Investigation of Baffled Slots in the NASA Ames 14” x 14” Indraft Wind Tunnel

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Abstract

This paper describes some initial work to improve the understanding of baffled wall slots in the test section of the 11 × 11-Ft Transonic Wind Tunnel (11-Ft TWT) and their impact on flow quality. A wind tunnel experiment was conducted to study flow through the slots in the walls of the test section of the 11-Ft TWT. The goal is to provide data to validate Computational Fluid Dynamic (CFD) models of the slots as part of a larger effort to develop an accurate CFD simulation of the entire wind tunnel. An experimental study of two baffled slots was conducted in 14 × 14-In wind tunnel of the Fluid Mechanics Laboratory at the NASA Ames Research Center. Optical techniques including Unsteady Pressure Sensitive Paint and Particle Image Velocimetry along with pressure sensors and flow surveys (pitot-static and hot-wire probes). The details of the flow and associated pressure drops are critical parameters needed to enable simplified CFD modeling of the slots. The baffled slots in the 11-Ft TWT are known to generate a tone. A secondary objective of the test was to see if the simplified model generated the same tone with the eventual goal of designing a fix to eliminate it. Comparisons of CFD predictions of the flow in the simulated tunnel show good agreement with the experimental measurements of the mean flow and the measurements will provide the necessary data for developing an accurate simplified model of the slots for higher fidelity CFD simulations of the 11-Ft TWT.

I. Nomenclature

FML = Fluid Mechanics Laboratory
ARC = Ames Research Center
TWT = Transonic Wind Tunnel
CFD = Computational Fluid Dynamics
FOS = Factor of Safety
OAR = Open Air Ratio
uPSP = Unsteady Pressure Sensitive Paint
PIV = Particle Image Velocimetry
DMD = Dynamic Mode Decomposition
UPWT = Unitary Plan Wind Tunnel
PSID = Pounds per Square Inch Differential
PSD = Power Spectra Density
CAD = Computer Aided Design
u = axial velocity, m/sec
v = lateral velocity, m/sec
w = vertical velocity, m/sec

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II. Introduction

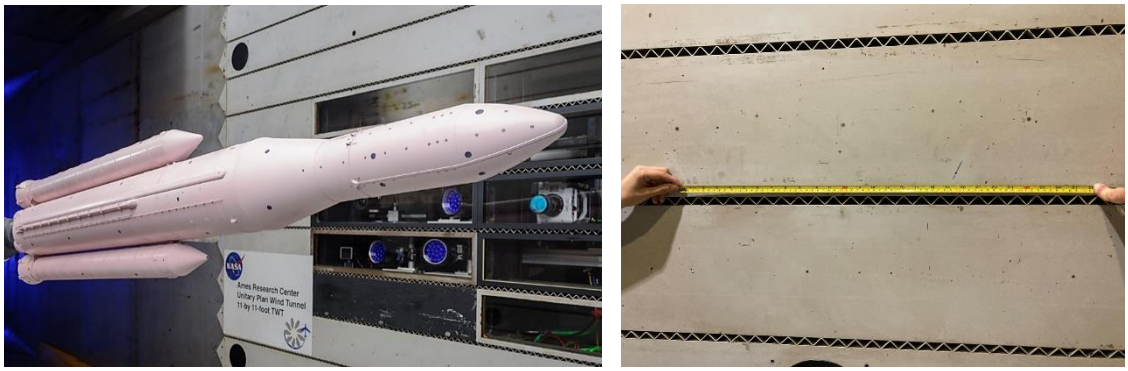
As aviation advanced from the 1930s, higher wind tunnel velocities became critical to aircraft testing. Experimental data at this new velocity regime would be essential to developing aircraft reaching supersonic speeds. Supersonic conditions in wind tunnels, however, proved to be a significant design challenge to replicate. Despite the model being surrounded by four walls, wind tunnel testing specifically aims to simulate the aerodynamic loads and flow field phenomena a test article encounters in free air. Because of the nature of wind tunnel experiments, experimentalists encounter several challenges: model support interference, wall interference, and mismatched Reynolds number.

In transonic and low-supersonic testing, a solid wall test section may cause issues in accurately replicating the conditions seen in free air due to the reflection of shock waves or restricting the flow around the model in an unrealistic manner. Goethert [1] proposed perforated walls as an approach to reduce supersonic wall interference effects observed with solid wall testing.

