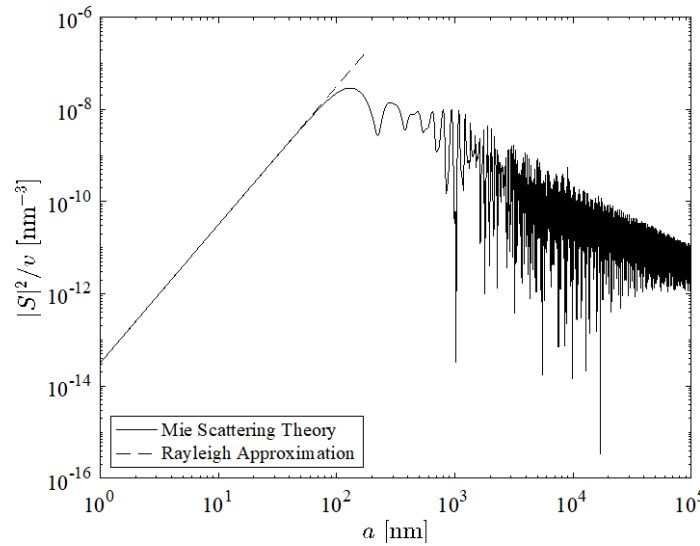


Figure 71. Mie scattering amplitude scaled by droplet volume

Topic 3: Experimental studies of the aero-optical jitter of the hemisphere-on-cylinder turret at various amounts of protrusion

Experimental studies of aero-mechanical jitter

Figure 72 presents some definitions that will be used to describe the turret parameters and angles. The turret is most simply described by its aperture size, A_p , diameter, D , protrusion distance from base to apex, H , and cylinder height, h . The angle at which the beam direction is pointing can be described by the azimuthal angle, β , and the elevation angle, γ . Varying elevation angle should not drastically change mechanical jitter imposed onto the beam. Therefore, for the experiments presented in this report, only an elevation angle of $\gamma=45^\circ$ was used. The turret used in the experiments presented in this work had a diameter of $D=0.30\text{ m}$ (12 in). Additionally, a conformal turret aperture, matching the radius of curvature of the turret, is used for all tests.

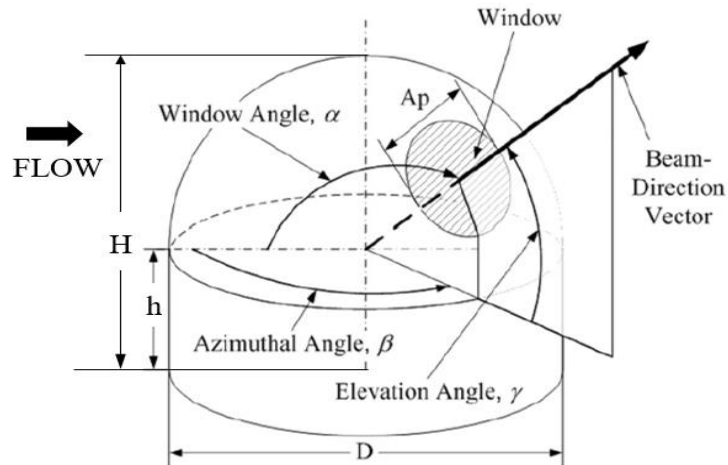


Figure 72. Turret definitions to describe parameters and angles

Wind tunnel test results for radial jitter imposed onto the beams are presented in Figure 73. Each plot represents a different Mach number test case and the rms radial jitter is plotted as a function of azimuthal angle for each turret geometry. The left subplots present the results for jitter measured using the OIRU configuration while the right subplots present the results using the reflector mounted blue laser diode. Here it can be seen that increasing the freestream Mach number results in more jitter imposed onto the laser beam for all configurations. More jitter was consistently measured on the OIRU beam than the reflector mounted blue laser diode beam because the OIRU beam experiences a double pass through the turret's optical path. In many instances, the jitter imposed onto both beams was higher for the cases of greater turret protrusion. However, the resultant jitter is clearly heavily dependent on many factors besides turret protrusion. The partial hemisphere produced significantly less jitter than the other configurations for most azimuthal angles while the hemisphere on full cylinder configuration typically produced the most beam jitter for most azimuthal angles.

Varying the azimuthal angle of the turret also caused variations in the amount of jitter imposed onto the beam, with azimuthal angles around 90 degrees typically causing the most jitter and the forward-looking angle of 0 degrees producing the least jitter. The internal architecture of the turret is not symmetric around the turret. Therefore, by varying azimuthal angle, the center of gravity of the turret as well as where the optical components are located changes.

Another visualization of the jitter test results is presented in Figure 74. Here, each plot corresponds to a different configuration. The measured jitter imposed onto the OIRU beam, the reflector mounted blue laser diode beam, and the bench measurements are plotted as a function of azimuthal angle. All plots within this figure correspond to measurements taken at a freestream Mach number of 0.5. Variations of resultant measured jitter from the OIRU beam and the reflector mounted blue laser diode as a result of changing azimuthal angle are still apparent in this alternate representation. Also plotted are the bench measurements made by turning the OIRU beam before entering the turret. These "bench measurements" record the jitter imposed onto the beam from only components on the optical bench, and not any mechanical contamination associated with the vibrating internal components of the turret. However, the measured contamination associated with the bench measurements may still be related to aero-mechanical forcing due the interconnected mounting of the bench, turret, and wind tunnel. It can be seen that the resultant jitter from just the bench measurements is substantial. In fact, in some extreme scenarios such as the partial cylinder case at an azimuthal angle of 0 degrees, the bench measurements alone produced more jitter than the jitter measured by the reflector mounted blue laser diode single pass measurement. Furthermore, the bench measurements do also have a slight dependence on azimuthal angle. This reveals that the way the bench, turret, and wind tunnel facility are mounted together, creates common mechanical contamination across the entire experimental setup.

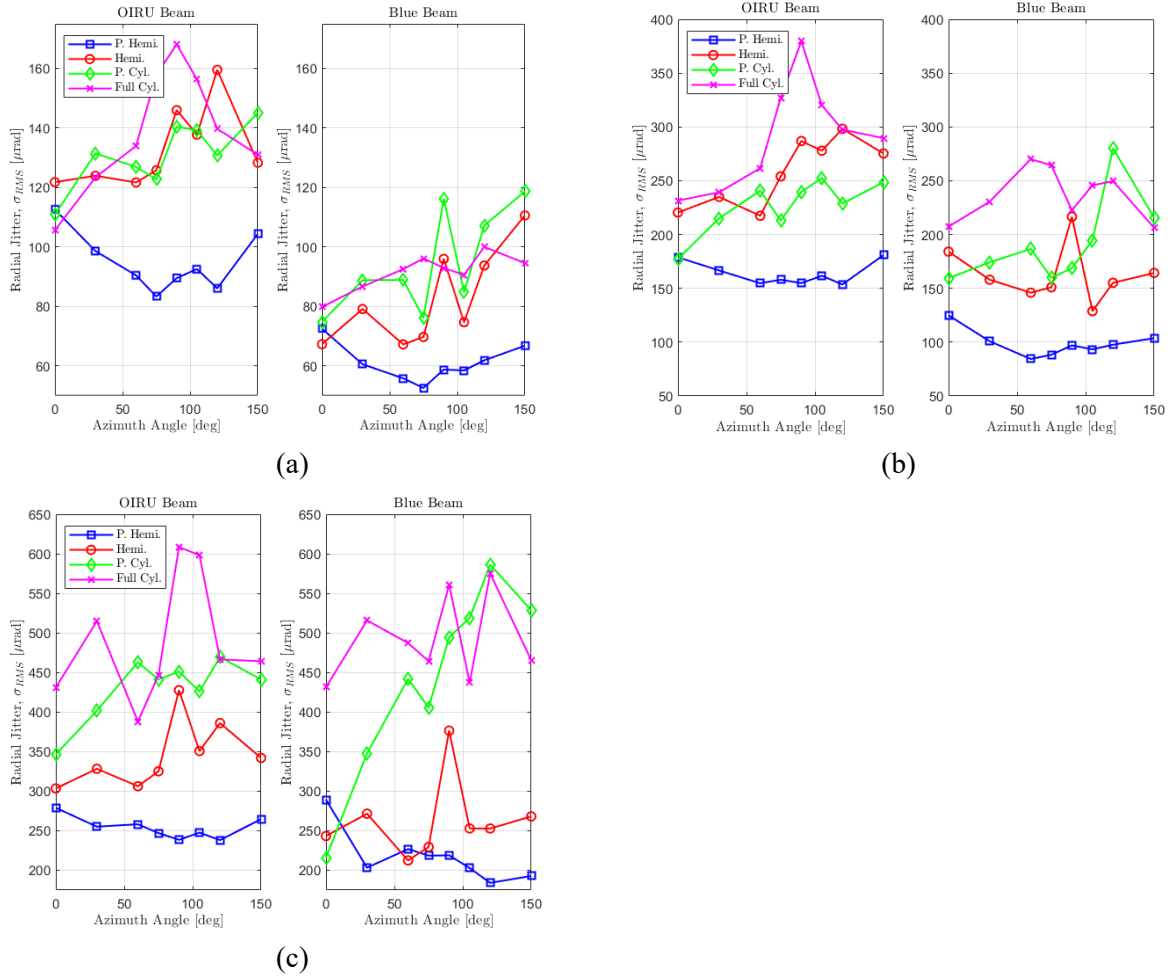


Figure 73. Comparison of resultant radial jitter for all four turret configurations (a) Freestream Mach number of 0.3 (b) Freestream Mach number of 0.4 (c) Freestream Mach number of 0.5

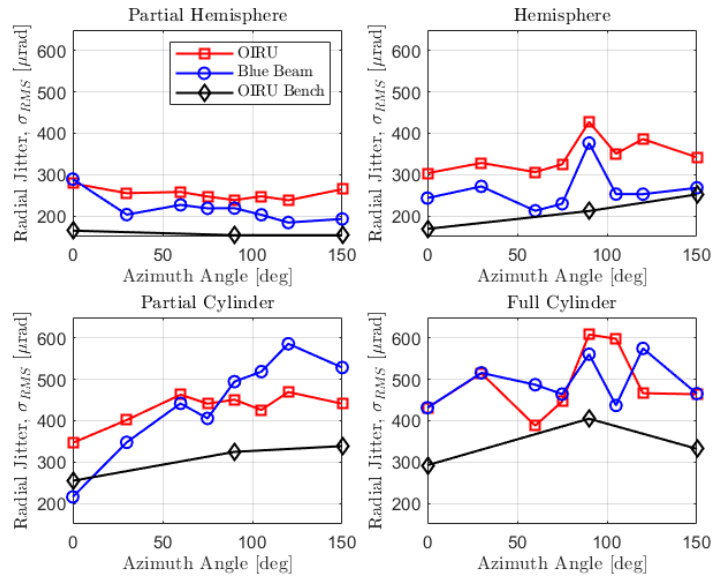


Figure 74. Comparison of resultant radial jitter for different turret geometries and measurement methods at Mach 0.5

This result makes it difficult to make concrete research assertions from strictly looking at the rms radial jitter results. The contamination imposed onto the laser beam is a function of many factors however some of which are specific to the architecture of this turret as well as the facility the system is being tested in. The goals of this research are to identify characteristics which are consistent between facilities and different turret designs, such as Mach number and geometry effects. To accomplish this, the spectra and accelerometer measurements are also be analyzed.

Figure 75 presents power spectral density results for the jitter measured on the hemispherical configuration in the 90-degree azimuthal angle position. The three left plots are the PSDs of the x-jitter, and the three right plots are the PSDs of the y-jitter. Results from all Mach number cases are also plotted. On the plots themselves, red represents the spectra from the OIRU measurements, blue represents the spectra from the reflector mounted blue laser diode measurements, and black represents the spectra for the bench measurements. In these results, it is immediately obvious that jitter associated with the bench comes from almost entirely low frequency vibrations with most of the energy at frequencies less than 900 Hz. Very low frequency peaks, such as at approximately 15-20 and 35-40 Hz for example are apparent in all measurements. Since the turret is rigidly mounted to the optical bench, which is rigidly mounted to the wind tunnel, it is difficult to determine which frequencies are associated with aero-mechanical forcing versus facility corruption. Unfortunately, in addition to being hard to distinguish, a coupling between these different experimental features also exists which makes isolating the jitter contribution associated with specifically aero-mechanical forcing difficult. Despite the lower frequency content being harder to distinguish the origins of the vibrations, at higher frequencies (greater than 900 Hz) almost no jitter comes from the optical bench components. This is expected as at some point, the optical bench will attenuate higher frequencies and act as a low pass filter. Therefore, these higher frequencies are associated with strictly the internal components of the turret. Two notable spectral peaks are at approximately 1 and 2.4 kHz. Neither of these spectral peaks are apparent in the bench measurements however are very prominent in the spectra for the OIRU measurements as well as the reflector mounted laser diode measurements. Between 650 and 750 Hz, there is also a large spike in the spectral content for both the OIRU beam as well as the reflector mounted laser diode beam while the bench measurements show relatively low spectral energy at this frequency. It is likely that these three spectral regions are likely associated with

different excited vibrational modes of optical components within the turret itself as they do not shift in frequency with increasing Mach number.

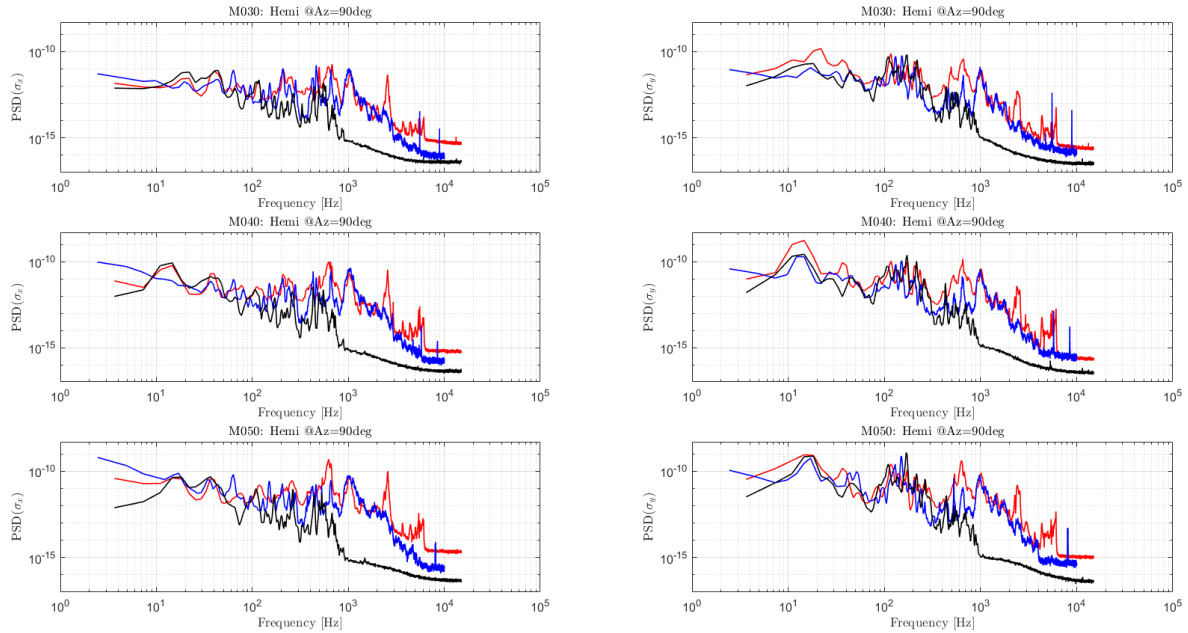


Figure 75. Power spectral density plots for x- and y-jitter at all Mach numbers for the hemisphere configuration at an azimuthal angle of 90 degrees

Figure 76 presents the PSD results for the x-jitter measured from the OIRU beam for all configurations at Mach 0.3, Figure 76(a), and Mach 0.5, Figure 76(b), at an azimuthal angle of 90 degrees. These results are plotted as a function of Strouhal number, $St_D = fD/U_\infty$, where D is the turret diameter and U_∞ is the freestream velocity. Previous studies have found that there are two major modes in the wake dynamics of a turret: antisymmetric, or alternate shedding of vortices off the back of a turret and symmetric vortex shedding. The antisymmetric, unsteady vortex shedding occurs in the normalized frequency range of, $St_D = 0.15 - 0.2$. Emphasized by a red dotted boxes in both subplots in Figure 76, are pronounced peaks located at $St_D = 0.19$. It is believed that these spectral peaks are associated with mechanical contamination due to the unsteady forcing caused by antisymmetric vortex shedding. This is further validated by the increasing energy associated with this spectral peak as a function of turret protrusion into the freestream flow. For the case of the partial hemisphere, the turret is only barely sticking into the flow. Therefore, the wake dynamics for the partial hemisphere case are dominated by symmetric vortex shedding and the unsteady, spanwise anti-symmetric forcing on the turret is minimal. Consequently, for the case of the partial hemisphere, the spectral peak at $St_D=0.19$ is small. On the other hand, for greater turret protrusion into the flow, such as the case of the hemisphere on full cylinder, the peak at $St_D=0.19$ becomes large and it is believed that the dynamics of the wake are dominated by unsteady, alternate vortex shedding. The well documented Strouhal range of 0.15-0.2 for wake dynamics of a hemispherical turret originated from investigating the fluid mechanics of the wake. This does not necessarily mean that the vibrational response of the system should demonstrate the same spectral phenomena however, a peak at $St_D=0.19$, is noticed here in the wind tunnel test results and is consistent across the varying Mach numbers.

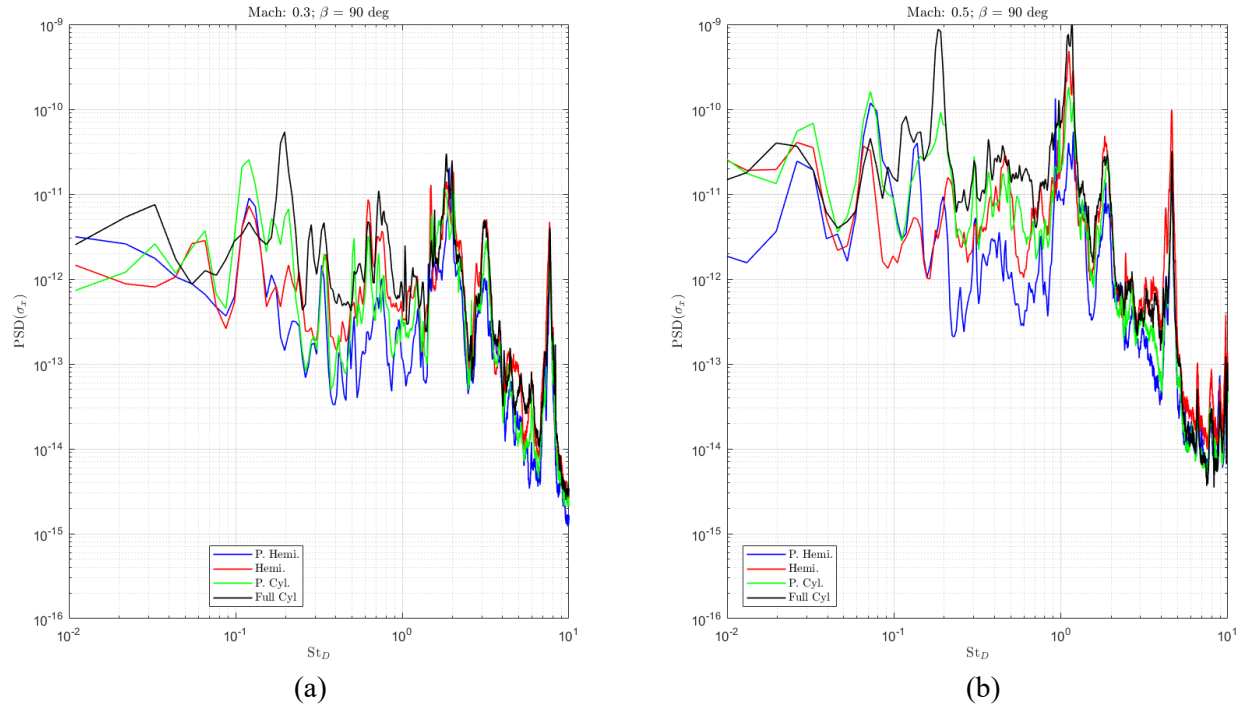


Figure 76. Power spectral density plots of x-jitter measured from the OIRU beam for all configurations at an azimuthal angle of 90 degrees and Mach number of 0.3 (a) and 0.5 (b)

Accelerometer measurements were also collected during the wind tunnel experiments. Although six accelerometers were used, the results associated with the two accelerometers attached to the turret mounting ring are going to be the emphasis of the following analysis. The locations of these accelerometers can be seen in Figure 77. Pre-multiplied power spectrums were calculated for the displacement vectors calculated from these accelerometer measurements for the Mach 0.3 and 0.5 cases, at an azimuthal angle of 90 degrees, and for both the hemisphere and hemisphere on full cylinder configurations. The utility of the pre-multiplied spectra is that it allows one to visually identify the highest contributing energetic frequencies. These results can be seen in Figure 78. Here, the blue line represents the spectrum for the hemisphere on full cylinder and the red line represents the spectrum for the hemisphere configuration. Figure 78(a,c) correspond to the Mach 0.3 cases and Figure 78(b,d) correspond to the Mach 0.5 cases. Additionally, Figure 78(a,b) correspond to the spectra from measurements collected by the streamwise accelerometer while Figure 78(c,d) correspond to the spectra calculated from the spanwise mounted accelerometer. Here it can be seen that in the streamwise direction, the hemisphere configuration produces more mechanical contamination which also significantly increases with Mach number. Peaks in the spectra exist between 650 and 800 Hz and at 1 kHz similar to the spectra of the beam jitter shown in Figure 65. In the spanwise direction, the hemisphere on full cylinder configuration produces more mechanical contamination which also increases with Mach number.

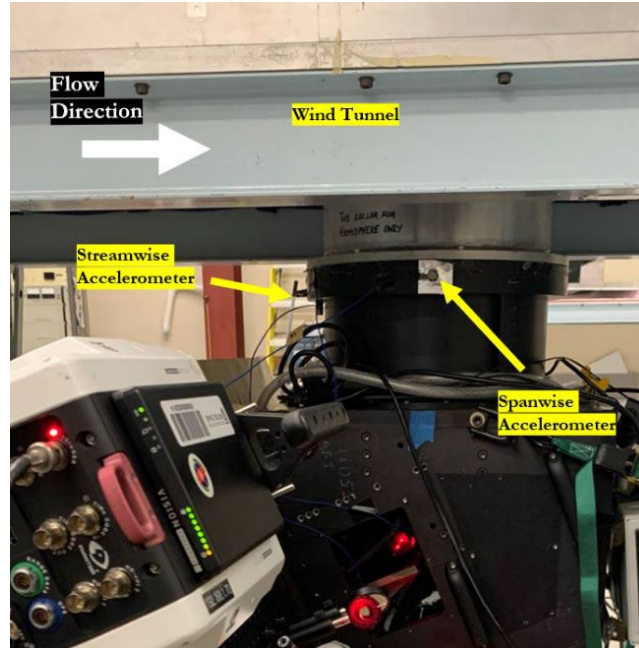


Figure 77. Streamwise and spanwise accelerometer locations attached to turret mounting ring

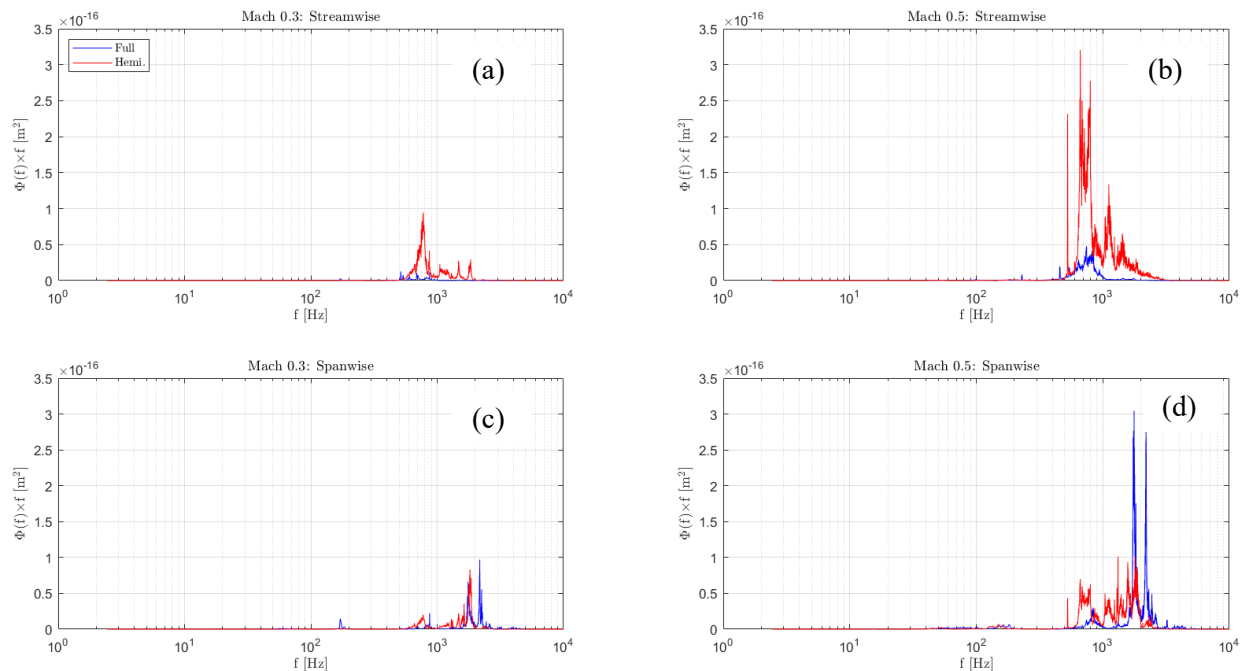


Figure 78. Pre-multiplied power spectral densities of displacement measurements for the hemisphere and hemisphere on full cylinder configurations at an azimuthal angle of 90 degrees. (a) The case of Mach 0.3 for the streamwise accelerometer (b) The case of Mach 0.5 for the streamwise accelerometer (c) The case of Mach 0.3 for the spanwise accelerometer (d) The case of Mach 0.5 for the spanwise accelerometer

AAOL-BC Flight Test Results

Jitter measurements were also collected using AAOL-BC. Figure 79 and Figure 80 present radial jitter results measured on the optical bench mounted green beam as well as the reflector mounted blue laser diode beam for the hemisphere and hemisphere on full cylinder configurations, respectively. As mentioned above, the Mach 0.5 measurements were collected at an altitude of approximately 3050 m (~10,000 ft) as well as 6700 m (~22,000 ft) to have measurement overlap for different dynamic pressures. When the green optical bench laser measurements are divided by two to account for the double pass, the two types of jitter measurements are in agreement with each other. Changing azimuthal angle also very minimally changes the resultant jitter imposed onto the beam. Figure 81 compares the jitter results from the reflector mounted laser diode source for both the hemispherical and hemisphere on full cylinder configurations at all tested Mach numbers. Interestingly, the jitter imposed onto the beam for the two different configurations are very similar across all Mach numbers.

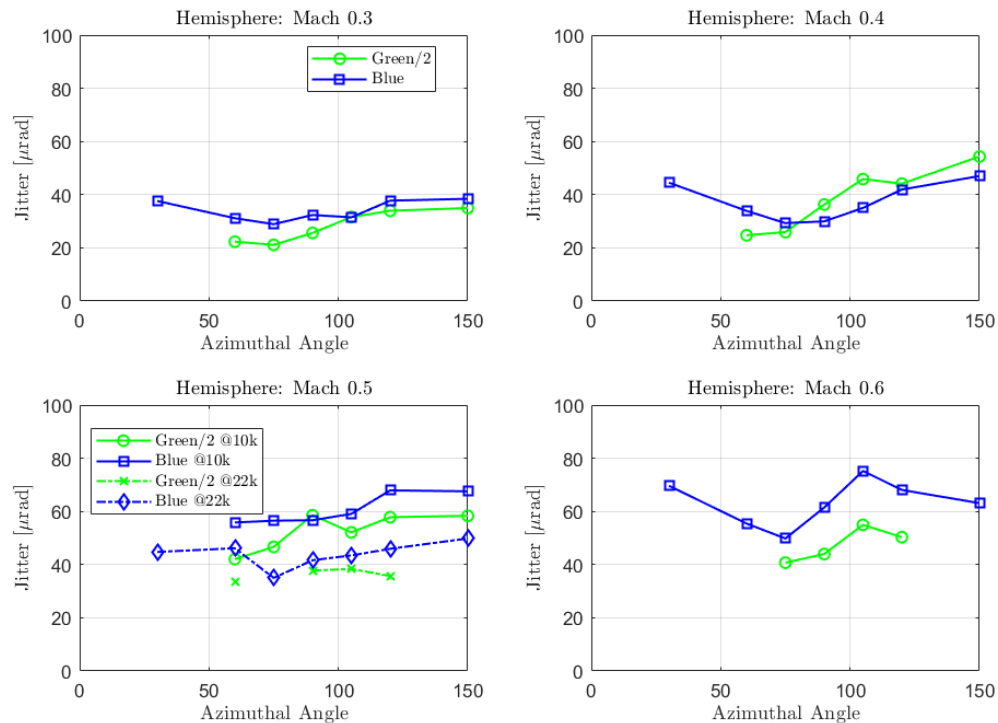


Figure 79. Radial rms jitter results from both the optical bench mounted green beam as well as the reflector mounted blue laser diode beam for the hemisphere configuration

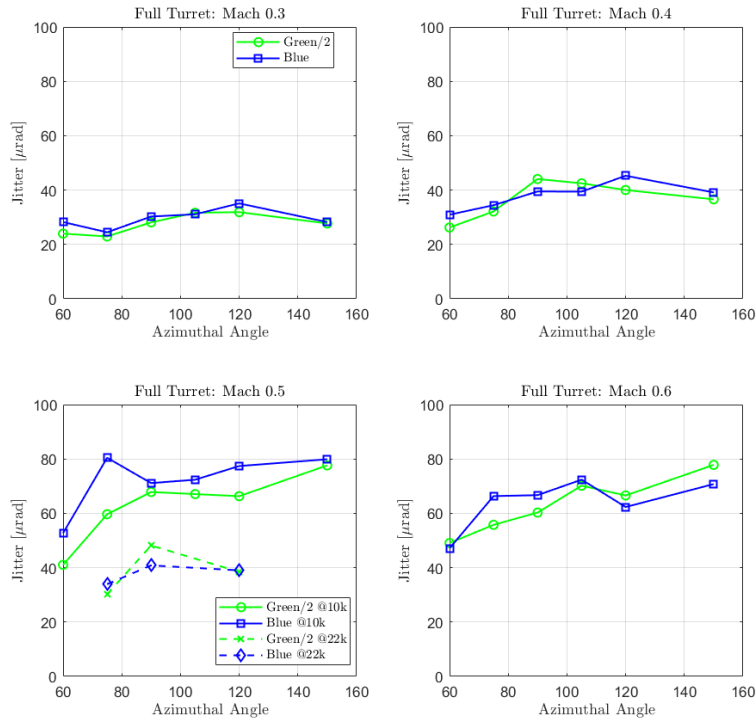


Figure 80. Radial rms jitter results from both the optical bench mounted green beam as well as the reflector mounted blue laser diode beam for the hemisphere on full cylinder configuration

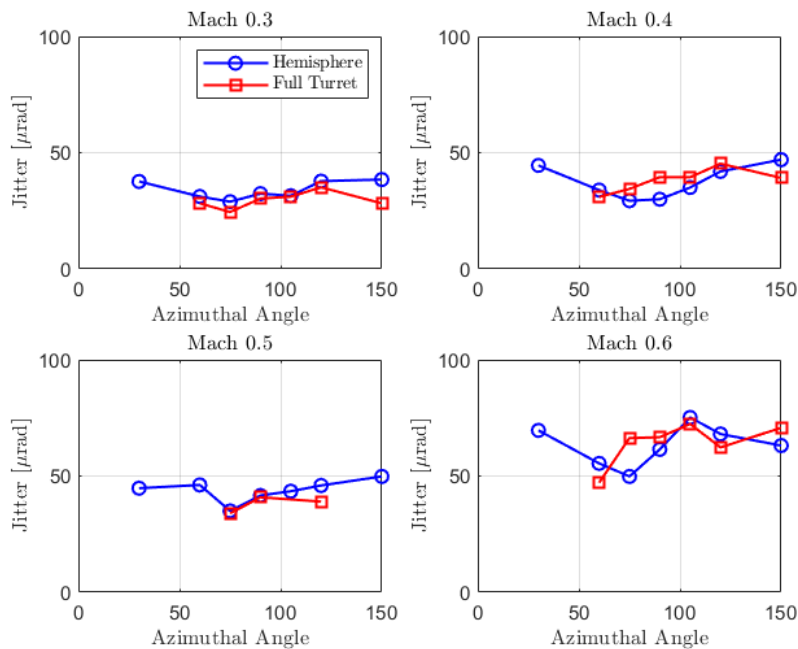


Figure 81. Radial rms jitter plots from the reflector mounted blue laser diode measurements for both the hemisphere and hemisphere on cylinder results

Figure 82 presents the power spectral density calculated from the reflector mounted laser diode measurements for both the hemisphere as well as the hemisphere on full cylinder configurations at Mach 0.3 and 0.5 and an azimuthal angle of 90 degrees. Here it can be seen that, similar to the wind tunnel spectra, high energy spectral peaks exist at around 1 kHz and between 650-750 Hz.