Calculations were made of the airspeed changes in wind tunnels for both partly opened and fully closed configurations. These calculations allowed for the wind tunnel researchers to develop how much slot open area was needed so that velocity corrections at subsonic speeds disappear [1]. Velocity corrections become increasingly necessary as flow speed approaches Mach 1, with shocks developing in the tunnel beyond this speed. Longitudinal slots eliminate the need for velocity correction in wind tunnel flow. Goethert demonstrated this in his 1947 transonic wind tunnel investigation, the first successful one in the U.S. Open and closed-circuit wind tunnels were used to determine the optimal slot open area minimizing velocity corrections at subsonic speeds.

Goethert's investigations demonstrated that for the "…cancellation of shock waves at wind tunnel walls it is necessary to provide a 'small-grain' porous wall which can match the 'flow inclination-pressure rise' characteristics of shock waves." [1]. Perforation patterns, spacing and arrangements all contribute to having the perforated walls be effective in eliminating shock wave reflections. Both computational and experimental studies provided the data supporting this effect of porosity.

A modern example of a porous-walled transonic wind tunnel and the main objective of this investigation is the NASA Ames Research Center Unitary Plan Wind Tunnel 11×11-Ft Transonic Wind Tunnel (11-Ft TWT) as seen in Fig. 1 [2]. The 11-Ft TWT test section is surrounded by a plenum and each wall of the test section includes 14 equally spaced, streamwise slots running the entire length of the test section. The slots are filled with baffles as seen in Fig. 1. The baffles help maintain the proper change in flow conditions across the shock waves and reduce the strength of the shock.



a) **b)**

Fig. 1 11-FT TWT baffled wall slots: a) 11-Ft TWT test section and b) close up of baffles

An unintended consequence of the slot baffles is the generation of strong tones as shown in Fig. 2. Fortunately, the tones appear to have little to no effect on the aerodynamic measurements of models.

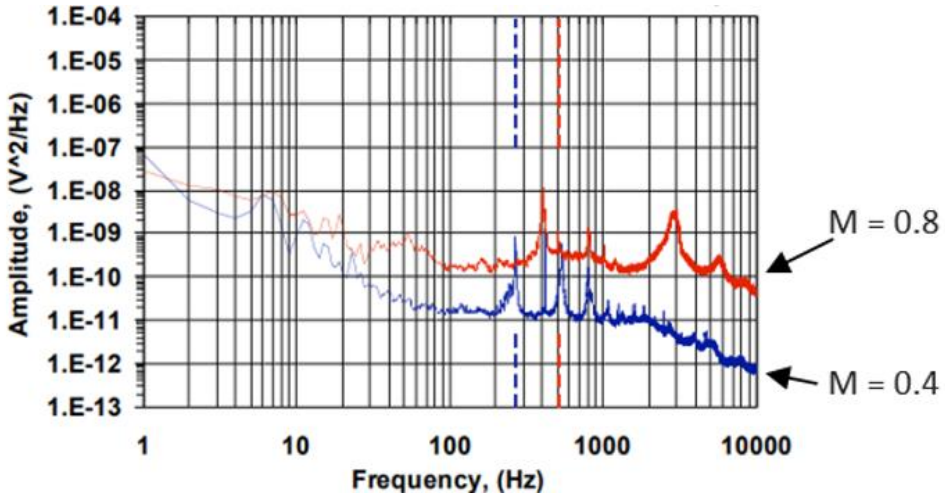


Fig. 2 Measured Slot Tones in 11-Ft TWT [3]

According to Amaya [3], slot tones were measure in the 11-Ft TWT which contributed to the turbulence and background noise. The tones associated with slot baffles are approximately 2.5-3 kHz, as seen in Fig. 2.

III. Scaled Experimental Setup

For this investigation, an experiment in the Fluid Mechanics Laboratory (FML) at NASA ARC was designed to emulate the flow through the slots in the 11-Ft TWT using a simplified truncated geometry (Fig. 3). In the FML, the maximum empty wind tunnel wind speed is approximately 200 m/s or Mach 0.60, with a Reynolds Number of 4 million per foot. The inflow to the wind tunnel passing through a 2-inch thick aluminum honeycomb followed by four 55% open area ratio screens.



Fig. 3 Test section (above) with acrylic plenum (below) [4]

This study had three main focuses. The first was to characterize the nature of the flow traveling into and out of the slots and the pressure drops generated by the flow passing between the inlet, test section and the plenum. Second is measuring flow in and out of the slots. This will help validate CFD simulations of the model wind tunnel flow, as

detailed in a companion paper [4]. The third goal was to modify the pressure distribution with a delta wing model to change the flow pattern into and out of the slots allowing for further comparison with companion CFD. The test configurations that were run to achieve the set goals: 1) empty tunnel, 2) with the delta wing and 3) with the delta wing with the slots covered with tape.