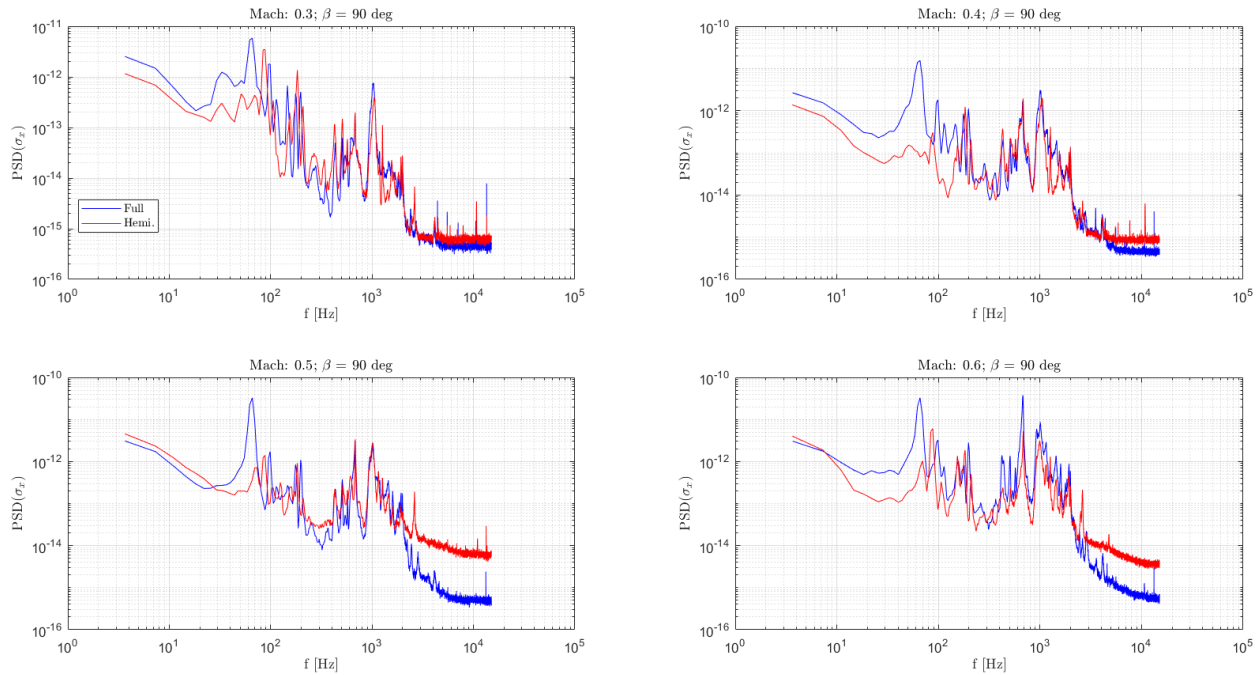


Figure 82. Power spectral density plots of x-jitter measured from the reflector mounted blue beam for the hemisphere and hemisphere on full cylinder configurations at an azimuthal angle of 90 degrees

Accelerometer measurements were also collected during the AAOL-BC tests. The analysis presented below will focus on the accelerometer measurements collected on the aircraft door above and to the side of where the turret mounts. The locations of these accelerometer measurements can be seen in Figure 83. Same as for the wind tunnel tests, pre-multiplied power spectrums were again calculated for the displacement vectors calculated from these accelerometer measurements for the Mach 0.3 and 0.5 cases, at an azimuthal angle of 90 degrees, and for both the hemisphere and hemisphere on full cylinder configurations. The results can be seen in Figure 84. Recall, the accelerometers were sampled three times as fast during flight testing compared to the wind tunnel testing. Therefore, the resulting spectrum spans a wider range of frequencies. It can be seen that a range of frequencies between 800 to 1200 Hz were particularly energetic which is in agreement with the jitter spectrum results plotted in Figure 82. The hemisphere on full cylinder case very clearly created more mechanical contamination as measured by the two door mounted accelerometers compared to the hemisphere configuration.

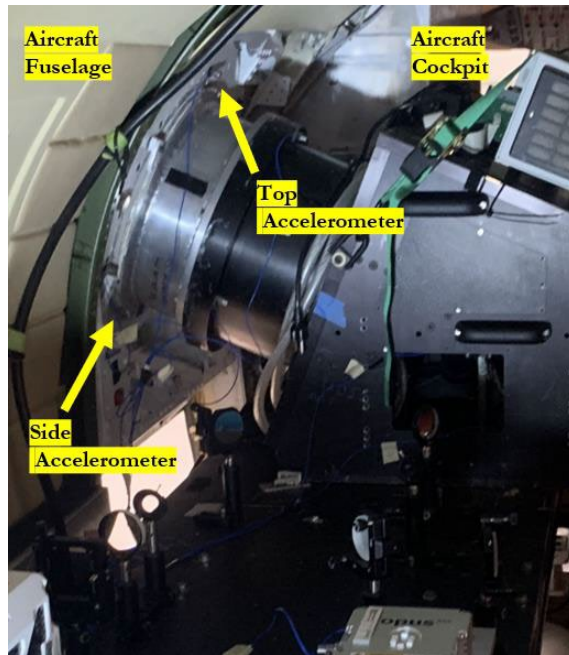


Figure 83. Accelerometer locations in AAOL-BC aircraft

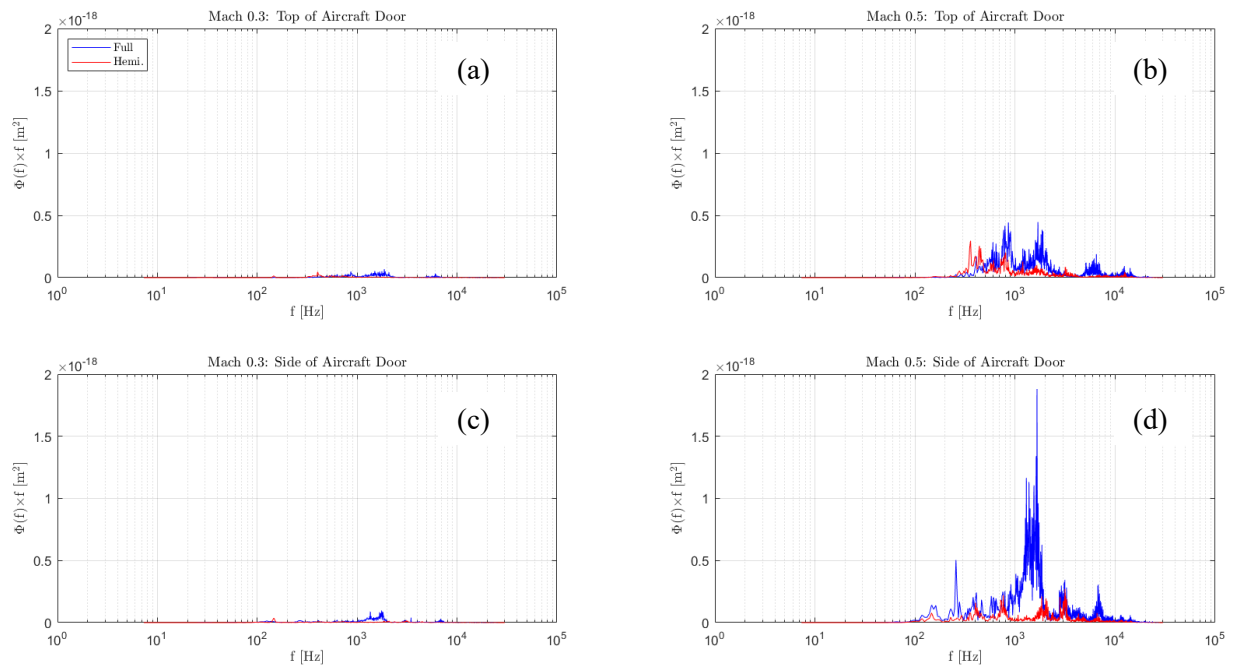


Figure 84. Pre-multiplied power spectral densities of displacement measurements for the hemisphere and hemisphere on full cylinder configurations during in-flight testing at an azimuthal angle of 90 degrees. (a) The case of Mach 0.3 for the streamwise accelerometer (b) The case of Mach 0.5 for the streamwise accelerometer (c) The case of Mach 0.3 for the spanwise accelerometer (d) The case of Mach 0.5 for the spanwise accelerometer

Comparison Between Wind Tunnel and AAOL-BC Test Results

The differences in findings between the wind tunnel tests and the in-flight tests are counterintuitive but not unreasonable. Despite best efforts to keep setups similar between wind tunnel and flight tests, the nature of these experiments is that the measured jitter is inherently susceptible to any differences in experimental apparatuses. Fundamentally, the differences in turret mounting, the base motion of the aircraft, and the difference between being within a wind tunnel facility and aircraft all introduce differences in setup that vibrational modes of system hardware are sensitive to.

Resultant rms radial jitter from both wind tunnel and in-flight testing did increase with Mach number. However, no noticeable scaling patterns were observed. It is believed that vibrational amplitude should scale with dynamic pressure. This was not noticed from either lab testing or in-flight testing results. The reason for this is likely because the experimental components subjected to a varying dynamic pressure only contributed to a portion of the overall resultant jitter. The modes and frequencies which may scale with increasing Mach number were simply washed out by other contaminating sources.

For both the jitter and accelerometer measurements, the distortions associated with lab testing were much greater than in-flight testing. More interesting than the quantitative differences between wind tunnel and in-flight testing are the qualitative differences in the resultant jitter. The wind tunnel test results demonstrated an increase in jitter imposed onto the beam with increasing turret protrusion distance. Although only two configurations were tested for the in-flight campaigns, this trend was not observed. In fact, the resulting rms radial jitter results during the in-flight tests were remarkably similar between the hemisphere and hemisphere on full cylinder configurations. This may be an indication that the increase in jitter with protrusion distance noticed during the wind tunnel tests may be associated with vibrations caused by increased tunnel blockage. The wind tunnel tests also showed more variation in resultant jitter when changing azimuthal angle. This is likely associated with the rigid mounting between the wind tunnel, turret, and optical bench. When the center of gravity of the turret changes due to a change in azimuthal angle in the wind tunnel facility, this change is felt by the entire experimental setup. This is reflected in the wind tunnel bench measurements where changing azimuthal angle changed the resultant jitter for when the beam only encountered optical bench components. In the aircraft, the turret is rigidly mounted to the aircraft door, however the plane itself has no opposite force acting on it. Therefore, forces acting on the turret and subsequently on the aircraft are likely dampened out. For the in-flight campaigns, very small differences in resultant rms jitter were noticed between different azimuthal angles.

The power spectrum results for jitter calculated from the wind tunnel testing revealed a prominent peak at $St_D=0.19$. It is believed that this peak is associated with the unsteady vortex shedding downstream of the turret. During the in-flight testing, no such peak was observed. It is possible that the existence of the wind tunnel walls serves to amplify these wake dynamics and for obvious reasons, this does not happen in-flight. Another possibility for the absence of this peak in the flight test results has to again do with the mounting mechanisms for the wind tunnel and in-flight testing. It is well documented that $St_D=0.15 - 0.20$ is the expected normalized frequency range for the unsteady vortex shedding downstream of the turret. However, for these tests, pressure was not measured. It may be possible that the unsteady pressure between $St_D=0.15 - 0.20$ manifests as $St_D=0.19$ in optical contamination for the wind tunnel tests but not the flight testing. The unsteady pressure field can cause certain vibrational modes but not necessarily at the frequency associated with the pressure field.

This point begins to express the difficulties associated with these experiments. Studying the origins and factors causing mechanical contamination imposed onto the laser beam will require meticulous investigation into the vibrational properties of every system component as well as detailed finite element analysis. Once all the system components vibrational properties and responses are known, the resultant "optical signature" associated with these vibrations should be modeled. Subsequently, experiment testing should be conducted but in an extremely controlled manner. Despite best efforts, the experiments presented here had slight (unavoidable) differences between experimental setups for the different turret configurations. Additionally, when using a wind tunnel facility, for transonic testing it is extremely difficult to decouple the shaking associated with the fan from the shaking of specific turret components.

Studies of the surface pressure fields on and around turret with different amount of protrusion

Power spectral densities were calculated from pressure measurements collected by the back location Kulite, as well as from PSP pressure values extracted from the turret in proximity to this Kulite location. Representative results are presented in Figure 85 where the blue line represents the power spectra from the PSP measurements and the red line represents the power spectra from the Kulite measurements. It can be seen that the two are in agreement. The fluctuations in the PSP power spectra can be further minimized by ensemble averaging over a greater number of local spatial points or by analyzing a longer portion of the time series of these spatial points. The resulting pressure fields from the PSP data were converted into pressure coefficients, C_p . The standard deviation of these C_p fields are presented in Figure 86 as a three-dimensional view, and Figure 87 as a two-dimensional, respectively. The three-dimensional perspective is viewing the backside of the turret and the two-dimensional view is from the top view of the turret. Each row of plots corresponds to a different turret configuration from least to most protrusion. Each column corresponds to each Mach number tested where Mach 0.3 are the left plots, Mach 0.4 are the middle plots, and Mach 0.5 are the right plots. The high Mach number case for the hemisphere on full cylinder configuration was tested at Mach 0.487 instead of Mach 0.5 due to wind tunnel power restrictions.

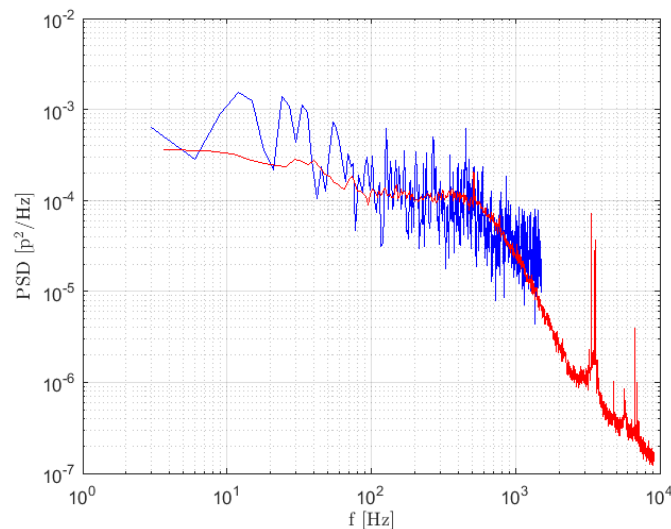


Figure 85. Power spectral density comparison between the back location Kulite and PSP measurements in proximity of this Kulite location

For the partial hemisphere case, it can be seen that the standard deviation remains fairly constant over the turret surface across all Mach numbers. The standard deviation in the wake region and sides of the turret is notably higher for the Mach 0.3 case compared to the Mach 0.4 and 0.5 case. This is due to a weakened signal to noise ratio by normalizing by the tunnel dynamic pressure. The wake region also reveals pronounced and organized increases in standard deviation on either side of turret angled inwards towards the turret centerline. These standard deviation striations are associated with vortex shedding from the portions of the partial hemisphere away from the centerline. Since the turret is only partially protruding into the flow, there is a small stagnation region on the front of the turret and most of the incoming freestream turbulence structures are able to convect over the top rather than around the sides. The narrow wake, made evident by the increases in standard deviation, is associated with the flow that convects around the sides of the partial hemisphere. For the case of the hemisphere, the standard deviation on the turret surface again looks fairly constant, however now a separation line is clearly visible on the top of the turret. The non-uniformities in the separation line on the turret are likely associated with the realistic turret features such as pressure ports, gaps, and small cavities between different turret components. The wake region of the hemisphere configuration also reveals a higher standard deviation

however, the standard deviation of the wake for the hemisphere case is more disorganized than that of the partial hemisphere. This may be associated with a battling between the flow convecting over the top versus around the sides of the turret. Additionally, the wake appears to be much wider for the hemisphere case compared to the partial hemisphere case. This likely suggests that for the partial hemisphere case, the flow remains attached longer than for the cases of greater turret protrusion. Despite only being 38 mm different in protrusion distance, the standard deviation surface plot for the hemisphere on partial cylinder configuration looks very different than that of the hemisphere configuration. The standard deviation on the turret surface across all Mach numbers increases drastically compared to the hemisphere and partial hemisphere cases, and the separation line on the top of the turret is also more pronounced. The wake region has a standard deviation that is markedly higher than that of the hemisphere cases. Since some of the cylindrical base is now showing, there is a larger stagnation region on the frontal portion of the turret. Therefore, more turbulent structures are forced to convect around the sides of the turret. It is expected that the strength of the necklace vortex will increase with larger cylindrical base protrusion. The full turret configuration reveals similar phenomena to the hemisphere on partial cylinder case. A higher standard deviation is noticed on the entire surface of the full turret's hemispherical portion and a clear separation line is visible. Again note that the turret used in these tests is not free from imperfections. The pressure turret used here was designed to match a functioning beam director and as such, crevices and pressure ports are scattered across the turret body. These turret qualities create physically small, yet noticeable pressure variations on the turret. It is important to recognize that these pressure field characteristics are not specific to turret geometry, Mach number, or facility but rather the architecture of the turret used for testing here, and they will not be the emphasized of this report.

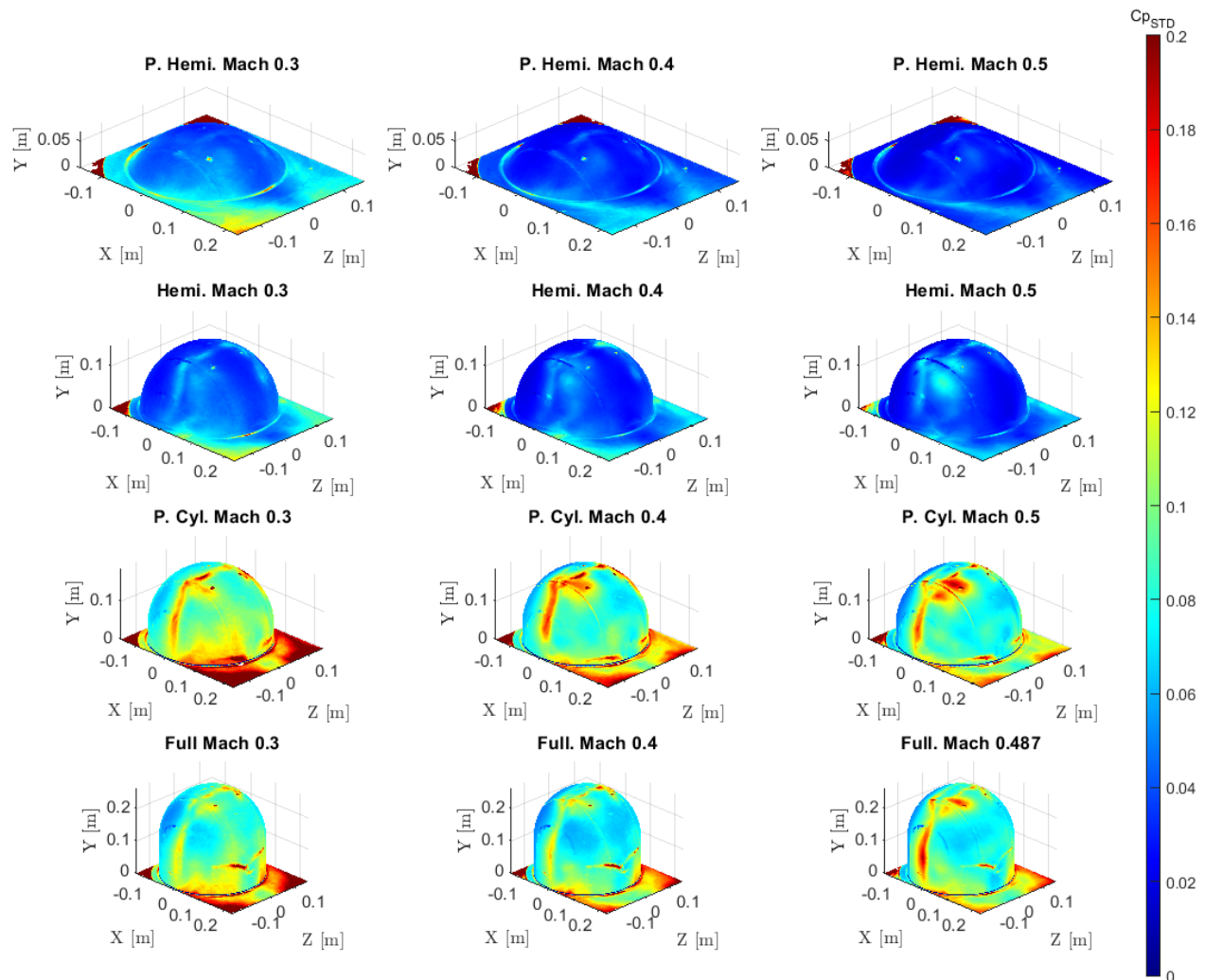


Figure 86. Three-dimensional plots of the pressure coefficient standard deviation surface plots for each configuration and Mach number. Flow goes from left to right

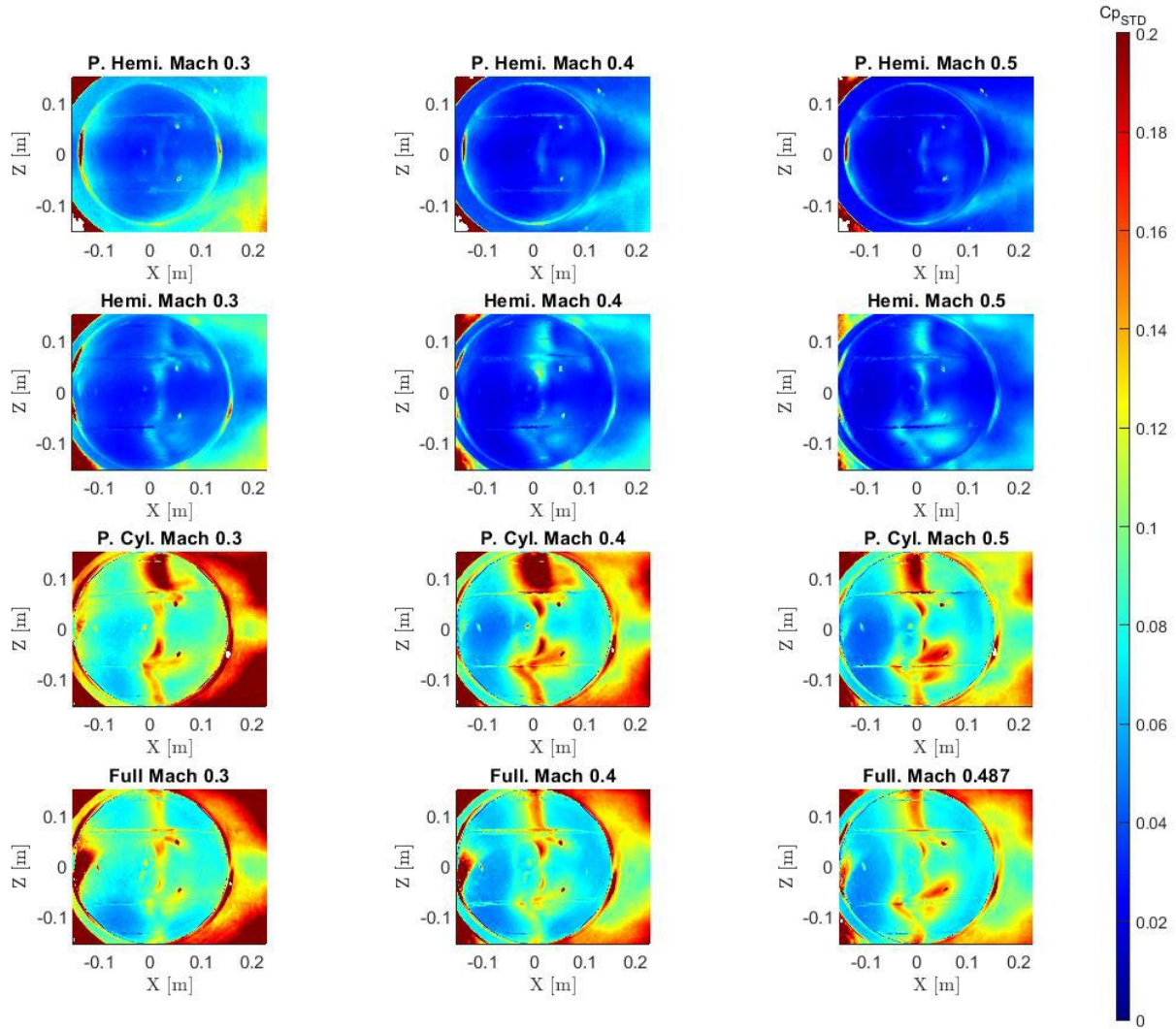


Figure 87. Two-dimensional plots of the pressure coefficient standard deviation surface plots for each configuration and Mach number. Flow goes from left to right

POD analysis

POD was performed on the fluctuating pressure fields to study prominent spatial features in the flow for $M = 0.5$ only. POD was performed for the wake and dome regions together which are shown in Figure 24 as the purple and yellow meshes. This allowed us to relate flow features from the two regions. The first four POD modes for each geometry are shown in Figure 88 along with the modes' associated relative energy. The relative energies of the first ten modes for the three geometries are shown in Figure 89.

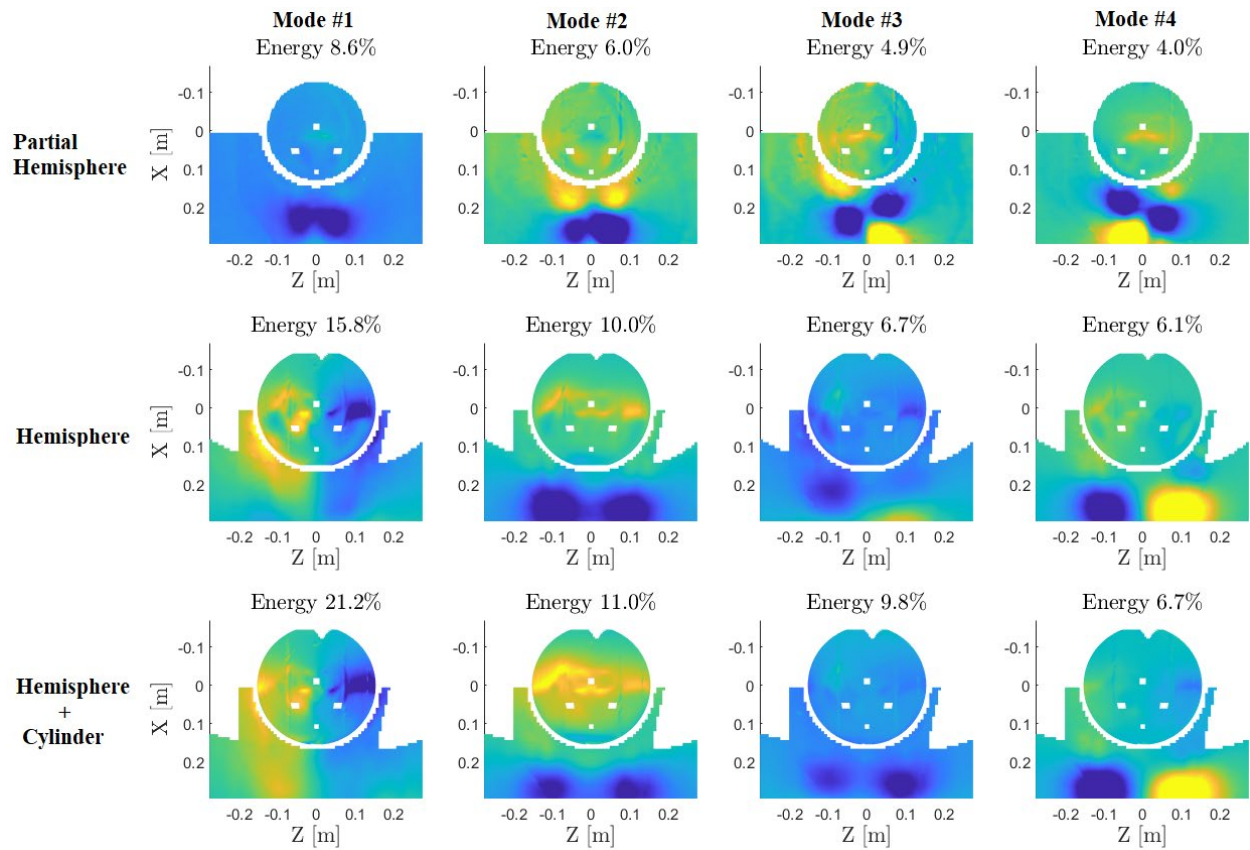


Figure 88. POD modes for each geometry with associated modal energy. $M = 0.5$

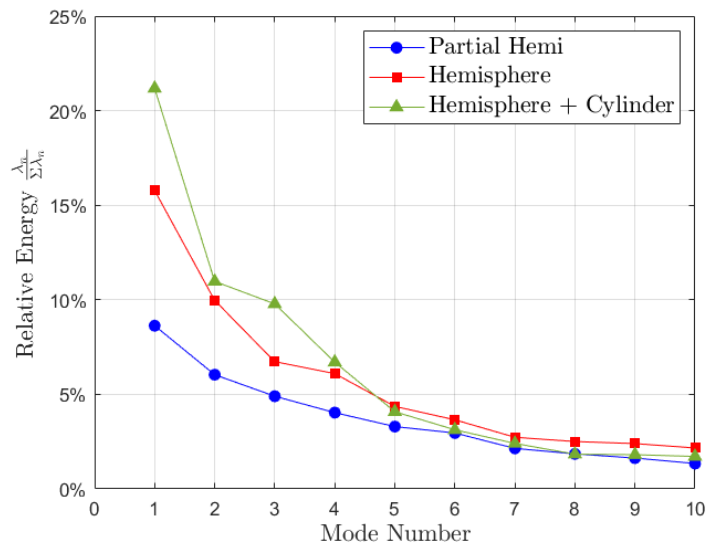


Figure 89. POD modal energy for each geometry. $M = 0.5$

The hemisphere and hemisphere + cylinder geometries have almost identical modes, except the hemisphere + cylinder has higher energy. The first mode contains 16% and 21% of the total energy for the hemisphere and hemisphere + cylinder, respectively. This mode is mostly anti-symmetric in the cross-stream direction. The pressure fluctuations from the separation line are correlated with the separated region of the wake. This correlation is shown in Figure 82 where areas with dark blue are strongly correlated, and yellow regions are anti-correlated with the dark blue region, with green being neutral. The anti-symmetric nature of mode 1 is a result of unsteady alternating vortex shedding that has been seen throughout literature [25, 56, 57]. The second mode for the hemisphere and hemisphere + cylinder geometries, which contains 10% and 11% of the total energy, respectively, looks similar to the C_p , rms(s) maps with the strong correlation on the top of the sphere corresponding to the fluctuations from the separation region. This region is rather thick and not uniform in the cross-stream direction due to the surface features on the top of the hemisphere some of which appear in the POD mode. Also evident is a pair of correlated regions in the wake related to the counter-rotating horn vortices. The flow moving over the top of the turret is pulled downward towards the wall. At the point where this downwashed flow reattaches to the wall, there is a relatively large increase in pressure. For mode 2 this wake reattachment region and the separation region are anti-correlated, which is similar to what [51] described as a wake “breathing” mode. As the separation line moves upstream it causes an increase in pressure on top of the turret, as it is now in the separated region, while at the same time causing a decrease in pressure at the wake reattachment location. The decrease could be because the flow, which separates earlier than the apex, is moving slower so it has less momentum to hit the wall with reattachment. Then if the separation line moves downstream, we get opposite effects. From modes 1 and 2, we see that the separation line on the turret is fairly strongly correlated to the wake structures. It is interesting to note that these two modes contain different wake structures and since POD modes are statistically uncorrelated, the separation zone in mode 1 and the wake reattachment zone in mode 2 were statistically uncorrelated. However, they do both appear in mode 4 so they are not completely independent. The third mode for the two geometries shows correlation of the wake but there is very little correlation with anything on the turret, aside from some regions of the separation line for the hemisphere, which shows a decoupling of the wake from the turrets geometry for this mode. Also, for the hemisphere mode 3, there is a slight asymmetry. Mode 4 shows a strong anti-correlation in the wake similar to mode 1, which is again related to the alternating vortex shedding off of the turret. This mode was also seen in [31] where the alternating pockets continued downstream, which in this case, if the wake region was extended downstream, we would expect to see another set of correlated regions, but with a blue region on the positive Z side and a yellow region on the negative Z side. This mode also has anti-correlation between the dome and the wake as was seen in mode 2. Here, there is also a slight correlation between the flow on the top of the dome, and the flow wrapping around the base of the turret, similar to mode 1.

Fundamentally different behavior is noticed in the POD modes for the partial hemisphere geometry compared to the hemisphere and hemisphere + cylinder geometries. The primary mode, containing 8% of the total modal energy, is symmetric with two pockets of highly correlated fluctuation in the wake corresponding to the reattachment explained previously. As there is very little correlation with any region on the turret, aside from a weak correlation with the short separation line on top of the turret, the wake for the partial hemisphere is mostly decoupled from the turret, which is a prominent departure from the flow dynamics over the hemisphere and hemisphere + cylinder which had strong correlation between the separation line and the wake for the first two modes. The second mode containing 6% of the energy is also related to the vortices in the wake and is also symmetric. However, there is now a region of anti-correlated fluctuation shown in yellow in between the turret and the further downstream wake structure shown in blue. There is a faint blue region on the top of the dome around (0,0), with a faint yellow region on the downstream section of the dome. This mode could be thought of as a companion mode to the first mode showing movement of the reattachment region up and downstream. As the high pressure reattachment region moves upstream, the region upstream would see a pressure increase, while the region downstream which no longer has flow reattaching over it would experience a decrease in pressure. In this case, the yellow region of the mode would correspond to the region of increasing pressure while the blue region would correspond to the

decreasing pressure region. If the reattachment region instead moves downstream, the direction of change in pressure would flip with the yellow corresponding to dropping pressure and the blue corresponding to increasing pressure. Another possible interpretation of this mode would be that the yellow region corresponds to the fluctuation of the reattachment lines along the sides of the separated region, while the blue region is the same as the blue region in mode 1. Modes 3 and 4 are again related to the structures in the wake, but also include contribution from flow over the top of the dome. They are slightly asymmetric both in the wake and on the dome, but not as anti-symmetric between positive and negative Z as seen in mode 4 for the other geometries. The asymmetries are slightly offset which may be explained by a much less dramatic alternation in the vortices shedding mostly from the top instead of around the sides of the turret. This mode seems to be approaching the alternating vortices seen in mode 4 for the hemisphere and hemisphere + cylinder. These modes all look fairly similar and from all of them together, we can see the vortex structures fluctuating and shedding downstream. From these modes we can also see that the wake is getting larger as protrusion increases, based on the size of the dark blue region in mode 1 for the partial hemisphere and mode 2 for the hemisphere and hemisphere + cylinder. In the plot of modal energies of the different geometries in Figure 83 we can see that the flow grows more “organized” as protrusion increases as the leading modes contain more of the total energy of the system. The first three modes for the hemisphere and hemisphere + cylinder contain 32% and 42% of the total energy respectively, whereas for the partial hemisphere the first three modes only contain 20% of the total energy.