With baffled slots in the floor, the first floor configuration has the baffled slots open with an empty test section. The second floor configuration uses a delta wing model at a 15-degree angle of attack. The third floor configuration also uses the delta wing at 15-degree angle of attack, but the slots are closed and sealed with aluminum tape. The flow passed through the slots and into the plenum (Fig. 3) that fits under the test section floor.

The experiment included two 24-inch truncated slots were installed in the floor of the 14 × 14-In wind tunnel. The 11-Ft TWT slots are 13 inches apart but for this experiment the spacing was limited to 8 inches of spacing between the slots.

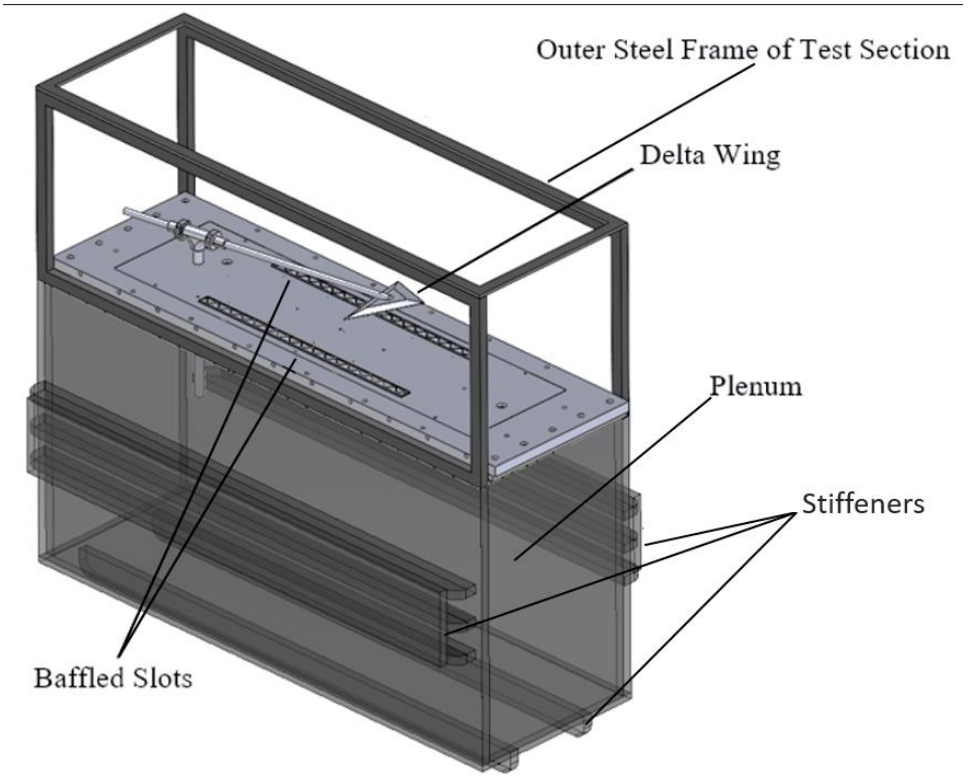


Fig. 4 Test Setup: Baffed slots, Delta Wing-model, and plenum

A. Slots

The baffled slots were manufactured based on both physical inspection and engineering drawings of the 11-Ft TWT. The selected design used in this test represents a compromise between inspection and drawings.

A 0.25 inch aluminum plate overlays the wooden floor for the purpose of creating the uniform surface temperature needed for uPSP measurements. The floor has two cutouts that are positioned 0.70 inches away from the test section walls. The 21.25 inch baffled slots are a truncated version of the full-scale baffled slots in the 11-Ft TWT. Fig. 4 shows the slots flushed in the test section floor and Fig. 5 shows the Computer Aided Design (CAD) of the baffled slots. The slots were constructed of bent sheet metal. The full length of the baffled slots is 20.8 inches long by 0.648 inches and a depth of 2.25 inches. While the full-scale slots of 11-Ft TWT have the same width and height but are 22 feet long.