To understand the temporal dynamics of these dominant structures in the pressure field, spectra of the time coefficients for the first four modes of each geometry were calculated. The spectra were calculated using a Hanning window and block averaged using 10 blocks. The results which can be seen in Figure 90. Spectra of time coefficients for POD modes 1-4 for each geometry. $M = 0.5$ are plotted against Strouhal number, $St_D = fD/U_\infty$, which is then normalized frequency based on the turret diameter.

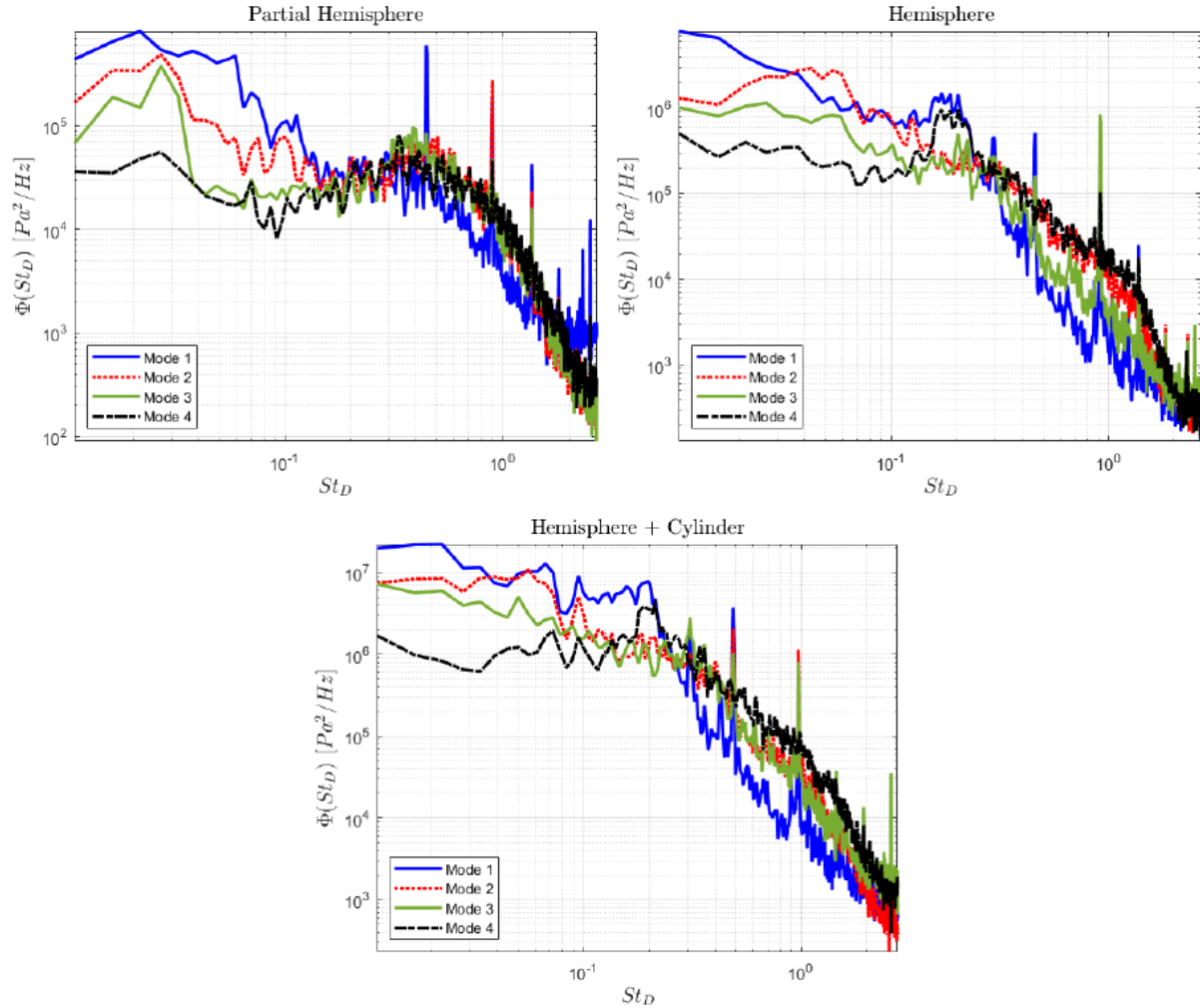


Figure 90. Spectra of time coefficients for POD modes 1-4 for each geometry. $M = 0.5$

For the hemisphere, spectra are shown in the top right plot of Figure 90. Spectra of time coefficients for POD modes 1-4 for each geometry, $M = 0.5$. The anti-symmetric Modes 1 and 4 have noticeable peaks at $St_D \approx 0.18$. This is consistent with results obtained in [25,31] and is associated with anti-symmetric vortex shedding. The spectra of modes 2 and 3 for the hemisphere do not have any noticeable peaks. The hemisphere + cylinder case shown in the bottom plot of Figure 90. Spectra of time coefficients for POD modes 1-4 for each geometry. $M = 0.5$ does not have a distinct peak for the first mode, but rather has high energy for all low frequencies up to $St_D \approx 0.2$, above which it drops off. For mode 4 there is a clear peak at $St_D \approx 0.2$. As with the hemisphere, modes 2 and 3 do not have any prominent peaks. For the partial hemisphere the first mode has high energy in the lower frequencies with a peak at $St_D \approx 0.27$, while modes 2-3 have a clear hump that peaks around $St_D \approx 0.45$. These peak fall in the range of $St_D = 0.2-0.5$ that is associated with symmetric vortex shedding [57]. There are also sharp peaks throughout the spectra that are likely from the equipment electronic noise. In addition to having a peak at a different location compared to the hemisphere and hemisphere + cylinder spectra, the partial hemisphere has a much different spectra shape with a much more gradual hump. For all modes and turret geometries, the lower frequencies $St_D < 0.5$ contain most of the spectral energy. It is worth noting that the partial hemisphere modes 3 and 4 have a higher peak frequency than mode 4 for the hemisphere and hemisphere + cylinder, as these modes seem similar. As suggested before, it seems like the partial hemisphere modes 3-4 would turn into hemisphere mode 4 as the protrusion is

increased and based on the spectral peaks, we can see the frequency would decrease as well. A possible source of this change could be the separation occurring on the turret, which seems to increase greatly in strength and correlation with the wake between the partial hemisphere and hemisphere, based on its presence in the first two modes. Also, it is a bit unusual how the correlation is not very strong for the separation line in any of the modes for the partial hemisphere, suggesting weak separation dynamics. These results also somewhat disagree with previous numerical studies where separation over a partial hemisphere was clearly evident [58, 59], so additional studies are needed to resolve this issue. In the partial hemisphere mode 3, the unsteady separation line is a little clearer extending from about $Z=0.05$ all the way to the edge of the turret at about $Z=-0.1$.

Joint POD Analysis

While we can gain good insight into the effects of different protrusions through POD, JPOD allows for a much more direct comparison of the prominent flow features between different geometries. The pressure fluctuation data was used to perform JPOD analysis. The first five modes are shown in Figure 91. These modes are almost identical to the regular POD modes of the hemisphere and hemisphere + cylinder and follow the same interpretation. Mode 5 for the POD was not shown, however, for the hemisphere and hemisphere + cylinder it was also similar to the JPOD mode 5. This mode has a pair of correlated structures in the wake colored yellow that are anti-correlated with another pair of structures downstream which are shown in blue, and also anti-correlated to the separation line region on top of the dome, also blue. This mode is similar to the POD mode 2 for the partial hemisphere and is related to the wake “breathing.” As explained for the partial hemisphere mode 2, this JPOD mode 5 can be thought of as a companion mode to JPOD mode 4, corresponding to the up and downstream movement of the reattachment point.

In the plot of energy shown in Figure 92(a) the shift in dominant modes between the partial hemisphere and hemisphere is obvious. The primary mode for the partial hemisphere is mode 3, with 19% of the total energy, which is a symmetric mode related to the wake, where the most energetic mode for the hemisphere and hemisphere + cylinder is mode 1, with 13% and 17% of the total energy, respectively, which is an anti-symmetric mode related to the separation off the sides of the turret and the separated region. Mode 2 is the second most energetic mode for the hemisphere with 10% of the total energy and is the third most energetic for the hemisphere + cylinder containing 13%. For the partial hemisphere, this mode has a lower relative energy of 6%. Interestingly, however, this mode is still the second most energetic for the partial hemisphere; showing there is in fact some inverse relation between the flow on top of the turret and the wake for the partial hemisphere, despite not showing up clearly in the POD modes.

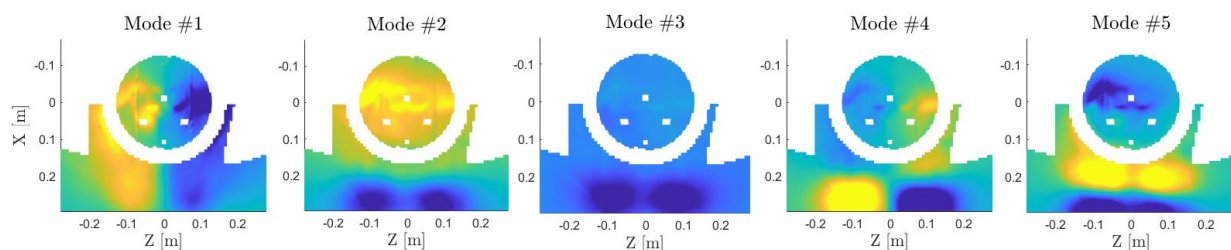


Figure 91. JPOD modes for $M = 0.5$

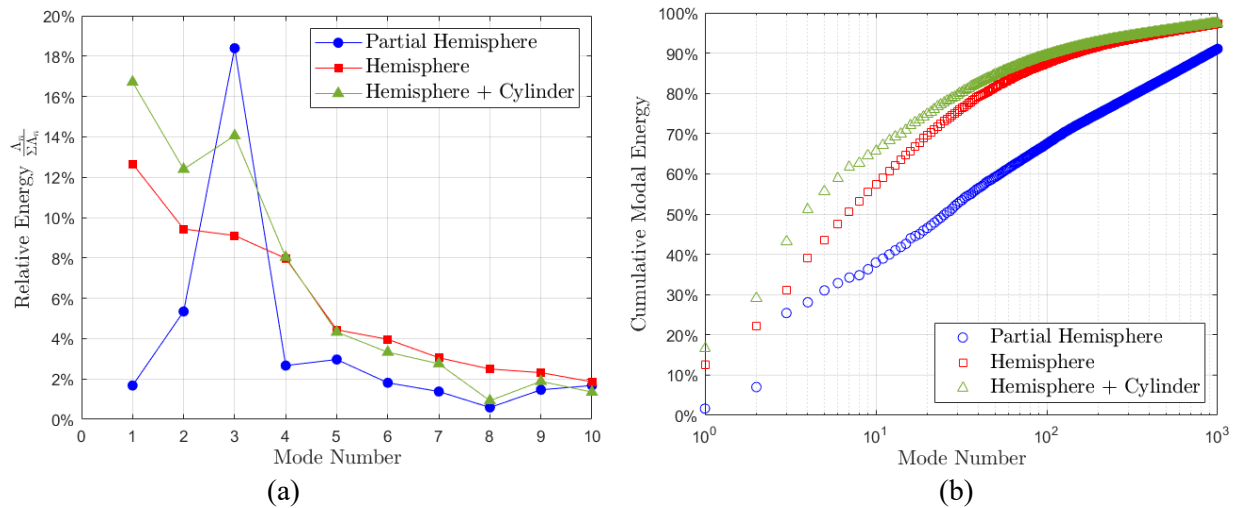


Figure 92. JPOD mode (a) individual energy and (b) cumulative energy for each geometry, $M = 0.5$

Mode 3 is prominent for all three geometries being the most energetic mode for the partial hemisphere (18%), the second energetic mode for the hemisphere + cylinder with 14% of the energy, and the third energetic mode for the hemisphere with 10%. This leads us to conclude that a coherent wake is a significant flow feature for all geometries. As for mode 1, while it is the primary mode for the hemisphere and hemisphere + cylinder, it is not even in the top 5 modes for the partial hemisphere case with less than 2% of the total energy. Therefore, between the 45% protrusion of the partial hemisphere and the full hemisphere protrusion, the anti-symmetric separation and “horn” vortices grow more prominent. With the increased protrusion, the separation in general becomes stronger, and mode 2 also increases in relative strength. It doesn’t appear as though mode 3 loses energy as protrusion increases, since this mode has relatively high energy for all geometries. Mode 4 seems like a combination of modes 1 and 2, with anti-correlation side to side and dome to wake. Mode 5 is similar to mode 2 with anti-correlation between the separation line and the wake, however, there is an additional anti-correlated wake region. This mode is the 3rd highest energy mode for the partial hemisphere, and it is similar to the partial hemisphere’s POD mode 2. However, despite being the third mode, it only holds a relatively low 3% of the total energy. For the hemisphere and hemisphere + cylinder, this mode is the fifth most energetic, however, it holds a higher portion of energy than the partial hemisphere at 5% of the total energy.

From the cumulative energy plot in Figure 92 (b) we can get an idea of the organization of flow for the different geometries. As protrusion decreases, the cumulative energy decrease consistent with the smaller $C_{p,rms}$ values observed in Figure 86 and Figure 87. The hemisphere + cylinder is most organized requiring about 110 modes to have 90% of the total energy, while the hemisphere requires about 150 modes, and the partial hemisphere, which is significantly less organized, requires about 900 modes to reach 90% of the total energy.

Spectra of the time coefficients for the first four JPOD modes of each geometry were calculated using a Hanning window and block averaging with 16 blocks that are 0.33 seconds in length. The spectra of the first three modes are plotted versus Strouhal number, St_D , in Figure 93. For mode 1 corresponding to the asymmetric correlation, the spectra of the hemisphere and hemisphere + cylinder look similar to the spectra of their POD mode 1 which is expected as the JPOD and POD mode 1 look very similar. Both have a peak at $St_D \approx 0.19$, which again is associated with the asymmetric vortex shedding. The hemisphere + cylinder case has a clearer peak with less energy in the lower frequencies below $St_D \approx 0.19$ than the spectra of its POD mode 1. The partial hemisphere has much lower energy in the lower frequencies than the other two geometries, with a peak at $St_D \approx 0.4$. The energy for frequencies higher than this drops off, following the spectra of the hemisphere fairly closely. For mode 2 corresponding to

the separation-wake relationship, the hemisphere and hemisphere + cylinder both have higher energy for the lower frequencies that decreases for higher frequencies with no prominent peaks. The partial hemisphere, however, has lower energy for the lower frequencies and has a slight peak around $St_D \approx 0.45$, then dropping off for higher frequencies, again following closely the spectra of the hemisphere. For mode 3, which corresponds to the strong correlation in the wake, the hemisphere and hemisphere + cylinder have higher spectral energy at lower frequencies, with a slight peak at $St_D \approx 0.3$, and dropping off for higher frequencies. This falls within the range of Strouhal numbers, $St_D \approx 0.2 - 0.5$, expected for symmetric vortex shedding [57]. The partial hemisphere again has lower energy compared to the other two geometries in the higher frequencies with a peak around $St_D \approx 0.45$, then drops off, following the hemisphere spectra.

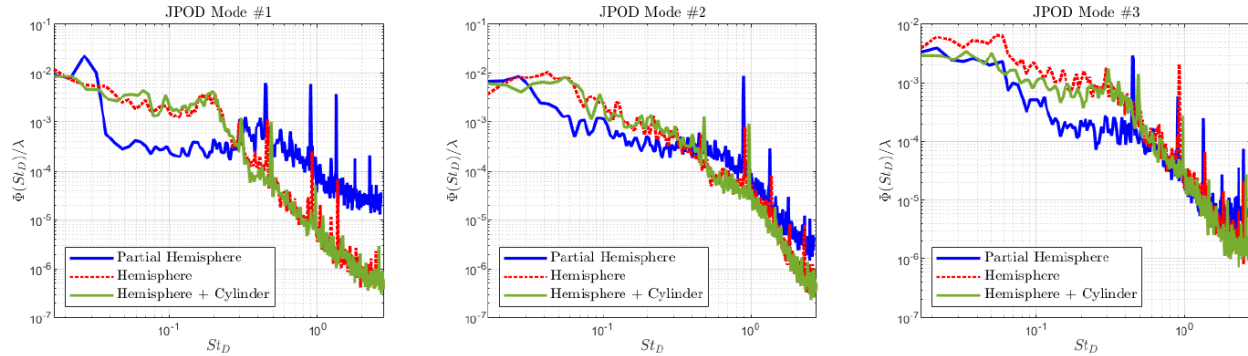


Figure 93. JPOD spectra, normalized by modal energy. $M = 0.5$

The spectra were normalized by the energy for a given mode, λ_n , to better compare the relative distribution of energy for the different geometries, which is shown in Figure 93. The hemisphere and hemisphere + cylinder collapsed very well for modes 1-3. The spectra of the partial hemisphere, however, has a much different shape and doesn't collapse as well. For mode 3 it remains well aligned with the hemisphere, and now the hemisphere + cylinder as well, for higher frequencies. For frequencies between $St_D = 0.06 - 0.4$ the partial cylinder has lower energy than the hemisphere and hemisphere + cylinder. This overall agreement for the three geometries is expected as mode 3 is significant for all three geometries. It also makes sense that there is a drop in energy for the lower frequencies, as these are generally more associated with asymmetric vortex shedding, where the symmetric vortex shedding tends to occur at higher frequencies [57]. For the partial hemisphere, mode 2 has lower energy for the lower frequencies $St_D < 0.4$ and higher energy for the higher frequencies $St_D > 0.4$. For the partial hemisphere, the spectral peak in mode 1 is at a higher frequency than the other geometry's peaks, with its lower frequencies having lower energy and its higher frequencies having higher energy. Overall, the energy of this mode is distributed more evenly across different frequencies than it is for the other geometries.