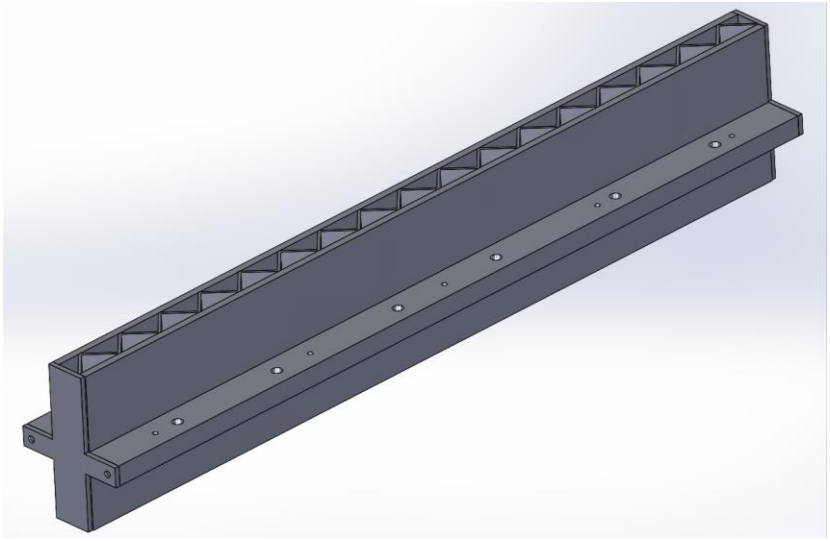


Fig. 5 Baffled Slots CAD

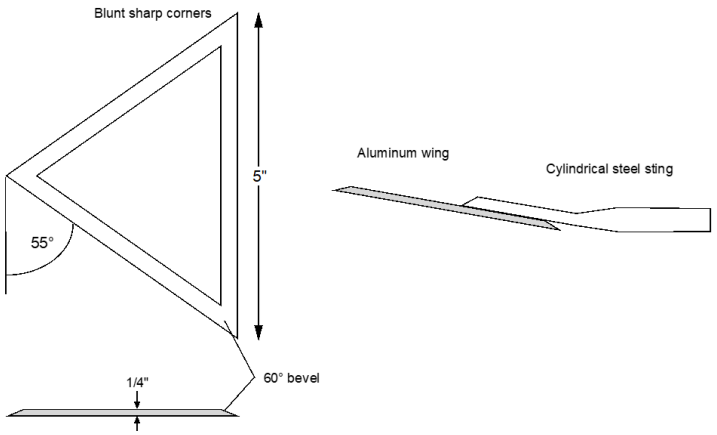
B. Plenum

Because of their structural integrity, lightweight design, and transparency, 0.75-inch thick Chemcast acrylic panels were chosen for the plenum. To ensure airtight operation, these panels are sealed with Apiezon Sealing Compound. The acrylic walls bow inwards from the internal airflow. Reinforcing the panels, 0.75-inch thick acrylic stiffeners are shown in Fig 4. These stiffeners distribute forces and prevent local deformation at 6 psid, as a worst case scenario.

Using SolidWorks, a Finite Element Analysis (FEA) was conducted with 6 psid of uniform pressure applied to all faces. In the worst-case scenario, the acrylic panels showed a maximum displacement of 0.0854 inches at their center. The Factor of Safety was calculated to be 6.23.

The size of the plenum was chosen to maximize volume to simulate the sizable plenum in the 11-Ft TWT.

C. Delta-wing model



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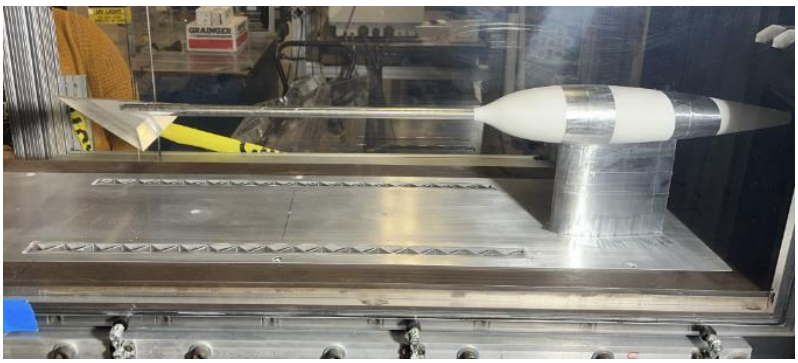


b)

Fig. 6 a) Delta Wing orthogonal drawing and b) delta wing model in test section

The experiment used a delta wing with a 7-inch span (Fig. 6a)) at 15-degree angle of attack. This configuration was designed to alter the floor pressure distribution and change the flow pattern through the slots. The delta wing-model was in position 2 (Fig. 7), so that there would be a bias in the pressure distribution to one side of the slots and floor. Positions 1 and 3 were designed to perturb the flow upstream and downstream of the slots and were not used for this experiment. The floor pressure distributions were compared to CFD. The delta wing model were used with 2 of the floor configurations.

IV. Instrumentation

A wide array of instrumentation was employed throughout the experiment. Wiring from the Kulites, pressure taps, hotwires, and thermocouples (Fig. 7), were routed through the floor and into the plenum. A small opening in the plenum allowed the wire bundle to connect to the data acquisition system.

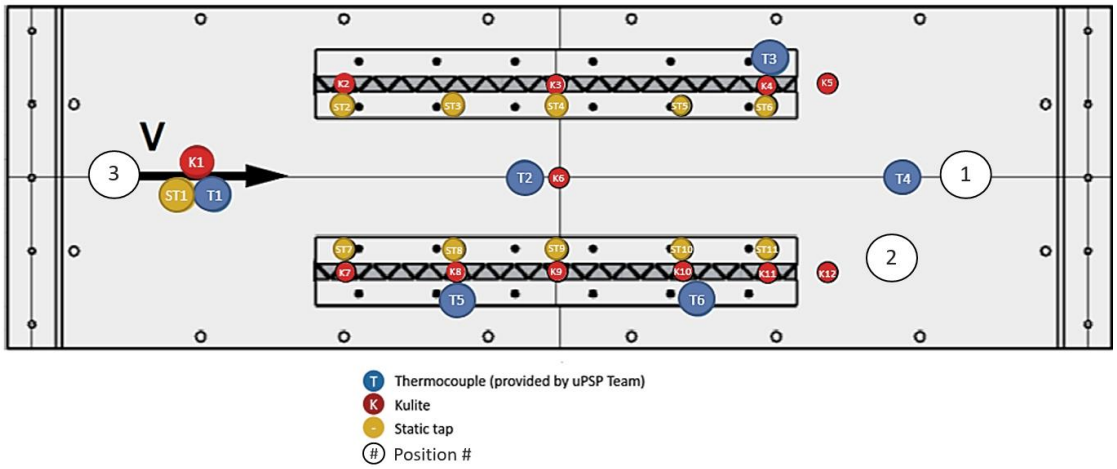


Fig. 7 Test section floor and instrumentation schematic

A. Kulites and pressure taps

Unsteady pressure measurements were made using 12 Kulite pressure Transducers (model XCEL -12A-100-2D). Four of these Kulites were mounted flush with the test floor surface while the remaining eight Kulites were mounted mid-depth of the baffled slots. These are high-temperature, short-length pressure transducers with a pressure range of 3 psid.

Pressure taps were connected to pneumatic tubing to an ESP Pressure Scanner. The floor had rows of pressure taps consisting of fives taps located 4 inches off the centerline. 11 are mounted flush with the surface of the floor, while the other 11 are mirrored on the underside of the floor, located as shown in Fig. 7. Pressure taps with positioned in this order to detect the flow coming in and out of the slots. Pressure differential measurements are recorded.

B. Boundary layer probe and thermocouples

A pitot probe was used to measure the total pressure profile through the boundary layer while the two-axis hot-film probe was used to capture unsteadiness of the flow. The boundary layer probe was one previously used to measure the boundary layer on an Orion Capsule model (Fig. 8) [6] in the 11-Ft TWT, the probe was driven by a stepper motor and translation stage.

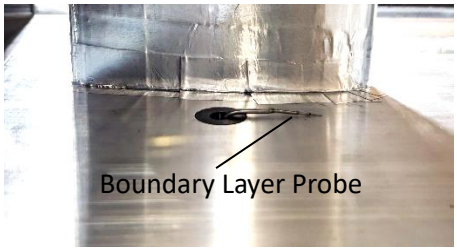


Fig. 8 Boundary Layer probe on Test section floor

The probe tip geometry allows total pressure measurements to be as close as 0.0049 inches above the surface, and the traverse has approximately 4 inches of travel. The probe performed a survey where it started 0.08 inches for the ground and travelled up to 2.0 inches, to capture the flow from the boundary layer to the freestream flow. The total and static pressure was measured at three locations using the boundary layer probe with 10 inches of water and is placed at position 1, shown in Fig. 7.

Temperature measurements were made to use six thermocouples. The thermocouples were positioned 0.03 inches under the surface of the floor and were used to determine local temperature surface along the surface for uPSP measurements.

C. uPSP

In addition to the time averaged pressure measurements taken by the pressure scanners, uPSP was used to measure time-resolved surface pressure distributions across the entire test section floor. A cage using 80×40 aluminum beams was designed around the test section to mount four Phantom v2512 cameras and 6 Innovative Scientific Solutions, Inc. blue LED lamps. Two cameras positioned directly over the test section and the remaining two cameras positioned on each side of the test section to provide angled views along the side walls. Two LED lamps were mounted above the ceiling, and two mounted on each side of the sidewalls to ensure uniform illumination and maximize paint excitation, as seen in Fig. 9.