Normalizing by modes' energies helps to collapse the hemisphere and hemisphere + cylinder cases quite well since their spectra have similar shapes. However, the partial hemisphere has a very different shape so dividing by mode energy just offsets it upward. From Figure 93, we can see how the partial hemisphere and hemisphere align very well for the higher frequencies. It seems that as the protrusion increases, only the lower frequency energies of these modes increase, up until the full hemisphere is reached. At this point, the energy at all frequencies increases as the cylinder brings the hemisphere away from the wall and more flow is organized into these modes.

Force analysis

Since this work is concerned with investigating how the surface pressure field is acting on the turret for various geometries and Mach numbers, it is straightforward to extend the analysis to calculate what the resultant net forces are acting on the turret [54]. By integrating the surface pressure field over the

turret, a resultant net force can be calculated as described by, $F_i = \int_S p(s) n_i(s) ds$, where $n_i(s)$ is the unit inward normal vector. For each turret configuration, the pressure field is discretized using a Delaunay triangulation. The area and unit vector of each local triangle on the turret surface is calculated. Figure 94 presents the normalized rms net force calculated over the turret for each turret configuration and Mach number. The net force is normalized by dynamic pressure and the cross-sectional area of the turret. Only the normalized net force results acting in the spanwise direction are presented. Since two cameras were used to extract three-dimensional surface pressure measurements around the turret and the wake, sides, and backside of the turret were the primary regions of interest, the front and top of the turret were not imaged sufficiently to make accurate net force calculations in the streamwise and wall normal direction. Generally, in the spanwise direction, the greater the protrusion, the more net force imposed onto the turret. The spanwise antisymmetric shedding, discussed in this report, is the most probable cause for the higher normalized net force in the spanwise direction at larger turret protrusions. The partial hemisphere configuration has minimal spanwise net force since there was minimal unsteady forcing acting in this direction.

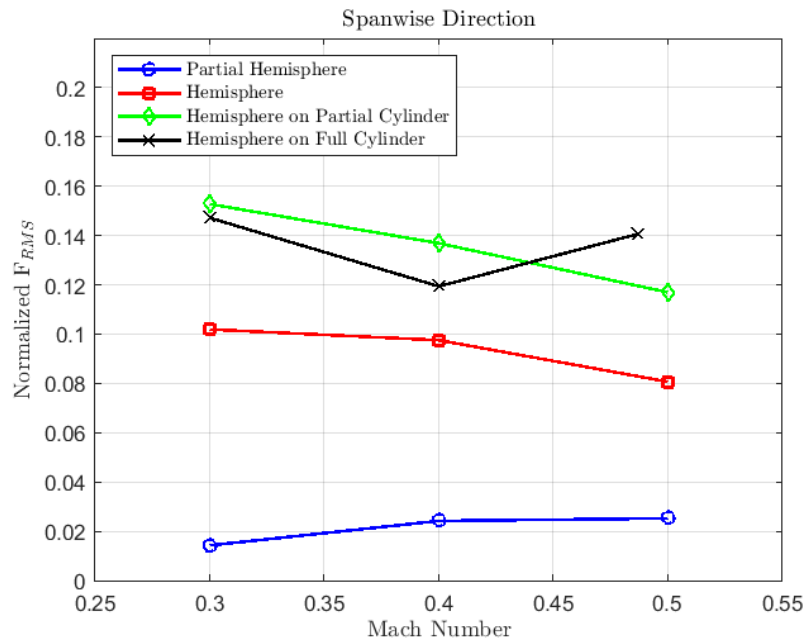


Figure 94. Normalized force rms calculated on the turret pressure field for each configuration and all Mach numbers in both the streamwise and spanwise directions

Topic 4: Focused Malley probe as spatially localized aero-optical sensor

Results for Jitter probe

A plot of the power spectra of the beam jitter at different beam apertures for Mach 0.4 flow is shown in Figure 95. The spectrum for the smallest beam corresponds to the local beam jitter, since there is no attenuation due to beam size for this beam. The shape of the spectrum agrees with similar measurements of the local beam jitter in turbulent boundary layers [9]. As the beam aperture gets larger, the attenuation of the beam jitter spectra begins at higher frequencies, and the lower bound of attenuated frequencies shifts to the smaller frequencies. This behavior is expected because the effect of the larger beam apertures should be to spatially average beam jitter from small-scale structures in the boundary layer that correspond to higher frequencies in the power spectra. There are a few factors in this plot not due to aero-optical effects that should be explained. The higher amplitude noise at frequencies below 1 kHz is mostly due to mechanical vibrations that are present when the wind tunnel is in operation, and the power spectra for different apertures in this range tend to converge. At the higher frequency end, these plots tend to reach a noise floor, which varies slightly for each measurement set. This noise floor due to the sensor/electronics noise masks any of the signal below it. In addition, all of the sharp spikes near 20 kHz and above 30 kHz in the spectra are due to electronics/sensor noise. Both the noise floor and the mechanical vibrations are left in Figure 95.

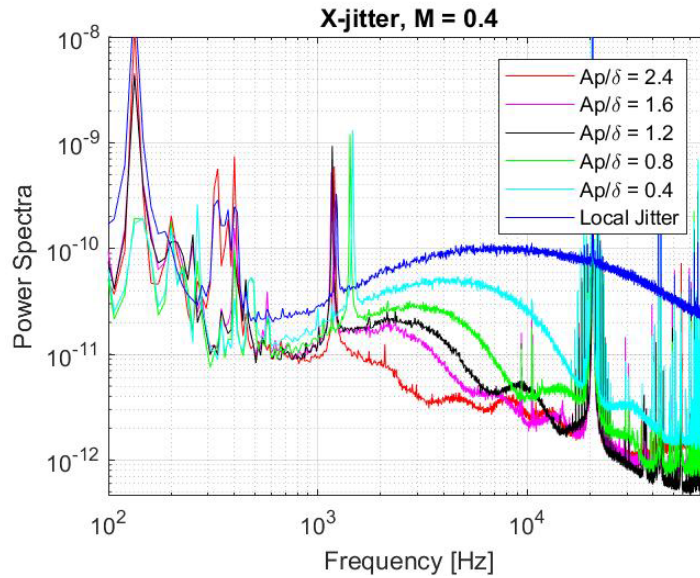


Figure 95. Power spectra of global beam jitter for different beam apertures in the streamwise direction at a free stream Mach number of 0.4

In [60] it has been shown that the theoretical ratio of global jitter spectral amplitude to local jitter spectral amplitude for one-dimensional periodic wavefront in the streamwise direction can be expressed through the aperture dependent transfer function, called $G_{Stream}(z)$,

$$G_{Stream}(z) = \frac{|\theta_G(f; Ap)|}{|\theta(f)|} = 2 \left[\sin(\pi z) - \pi z \cos(\pi z) \right] / (\pi z)^3 \quad (26)$$

where the parameter $z = Ap/\lambda$ is the aperture diameter divided by the spatial wavelength. For convective structures traveling at the same speed of U_c , the spatial wavelength is defined as $\lambda = U_c/f$, where of convective velocity U_c is approximately 0.82 of U_∞ for subsonic boundary layers. Z-parameter is related to the aperture-based Strouhal number as:

$$z = \frac{Ap}{\Lambda} = \frac{Ap}{U_c / f} = \frac{Ap \cdot f}{U_c} = \frac{Ap \cdot f}{U_\infty} \frac{U_\infty}{U_c} = \frac{1}{0.82} \frac{Ap \cdot f}{U_\infty} = 1.22 St_{Ap} . \quad (27)$$

Figure 96 shows the ratios of the global jitter power spectra to the local jitter power spectra for various beam diameters, expressed as Ap/δ -parameter as a function of z (or equivalently, as a function of St_{Ap}). The model in Eq. (8) predicts that all spectra ratios should collapse onto a single curve. Indeed, all spectral ratios exhibit a collapse for $z < 1$ and collapse fairly close to each other for higher values of z , possibly due to noise interference having more of an effect as the signals get weaker and approach the noise floor. For all tested beam diameters, the ratios monotonically decrease for all $z < 1$. When $z > 0.8$, which corresponds to $St_{Ap} > 0.65$, the power spectra ratios are less than 0.1, indicating that due to the aperture-averaged effect, amount of spectral power of the global jitter at higher-frequency range is suppressed by more than one order of magnitude. All spectral ratios exhibit a small secondary peak between $z = 1$ and 2.5, and even smaller tertiary peak above $z = 2.5$.

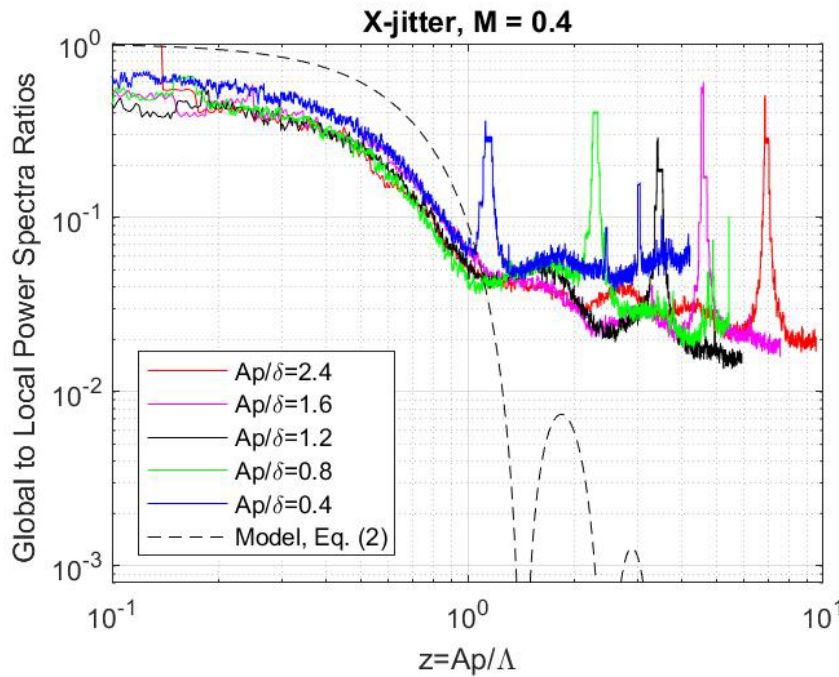


Figure 96. Ratios of global to local beam jitter power spectra for different beam aperture sizes in the stream-wise direction, processed with a smoothing algorithm to reduce noise, at a free stream Mach number of 0.4. The squared G-function is also presented as a dashed line for comparison

The square of the aperture dependent transfer function from Eq (8) is also plotted in Figure 96 for comparison. The model correctly describes a qualitative behavior of the experimentally-observed power spectra ratios, including a monotonic decrease for small $z < 1.5$, and the presence of the secondary and the tertiary peaks between $z = 1.5$ and 2.5 and between $z = 2.5$ and 3.5, respectively. However, the model-predicted attenuations are much stronger than the experimentally-observed ones. One reason for the amplitude mismatch is that the model was developed for one-dimensional wavefronts, and therefore implying a spanwise uniform wavefronts. The actual wavefronts are highly two-dimensional, contributing to larger values of the global jitter.

These experimental results demonstrate that indeed the corrupting effects due to the tunnel wall boundary layers on the global jitter can be suppressed if the aperture of the beam passing through the boundary layer is large enough. For instance, as discussed earlier, in order to achieve an attenuation of

more than an order of magnitude, z should be larger than one, which corresponds to $St_{Ap} > 0.65$. Recalling the definition of Shrouhal number, $St_{Ap} = \frac{Ap \cdot f}{U_\infty}$, this implies that the boundary-layer related effect on the global jitter spectrum will be small for frequencies $f > 0.65 \frac{U_\infty}{Ap}$.

These results can be used to help determining the size of beam needed to effectively eliminate jitter effects from the optical distortion from the boundary layers so that the flow features of interest at the focus location will be more easily recognizable when analyzing the power spectra. The end goal of the work is to develop a focused version of the Malley probe that will utilize the effect of spatial averaging to attenuate the effect of the tunnel wall boundary layers on beam jitter, while still being sensitive to features within the free stream of the test section near the focal point.

In order to obtain an accurate measurement for the separation between the two focal points at the measurement location inside the tunnel, the high-speed camera was moved in place of the test section and translated to have these focal points on the camera sensor. The separation between these focal points was then measured in pixels and converted to meters. This separation distance of 5.15 mm was kept constant throughout the experiments, with the exception of Case 1 at 110 kHz, which was taken earlier and had the spot separation measured to 5 mm with a ruler.

Results for Focused Malley probe

The streamwise jitter power spectra for both beams of the focused Malley probe for Case 1 with a C/L ratio of 20% is shown in Figure 97(a). The spectrum taken from a conventional jitter probe, consisting of a small aperture laser beam, is shown for comparison. It should be noted that this was the only test case without the focal point separation distance measured precisely with the camera. While there is a noise floor and some spikes due to noise, the peaks at twice the vortex shedding frequency of 19 kHz and to a lesser extent the peaks at the vortex shedding frequency of 9.5 kHz are clearly resolved by the focused Malley probe. The peak at twice the vortex shedding frequency is much stronger, as expected, due to vortices shedding off both sides of the cylinder and mixing in the wake. This effect was also observed in the previous experiments for the same flow with the focused jitter probe [45]. As it will be shown later, the signal from these two peaks is still sufficient to obtain a cross-correlation between the two focal points for a convective velocity measurement. For runs with large C/L ratios and lower sampling frequencies, the global jitter spectra also exhibit signs of aliasing above 20 kHz. This is due to the lower sampling frequency of the focused Malley probe with large C/L ratios compared to the conventional jitter probe.

For the phase plot for Case 1 shown in Figure 97(b), there is a clearly visible slope trend from around zero to 40 kHz, which is also consistent with other test cases, and this frequency range was used to compute the linear fit over the unwrapped phase for all test cases unless stated otherwise. The R^2 value of 0.92 for the linear fit shows a high degree of correlation, and the phase slope yielded a convective velocity of 125 m/s and a U_c/U_∞ ratio of 0.826. This value of the convective speed is consistent with the expected value of the convective speed in the wake downstream of the cylinder of about 0.8-0.9 of the freestream speed.

The streamwise jitter spectra and phase plots for Case 2 at a C/L ratio of 20% are shown in Figure 98. There are more points deviating from the fit than for Case 1, but there is still a clear slope trend visible in the selected frequency range. It is worth noting that the points which deviate from the slope trend tend to be at the same frequency as the spikes at the vortex shedding frequency and twice the vortex shedding frequency. At these frequency values, for both test cases with C/L ratios of 20%, the phase goes to zero. Frequencies with zero phase values usually indicate the presence of mechanical contamination, and the observed zero phases may be due to shedding-related vibrations at these frequencies being imposed on the tunnel glass. The R^2 value was 0.89 for the linear fit, and the phase slope yielded a convective velocity of 138 m/s and a U_c/U_∞ ratio of 0.907, which is similar to the value computed for Case 1.