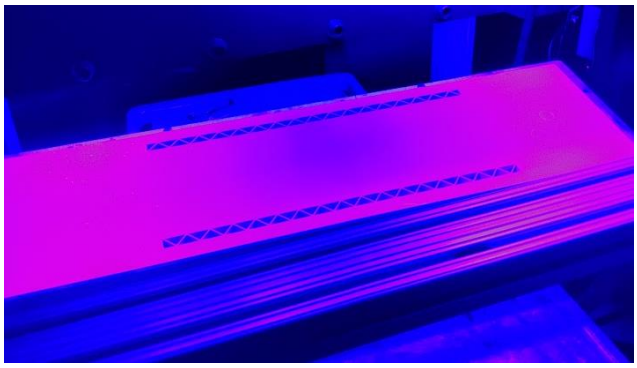


Fig. 9 uPSP on test section floor with UV excitation

D. PIV

Particle Image Velocimetry (PIV) was used to measure the flow in a plane as close as possible to the floor. The laser is from Spectra Physics, model PIV-400 and the system utilized two cameras with 45mm lenses to image the laser sheet. The laser itself has a spread angle of 5 degrees that was visualized in a program called VINCI [7] to determine the correct optical positioning for the two LaVision16 megapixel PIV cameras. The laser system required a certain distance to travel for the beam to spread as seen in Fig. 10. The system requires smoke particles in the flow that are imaged to determine the instantaneous velocity in the laser sheet. Mineral oil seeding was introduced through the inlet via a smoke stream array and vent to the compressor.

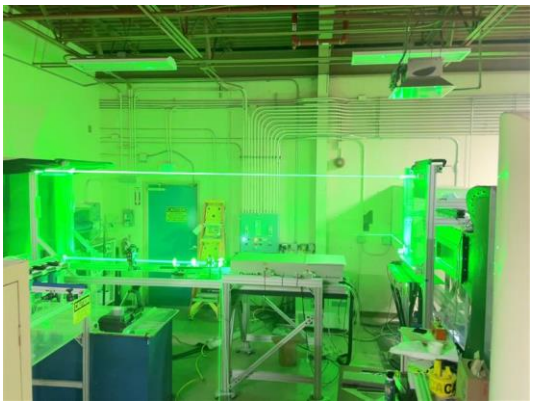


Fig. 10 PIV Laser Layout

V. Results

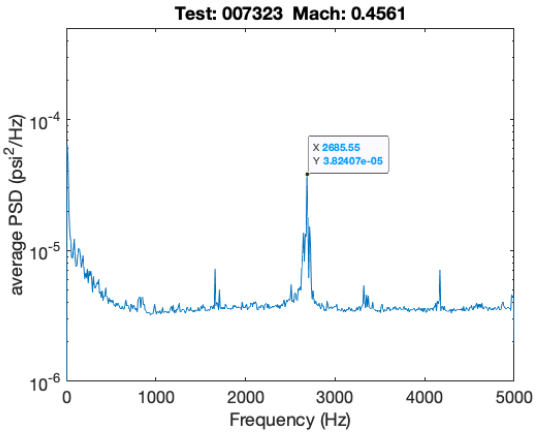
A. Unsteady Kulite Pressures

Based on the Kulite data, the slot tones generated by the truncated baffled slots were comparable to the slot tones generated by the 11-Ft TWT. A Mach sweep ranging from Mach 0.14 to 0.57 was conducted and data were acquired at a sampling rate of 30,000 Hz for a 3 second duration. A low-pass filter was used to remove high frequency noise, such as electrical and mechanical noise commonly seen in wind tunnel environments. The slot tones were not

present during the lower Mach runs but appeared in the higher Mach runs. Kulite data was also collected for all the floor configurations.

B. uPSP

The uPSP measurements were consistent with the unsteady Kulite measurements on the test section floor adjacent to the slots. Per discussion by Lash, et al. [8], the uPSP data showed a consistent trend in the traveling wave location variation with Mach number. When reaching Mach 0.56, the propagation speed of the traveling wave in the direction along the streamline is approximately equal to the speed of sound. This phenomenon may be related to the acoustic wave generated in the plenum. Results from uPSP testing include Average PSD of uPSP Pressures as seen in Fig. 11. Magnitude and Phase of DMD Mode are shown in Figs. 12 and 13.