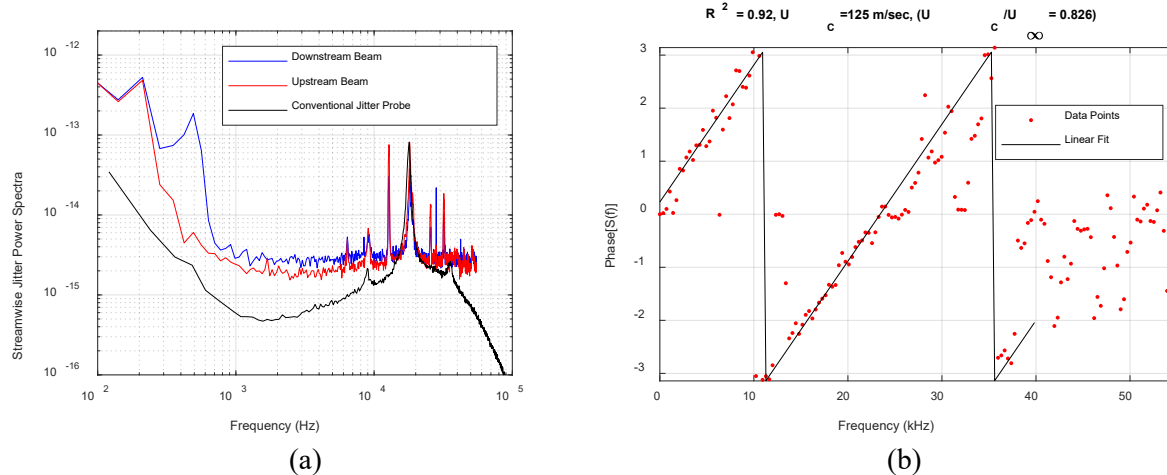


Figure 97: Case 1, Focused Malley probe streamwise jitter (a) power spectra and (b) phase plot for Mach 0.44 flow 5.5 diameters downstream of cylinder, with a C/L ratio of 20% and $L = 425$ mm, sampled at 110 kHz

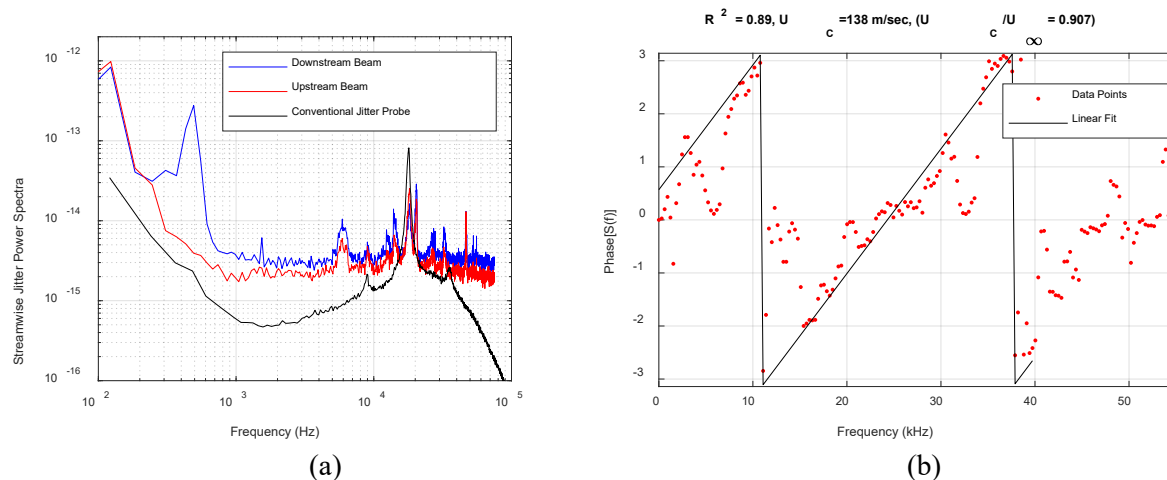


Figure 98. Case 2, Focused Malley probe streamwise jitter (a) power spectra and (b) phase plot for Mach 0.44 flow 5.5 diameters downstream of cylinder, with a C/L ratio of 20% and $L = 405$ mm, sampled at 150 kHz

Figure 99 shows the spectra and the phase plots for a lower ratio of C/L ratio of 15%. At this ratio, there are some significant noise spikes present in the jitter spectra, as shown in Figure 99(a), at higher frequencies, which likely contributed to the deviation at higher frequencies in the phase plot shown in Figure 99(b), but the spikes in the spectra at the vortex shedding frequency and twice the vortex shedding frequency are still strong enough to provide a clearly visible slope in the phase plot up to around 40 kHz.

The amplitude discrepancy between the upstream and downstream beam spectra is likely due to differing noise floors in the spot centroid calculations, as each individual spot had slight variations and individually selected thresholding values. While thresholding greatly mitigates the effects of interference patterns, there are bound to still be some effects from interference at the edge of the thresholding range, and these effects will be unique to each spot, potentially resulting in a different amplitude for the noise floor between the spots for the upstream and downstream beams for each test case. Potential ways to reduce this noise floor for future experiments will be discussed in the next section. For this case, the R^2

value of the linear fit was 0.96, with a value for the convective velocity of 131 m/s and a U_c/U_∞ ratio of 0.861, consistent with the values for Cases 1 and 2.

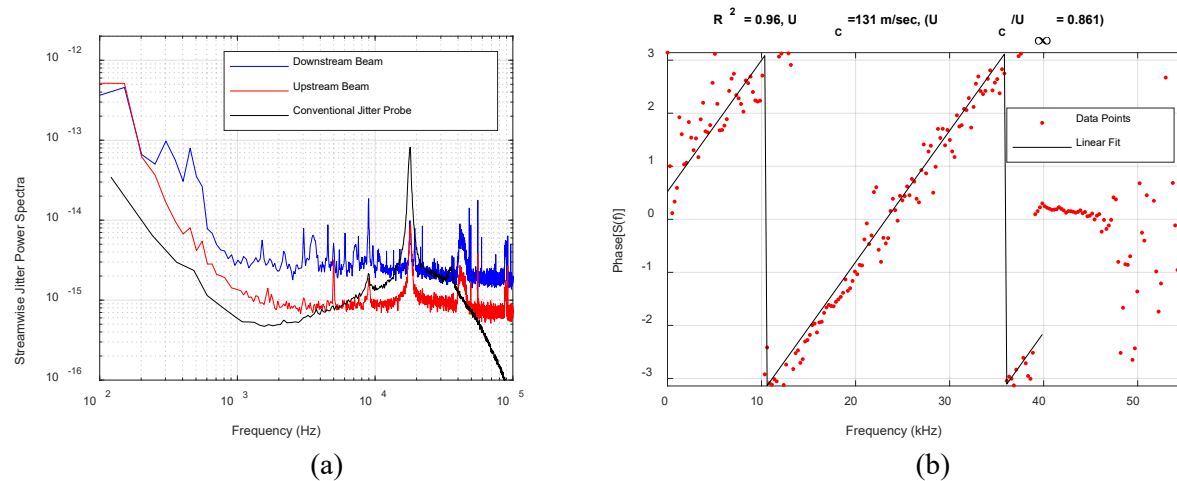


Figure 99. Case 3, Focused Malley probe streamwise jitter (a) power spectra and (b) phase plot for Mach 0.44 flow 5.5 diameters downstream of cylinder, with a C/L ratio of 15% and $L = 285 \text{ mm}$, sampled at 220 kHz

Figure 100 shows the streamwise jitter power spectra and phase plot for Case 5, taken downstream of the cylinder at an even lower C/L ratio of 5% and a sampling frequency of 720 kHz. As can be seen from the jitter spectra in Figure 100(a), the spikes at the vortex shedding frequency and twice the vortex shedding frequency are both visible, which leads to a slope from the signal visible in the phase plot, shown in Figure 100(b), up to 23 kHz, but no linear phase slope is visible at higher frequencies. This is expected, as the noise floor in the spectra overrides any flow signal at these higher frequencies, since the spikes due to vortex shedding, which are the flows of interest, are only present at lower frequencies. There is a steep drop-off in the unwrapped phase, which is used to compute the slope, above 23 kHz, so for this test case, only the frequency range below this value was used to compute the slope in order to not introduce error from noise into the calculation. This increased noise is likely due to the fact that the lower signal magnitude for the C/L ratio of 5% is smaller compared to the constant camera pixel size across all C/L ratios, which would result in more noise relative to the signal. The amplitude discrepancy between the upstream and downstream spectra in Figure 100(a), is likely due to differing noise floors for each individual spot, as discussed earlier. Aliasing is not likely the cause of the flat spectra at the high end of the frequency range due to the high sampling frequency of 720 kHz, and this effect is likely due to the noise floor for each spot. As a result of the increased noise, the linear fit for Case 5 had a smaller value R^2 value of 0.82, with the convective velocity of 140 m/s and a U_c/U_∞ ratio of 0.923.

For all of the measurements taken with the focal points placed in the freestream in the center of the tunnel approximately 9.5 cylinder diameters upstream of the cylinder, Cases 7-9, there was no noticeable slope to obtain any measurement from any of the phase plots. For example, Figure 101 shows the jitter spectra and phase plot for Case 7, taken in the free stream at a C/L ratio of 20%. As can be seen from the very low R^2 value of 0.069 and the non-physical U_c/U_∞ ratio well above one, there is no meaningful correlation or noticeable slope in this phase plot, as any signal that may be present is overridden by noise. This is expected, since the freestream region does not have any strong density fluctuations and, consequently, does not create any strong optical distortions.

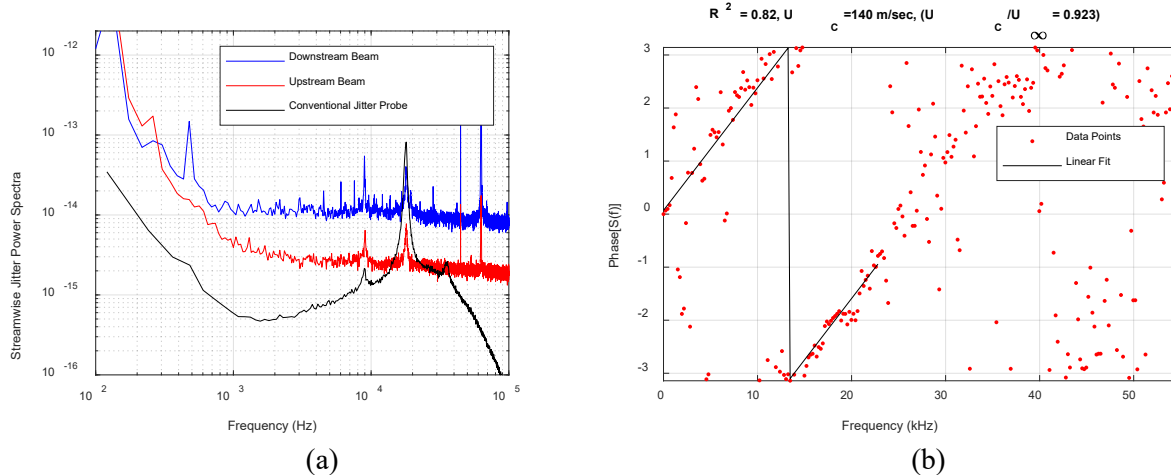


Figure 100. Case 5, Focused Malley probe streamwise jitter (a) power spectra and (b) phase plot for Mach 0.44 flow 5.5 diameters downstream of cylinder, with a C/L ratio of 5% and $L = 205$ mm, sampled at 720 kHz

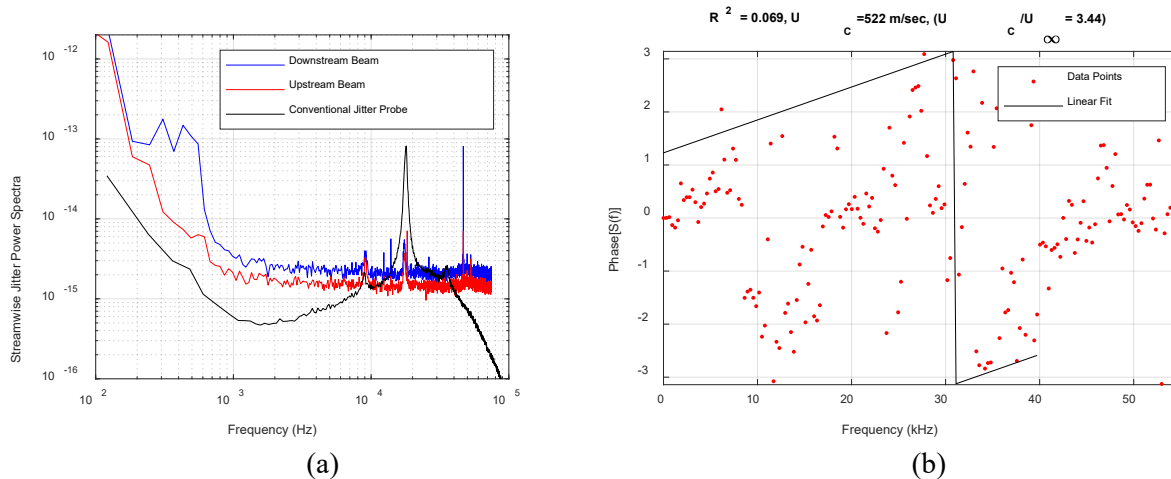


Figure 101. Case 7, Focused Malley probe streamwise jitter (a) power spectra and (b) phase plot for Mach 0.44 flow 9.5 diameters upstream of cylinder centered in the free stream, with a C/L ratio of 20% and $L = 405$ mm, sampled at 150 kHz

For the measurements taken with the focal points placed in the turbulent boundary layer approximately 9.5 cylinder diameters upstream of the cylinder, only test Case 10, shown in Figure 102, with a C/L ratio of 20%, yielded a phase plot with a well-defined slope due to the strong flow signal. This slope was visible up to a frequency of around 40 kHz, as with most of the cases with a visible slope for the cylinder's wake, and for Case 10 the R^2 value was 0.85 for the linear fit. The resulted convective velocity of 178 m/s and a U_c/U_∞ ratio of 1.17. Because this ratio should theoretically be around 0.82 for a turbulent boundary layer, this discrepancy is likely due to noise obscuring the signal, and potential sources of error as well as potential areas of improvement which could help alleviate such issues in future iterations will be discussed in the following section.

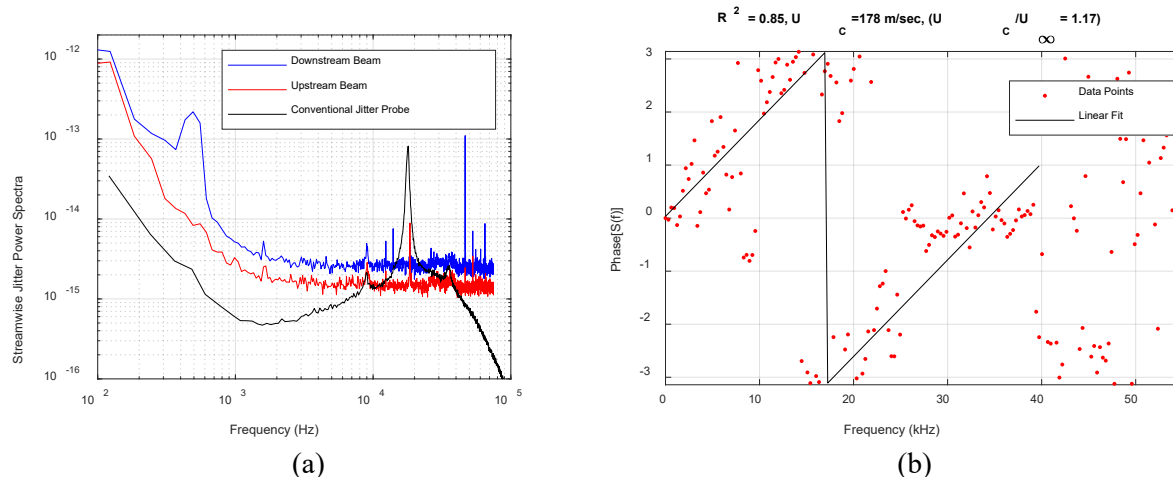


Figure 102. Case 10, Focused Malley probe streamwise jitter (a) power spectra and (b) phase plot for Mach 0.44 flow 9.5 diameters upstream of cylinder in the turbulent boundary layer, with a C/L ratio of 20% and $L = 405$ mm, sampled at 150 kHz

The results for all test cases which yielded well-defined slopes on the phase plots, along with a representative test case for the free stream, are summarized in Table 4. All of the linear fits had a high degree of correlation with an R^2 value above 0.8, and for larger C/L ratios of 15% and 20% taken in the wake of the cylinder, the linear fits had an even higher correlation with R^2 values of around 0.9 and above. For Case 1, the measurement region focal point separation was measured with a ruler, resulting in larger uncertainty in the distance between the focal points. For Cases 2, 3, and 5, where this separation was measured more accurately using the camera, the mean value of the convective to free stream velocity ratio was 0.897, and all three values fall within 4% of this mean, showing there is fairly good agreement across C/L ratios for measurement of the convective velocity in the wake of the cylinder. There was virtually no correlation for the freestream in Case 7, as expected, due to the optical signal near the focal points being too weak to be measurable, although future improvements to reduce this noise floor are possible. Although the boundary layer phase plot for Case 10 yielded a discernable slope which resulted in a convective velocity on the correct order of magnitude, the current noise floor was also an issue here, and resulted in a significant discrepancy between the measured value for the ratio of 1.17 and the expected value of 0.82. Overall, there are improvements that can be made to reduce the noise floor, but the good agreement between Cases 2, 3, and 5 in measuring the convective velocity in the wake of the cylinder serves as a proof of concept for the focused Malley probe as a novel local non-intrusive aero-optical wavefront measurement technique.

Table 4. Summary of U_c/U_∞ Results for Experiments with the Focused Malley Probe

Case Number	Measurement Location	C/L Ratio	R^2 of Linear Fit	Convective Velocity U_c (m/s)	Ratio U_c/U_∞
1	Cylinder's Wake	20%	0.92	125	0.826
2	Cylinder's Wake	20%	0.89	138	0.907
3	Cylinder's Wake	15%	0.96	131	0.861
5	Cylinder's Wake	5%	0.82	140	0.923
7	Free Stream	20%	0.069	-	-
10	Boundary Layer	20%	0.85	178	1.17

5.0 CONCLUSIONS

Below conclusions are provided for each topic.