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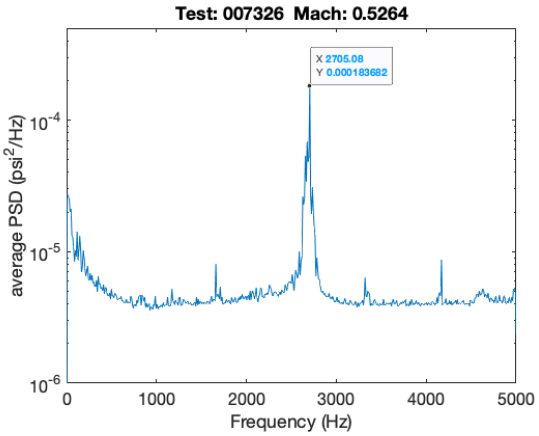

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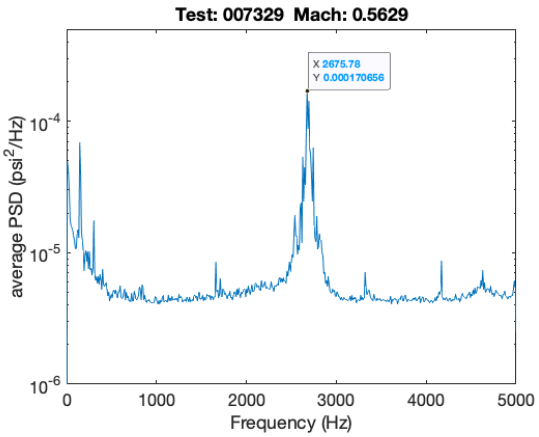

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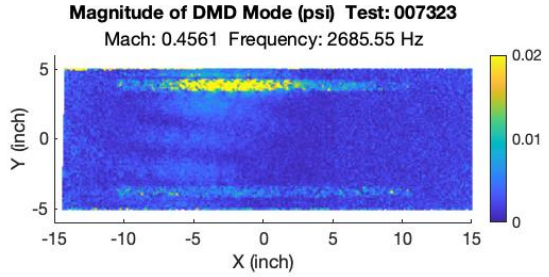
Fig. 11 Average PSD of uPSP Pressure a) Mach 0.46, b) Mach 0.53 and c) Mach 0.56



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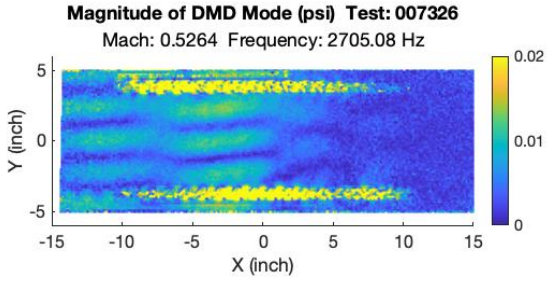

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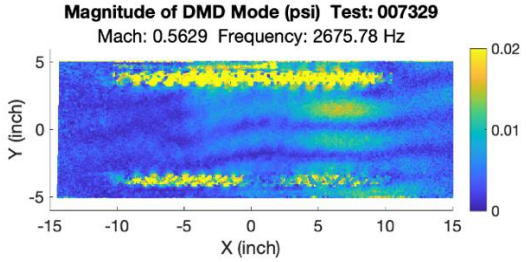

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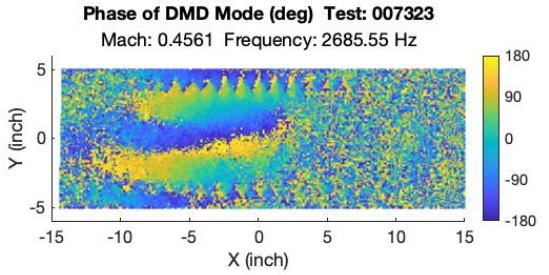
Fig. 12 Magnitude of DMD Mode a) Mach 0.45 , b) Mach 0.52 and c) Mach 0.56



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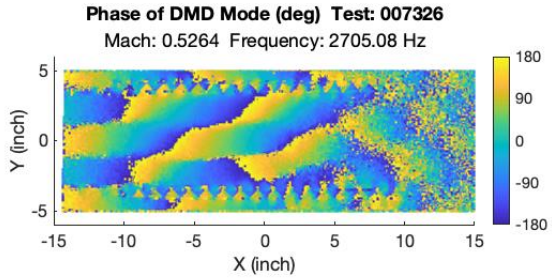

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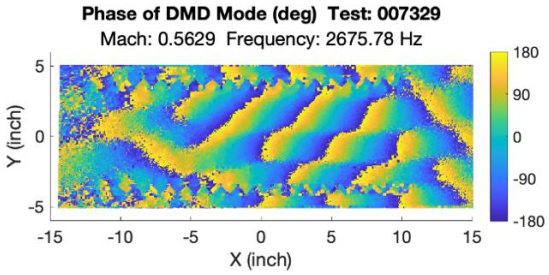

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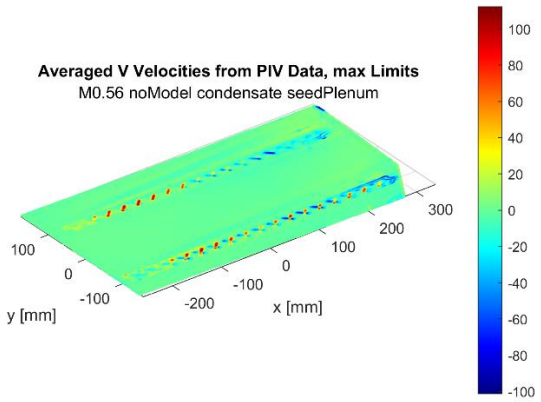
Fig. 13 Phase of DMD Mode a) Mach 0.46, b) Mach 0.52 and c) Mach 0.56

C. PIV

It was found that the flow phenomenon through the baffled slots was causing issues with this seeding technique. While the flow into the slots was visible in the processed data, the flow out of the plenum was not tracked by the cameras. This was because the density of seed material in the plenum was low. To visualize flow out of the plenum, seed material was introduced directly into the plenum with a minimal seed flow rate so as to match actual conditions as closely as possible. It was also found that when running the tunnel early in the morning at higher Mach conditions, water vapor would form in the test section which the PIV cameras could track. The flow was able to be fully captured using the PIV system with water vapor and the addition of seed material into the plenum. Averaged Velocities were documented in Fig. 14.



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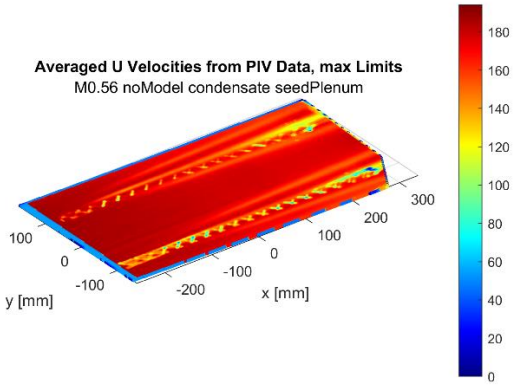

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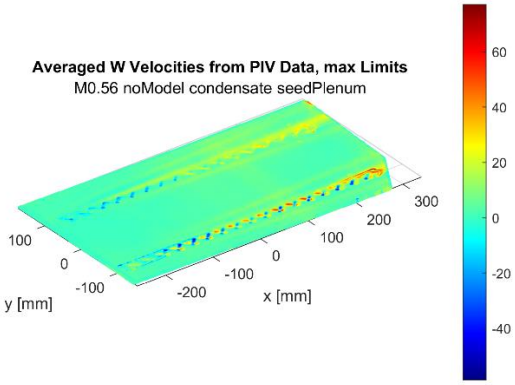

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Fig. 14 Averaged Velocities a) Averaged V, b) Averaged U and c) Averaged W velocities from PIV

VI. Conclusion/Future Work

The experiment for the baffled slots in the 14×14-In Wind Tunnel was completed with the intention of better understanding of the baffled wall slots and their impact on flow quality. A truncated model of the baffled slots was used with an acrylic plenum under the test section to best match the conditions seen in the 11-Ft TWT. Instrumentation including pressure sensors, flow surveys and optical techniques such as uPSP and PIV were used to examine the flow into and out of the slots. The data acquired in the test section produced the same slot tones as in the full-scale tunnel. The truncated model data of this study compared well with published data from the full-scale 11-Ft TWT. A comparison of CFD and experimental data for this configuration is presented in a companion paper published at this forum.

Future work for this study will include a more thorough examination of Kulite data for all three floor configurations. In addition, a comparison of the uPSP and PIV data with the Kulite measurement will be conducted.

VII. Acknowledgment

I would like to thank my mentors Dr. James C. Ross and Bruce Storms for their guidance. I also would like to thank my project lead Logan Halstrom, the FML's machinist David Keil, NASA Ames Fabrication Shop and Machine Shop for all their work they have done for this project in creating the baffled slots and floor, as well and the rest of the uPSP and PIV team. Lastly my reviewers, Kristen Matsuno and Avraham Gileadi.

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