Topic 1: Aerodynamic response of the spanwise oscillating turret: experiments and modeling

Conclusions from Experimental Studies

The oscillating turret assembly has been designed, built and experimentally tested in a subsonic tunnel over a range of Mach numbers between 0.3 and 0.6. The hemispherical turret is mounted on a thin aluminum beam, allowing the turret to freely move in the spanwise direction only. Only the hemispherical turret was inserted into the flow. The oscillating turret was designed using Euler-Bernoulli beam theory to oscillate at a predominantly single resonant frequency. The parameters of the mounting beam were tuned for the oscillating frequency to coincide with the wake-dominant frequency of $St_D \sim 0.15$, so the resonant aero-elastic interaction would result in forced turret oscillations.

The optical-based measurements confirmed that the turret oscillations were confined to the spanwise direction only. The time-resolved turret motion showed that the turret oscillated in bursts of pseudo-periodic motion, where the turret exhibited relatively stationary regime followed by periods of strong oscillations at a fixed frequency. The durations of these period of the oscillatory turret motion were found to be on the order of 100-200 D/U_∞ .

An extensive study using PSP was conducted in order to investigate the globally-reconstructed fluctuating pressure fields on and around both oscillating and stationary turrets. The spatial distributions of temporal rms values of the pressure coefficient in the wake indicate that flow-induced turret oscillations suppress the total pressure energy and increase the wake size at all tested Mach numbers. Analysis of the surface convective velocities around the turret linked the local increases in the fluctuating pressure to the unsteady necklace vortex in front of the turret and near the unsteady re-attachment line in the wake. The analysis also confirmed the increased wake size for the oscillating turret. A conditional analysis of the pressure fields during the stationary and the pure oscillating regimes for the oscillating case using a Morlet wavelet transform showed that the pressure spatial distribution in the wake is essentially the same during these different regimes, indicating long response times of the turret wake.

JPOD modal analysis was applied in order to investigate the spatial distribution and the spectra of the different wake modes for the oscillating and the stationary cases. It was found that the spanwise anti-symmetric modes have a sharp peak at $St_D \sim 0.17$, and this peak was substantially suppressed for the oscillating case at all tested Mach numbers. The spanwise-symmetric modes corresponding to the global symmetric motion, were found to be mostly unaffected by the turret motion. Therefore, the mechanical motion of the oscillating turret was responsible for the reduction of the overall pressure fluctuation of the wake by suppressing the global anti-symmetric wake motion. The results can be logically interpreted in the context of energy conservation, where the energy in the wake must be reduced in order for the flow to do work on the oscillating turret.

Due to aero-elastic interaction, the anti-symmetric wake motion was dynamically locked with the mechanical motion of the oscillating turret. An analysis of unsteady forces acting of the turret itself revealed that most of the unsteady forcing for both turret configurations occurs in the spanwise direction, and unsteady force spectra showed that the dominant frequency corresponded to the resonant oscillating frequency for the oscillating turret and the dominant wake response frequency for the stationary turret. The spanwise unsteady force was also demonstrated to be intermittent in time, explaining the bursts of the periodic turret motion for the oscillating case. The spectral transfer function, extracted from the simultaneous force and the resultant turret motion, agree reasonably well with the prediction from the linear second-order underdamped model.

Conclusions from simulations

The rigid simulations provided the baseline aerodynamic features as well as a means to assess the required spatial and temporal resolution necessary to simulate the massively separated flow. As a result, a

convergence study was conducted on the rigid hemisphere in which the spatial and temporal scales were independently varied. The results showed that the non-dimensional spacing on the turret (cross-stream and stream-wise) needed to be approximately 150 wall units which is comparable to requirements for Large Eddy Simulations. The temporal resolution was less critical to resolving the scales to match the experimental measurements. Additionally, capturing the incoming boundary layer thickness was essential to match experimental results; it was observed that the boundary layer thickness changed the height and size of the necklace vortex which would in turn alter the stagnation location and resulting separation behavior on the turret.

The analysis of the baseline, rigid simulation included surface pressure statistical and time accurate behavior. Pressure fluctuations on the turret surface showed a low frequency, large scale motion of the separation line followed by a band of strong, high frequency fluctuations due to the separated shear layer. The unsteady results show that four dominant modes can be identified in the pressure distribution: Symmetric modes, which move the separation point up and down-stream, and anti-symmetric modes, which cause the separation point to skew angularly. The transition between these modes, while stochastic in nature, does show a periodic tendency. The active modes on the surface have a direct influence on the wake symmetry and the structures present in the wake.

The fluid solver was next coupled to a simplified spring-mass-damper (MDK) structural model to incorporate turret motion in the coupled FSI simulations. The model design was collaboratively formulated to make it well suited for both experimental and computational investigations. The computational structural model attached the turret to the ground using an MDK system in the cross-stream direction. The results of the coupled simulations show subtle, yet apparent, differences to those of the rigid simulation. The shedding frequencies in the wake tend to change and the wake becomes more symmetric. The large scale motion of the separation line also transitions into more of a streamwise surging as opposed to an asymmetrically skewed oscillation.

Topic 2: Experimental studies in supersonic flow and related aero-optical effects to validate numerical codes

Cylindrical wall-normal pin arrays of various heights have been studied using optical methods, including schlieren imaging, acetone PLIF, acetone Mie scattering, and wavefront measurements using a Shack-Hartmann wavefront sensor. These methods have been used to visualize flow structures such as the lambda shock region, reattachment shocks, shock wave impingements, and the supersonic shear layer originating from the pin tips. It should be noted that a successful visualization of some flow features is possible because the SBR-50 facility at the University of Notre Dame allows for an accurate adjustment of the gas temperature, which makes Mie scattering visualization an appropriate method for the recognition of fine-scale structures in a mixing layer behind the pins.

The detailed visualization of the fine structure of the flow field in the shear layer demonstrates that the Mie scattering method is a powerful tool for the reconstruction of flow field details when the gas density gradients are too low to be well-detectable with commonly used techniques such as schlieren, aero-optical distortions detection, or even laser differential interferometry. In terms of sensitivity, this method is especially beneficial when the flow temperature is accurately adjustable.

Most features of the flow field acquired with these optical methods are well predictable. However, the description of a few peculiarities requires further analysis. Among them is the structure of the mixing layer behind the pin array where the pin-activated vorticity and flow acceleration through the 2D nozzle formed by adjacent pins leads to the generation of complex flow structures in the supersonic zone as visualized by Mie scattering. Another focus of upcoming efforts is a quantitative analysis of fast schlieren video and Shack-Hartmann datasets to reveal details of the flow velocity distribution behind the pin array.

Topic 3: Experimental studies of the aero-optical jitter of the hemisphere-on-cylinder turret at various amounts of protrusion

Conclusions on aero-mechanical jitter studies

The aero-mechanical forcing on a hemispherical turret is undoubtedly a problem for many optical applications. The experiments discussed here sought to quantify the aero-mechanical contamination imposed onto a hemispherical turret in a parametric study. Hemispherical turrets of different protrusion distances were tested in both a wind tunnel and in-flight at varying Mach numbers and azimuthal angles. Beam jitter and accelerometer measurements were collected which sought to identify qualitative trends in mechanical contamination as a function of Mach number and turret protrusion. For both wind tunnel and in-flight measurements, the resultant rms radial jitter imposed onto the laser beams increased with Mach number, however, no discernable scaling patterns were observed. For the wind tunnel tests, the resultant rms radial jitter also generally increased with greater protrusion into the freestream flow. This trend was not observed in the data collected from in-flight testing. Ultimately, facilitating studies to isolate the aero-mechanical forcing contribution to beam distortion from facility specific distortions is challenging. The results presented here are not meant to discourage the study of how vibrational contamination reverberates into optical contamination, they are simply meant to highlight the difficulties that lay ahead for researching this problem.

Conclusions for studies of the surface pressure fields on and around turret with different amount of protrusion

Wind tunnel surface pressure measurements using fast-response PSP were taken on a hemisphere-on-cylinder turret at various protrusion distances and Mach numbers. This parametric study was conducted in order to better understand the characteristics of the unsteady pressure field on the backside and wake of the turret. POD was used to identify the dominant spatial surface pressure modes acting on the turret and spectra was computed on the POD temporal coefficients to identify relevant surface pressure frequencies acting on the turret. The further the turret protruded into the freestream flow, the greater the presence of spanwise antisymmetric surface pressure distribution. This spanwise anti-symmetrical surface pressure distribution results from antisymmetric vortex shedding at a normalized frequency of $St_D=0.2$. By calculating the cumulative POD mode energy for each turret configuration, it was found that fewer modes were required to reconstruct a large percentage of total surface pressure energy for the greater turret protrusion cases.

For the case of the partial hemisphere, the spanwise anti-symmetrical vortex shedding was majorly absent, insinuating that at some protrusion distance, the surface pressure environment on the turret fundamentally changes. It was found that the surface pressure field of the partial hemisphere was overall less organized compared to the other configurations and no modes were especially dominant. The organization that was present in the modes mostly resulted from the flow in the wake, without much influence from the flow over the turret. However, when the protrusion increases to the hemisphere and hemisphere + cylinder, the unsteady separation becomes much more prominent and is connected to both the separated region and the reattachment region of the wake. One separation-related mode was a previously proposed spanwise symmetric “breathing” mode. Another significant mode is a strong anti-symmetric vortex shedding mode that becomes the main source of fluctuations in the pressure field and is related to the anti-symmetric fluctuation of the separation line. This anti-symmetric mode has a peak in its spectra at $St_D \approx 0.19$ for the hemisphere and hemisphere + cylinder, where the spectra of these modes had significant decrease in energy at lower frequencies below about $St_D = 0.2$ for the partial hemisphere. It is unclear whether the unsteady separation and anti-symmetric shedding gradually grow with protrusion or whether there is some point which the flow dynamics change suddenly. Overall, POD and JPOD analyses gave similar modes and spectra peaks; however, correlation in the flow related to the unsteady separation line was not as clear in the POD modes for the partial hemisphere. JPOD also provided a more direct comparison between geometries.

Net force calculations for all Mach number and turret configurations were performed. It was found that as turret protrusion distance increases, so does the spanwise net force acting on the turret, confirming the findings established in the POD results.

Topic 4: Focused Malley probe as spatially localized aero-optical sensor

The experimental studies of the global beam jitter imposed on a laser beam with different diameter by compressible subsonic turbulent boundary layers are presented. The time-resolved global beam jitter was measured using a single PSD. Measurements of the global beam jitter on the streamwise and the spanwise direction were performed and the analysis of power spectra were conducted. Various sources of error, effecting the quality of the measurements were investigated and possible ways to eliminate them are provided. It was found that for both components of the jitter, the aperture averaging effect resulted in a suppression of the beam jitter spectra at high frequencies. For the streamwise component of jitter, larger beam apertures lead to larger suppression. For both components of the jitter, the ratios of global to local beam jitter power spectra were also studied. For the streamwise component of jitter, the ratios were found to approximately collapse onto a single curve, when plotted versus a ratio of the beam diameter to the structure size. The results were also compared with an analytical model, developed earlier for the one-dimensional wavefronts, and a qualitative agreement between the results and the model was observed. The model was found to overpredict the amount of the suppression in the streamwise jitter spectra.

Preliminary measurements of localized aero-optical distortions using a novel non-intrusive local aero-optical wavefront measurement technique, termed the focused Malley probe. The probe consisted of two convergent-divergent laser beams, with focal points separated by a known distance in the streamwise direction. Global beam jitter of both beams were simultaneously measured using a high-speed camera, and the spectral cross-correlation analysis was implemented to extract the jitter spectra and the convective speed of the aero-optical structures near the focal points. It was demonstrated that the focused Malley probe is capable of correctly measuring the local jitter spectra and the related convective speed of the aero-optical structures near the focal points while suppressing aero-optical signal everywhere else via the aperture averaging effect. Measurements were performed with the focal points been placed in the wake behind a cylinder, in the free stream ahead of the cylinder, and in the wall turbulent boundary layer ahead of the signal. For the measurements in the wake of a cylinder where the focal point separation was measured accurately with the camera, C/L ratios of 20%, 15%, and 5% gave consistent convective velocity measurements within 4% of the mean and the expected convective speed. While the ratio of $C/L = 5\%$ also resulted in a reasonable estimate of the convective speed in the wake of the cylinder, the uncertainty of the measurements was higher due to the much lower signal magnitude of this lower C/L ratio resulting in a higher noise floor. No usable signal was measured above the noise level in the freestream region for any C/L ratio, and only one test case produced a noticeable phase slope due to the flow on the phase plot for the measurements of the turbulent boundary layer, but even this measurement had significant error. Despite these areas for improvement, the experiments in the wake behind the cylinder at C/L ratios of 20%, 15%, and 5% serve as a proof of concept that the focused Malley probe can be used to measure both streamwise jitter spectra and the convective velocity of the flow near the focal points.

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APPENDIX A - Publications resulted from this Project

Conference papers

- L. Butler, M. Lozier, and S. Gordeyev, "Effect of Varying Beam Diameter on Global Jitter of Laser Beam Passing Through Turbulent Flows", AIAA AVIATION Forum, 17 - 21 Jun 2019, Dallas, TX, AIAA Paper 2019-3385.
- A.L. Roeder, S. Gordeyev, and D.J. Wittich, "Wake Response Downstream of Spanwise-Oscillating Hemispherical Turret", AIAA SciTech Forum, 6 - 10 Jan 2020, Orlando, FL, AIAA Paper 2020-0685.
- Roeder, D. Kurihara, H. Sakaue, and S. Gordeyev, "PSP Studies of the Wake Response Downstream of a Spanwise-Oscillating Hemispherical Turret", AIAA AVIATION Forum, Jun 15-19, 2020, Virtual Event, AIAA Paper 2020-3237.
- L. Butler, and S. Gordeyev, "Local Aero-Optical Measurements of a Wake behind a Cylinder in Turbulent Flow using a Focused Jitter Probe", AIAA SciTech Forum, Jan 11-15 & 19-21, 2021, Virtual Event, AIAA Paper 2021-0937.
- M. Kalensky, B. Catron, S. Gordeyev, E.J. Jumper, and M. Kemnetz, "Investigation of aero-mechanical jitter on a hemispherical turret," Proc. SPIE 11836, Unconventional Imaging and Adaptive Optics 2021, 1183606 (1 August 2021)
- M. Kalensky, B. Catron, S. Gordeyev, E.J. Jumper, and M. Kemnetz, "Pressure sensitive paint measurements on a hemispherical turret," Proc. SPIE 11836, Unconventional Imaging and Adaptive Optics 2021, 1183607 (1 August 2021)
- L.N. Butler, and S. Gordeyev, "Development of the Focused Malley Probe as a Local Aero-Optical Measurement Technique," AIAA SciTech Forum, January 3-7, 2022, San Diego, CA, AIAA Paper 2022-0988.
- T.J. Bukowski, M. Kalensky, S. Gordeyev, and M. Kemnetz, "Modal analysis of pressure fields on and around turrets with different protrusions," Proceedings Volume 12239, Unconventional Imaging and Adaptive Optics 2022; 122390F, 2022.

Journal publications

- A.L. Roeder, and S. Gordeyev, "Wake Response Downstream of a Spanwise-Oscillating Hemispherical Turret", Journal of Fluids and Structures, Vol. 109, 103470, 2022.
- P.A. Lax, S. Elliott, S. Gordeyev, S.B. Leonov, and M.R. Kemnetz, "Visualization of Flow field behind Spanwise Cylindrical Pin Array in Supersonic Duct", submitted to Flow, Turbulence and Combustion, 2022.

APPENDIX B - Personnel

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LIST OF ABBREVIATIONS AND ACRONYMS

AAOL-BC	Airborne Aero-Optics Laboratory for Beam Control
AFRL	Air Force Research Laboratory
CFD	Computational Fluid Dynamics
CW	Continuous Wave
DDES	Delayed Detached Eddy Simulation
DGV	Doppler Global Velocimetry
DoF	Degree-of-Freedom
DMD	Dynamic Mode Decomposition
FLDI	Focused Laser Differential Interferometry
FSI	Fluid Structure Interaction
FSM	Fast-steering Mirror
JPOD	Joint Proper Orthogonal Decomposition
KCFD	Kestrel CFD/Kestrel Computational Fluid Dynamics
LDA	Laser Doppler Anemometry
LED	Light Emitting Diodes
LIF	Laser Induced Fluorescence
PSP	Pressure Sensitive Paint
PLIF	Planar Laser Induced Fluorescence
POD	Proper Orthogonal Decomposition
PSD	Position Sensing Device
MDK	Mass, Damping and Stiffness
Nd:YAG	Neodymium-doped Yttrium Aluminum Garnet
SWBLI	Shock Wave-boundary Layer Interaction
OIRU	Optical Inertial Reference Unit
OPL	Optical Path length

PC-PSP	Polymer-ceramic Pressure Sensitive Paint
PIV	Particle Image Velocimetry
PMT	Perspective Matrix Transformation
PTV	Particle Tracking Velocimetry
RTD	Resistance Temperature Detector
SHWFS	Shack-Hartmann Wavefront Sensor
SPOD	Spectral Proper Orthogonal Decomposition
SST	Shear Stress Transport
USAFA	United States Air Force Academy
UV	Ultraviolet
TPOD	Temporal Proper Orthogonal Decomposition

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