NASA's Unsteady Pressure-Sensitive Paint Research and Operational Capability Developments

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Extended Abstract

In the last three years, several advancements have been made to produce a new state-of-the-art capability in the field of Aerosciences. NASA's Aerosciences Evaluations and Test Capabilities (AETC)[1] Portfolio Office has funded a multi-year project to produce the unsteady Pressure-Sensitive Paint (uPSP) technology as an operational capability in key ground test facilities at NASA. The research and development has primarily been conducted at NASA Ames Research Center's (ARC) Unitary Plan Wind Tunnel (UPWT)[2] 11-by 11-ft Transonic Wind Tunnel (TWT). The NASA ARC UPWT is one of the ground test facilities under NASA AETC's Portfolio Office. AETC's goals are to provide the tools to deliver the technology innovations and breakthroughs necessary to address increasingly complex research and development challenges. AETC's integrated approach will consider the complimentary high-end compute capabilities necessary to advance analysis in conjunction with ground experimental capabilities.

The uPSP Capability Challenge Project is a demonstration of several different technologies: 1) the unsteady Pressure-Sensitive Paint (uPSP) technology, and 2) Project: Red Rover, establishing a secure, reliable, fast connection between experimental and computation facilities, leveraging NASA's computational resources within the High-End Compute Capability (HECC)[3] Project for processing, storing, and sharing data efficiently. This project demonstrates the technical diversity and technical inclusion need to advance the field of Aerosciences. The approach to combine subject matter experts in experimental methods, optical methods, production wind tunnel testing, network engineering, high-end computing, signal processing, grid generation, and visualization while establishing the required infrastructure for subject matter experts to have access to the data while the wind tunnel test is being conducted.

The most recent advancements for the uPSP technology have focused on three key areas: development of data products, robust processing pipeline, operational efficiencies and uncertainty quantification.

1. Data Products Development

The required data product for the uPSP technology to gain acceptance by the community-at -large is comparisons of the paint data to traditional discrete unsteady pressure transducers[4]. Recent work has

matured the analysis required to compare these two different data sources. A single uPSP measurement (either a grid nose or a single camera pixel) is dominated by camera shot noise. The integration of uPSP data over an area has shown benefits like reducing camera shot noise, however, aerodynamic flow-features are also attenuated with integration over an area. Figure 1 displays the uPSP integration previously was much lower than the discrete point sources measurements, i.e.. Kulites ® due to this integration. A Joint Acceptance Attenuation Factor, as a function of frequency, of the integrated pressure with uPSP data is under development and will be described in detail[5].
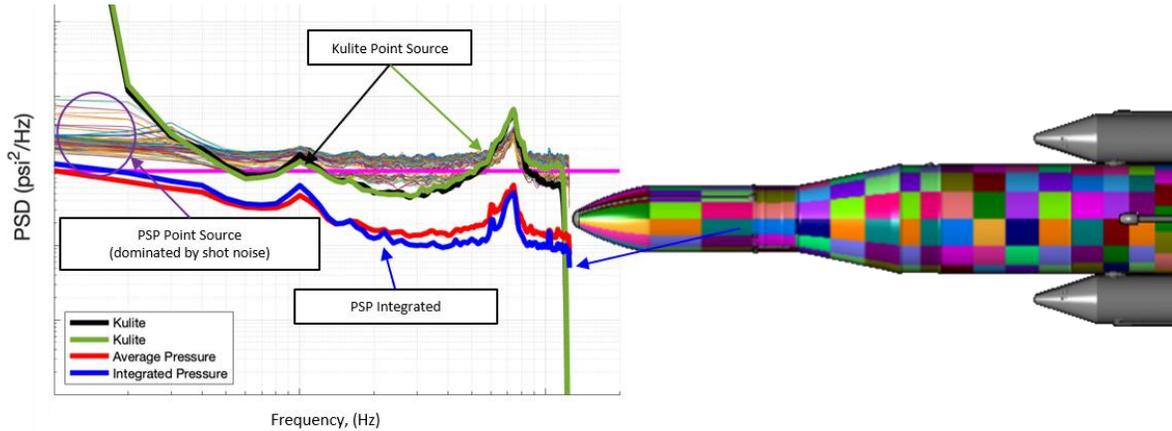

Figure 1: uPSP Patch Integration Comparison to Kulite Point Source Measurements

Other high-value data products like panel integrationsfor structural analysis, turbulent boundary layer convective velocity, dynamic mode decomposition (DMD)[6], and wavenumber-frequency[7] have been further developed using the uPSP data.

During the development of the patch integration methodology for structural analysis, the data has shown the uPSP technology would be excellent for tunnel tone diagnostics to detect what tones, or noise, are generated by the wind tunnel. By averaging over large patches of the uPSP data, all shot noise and aerodynamic features are attenuated by averaging. The only signals left are acoustics from the facility, as shown in Figure 2.
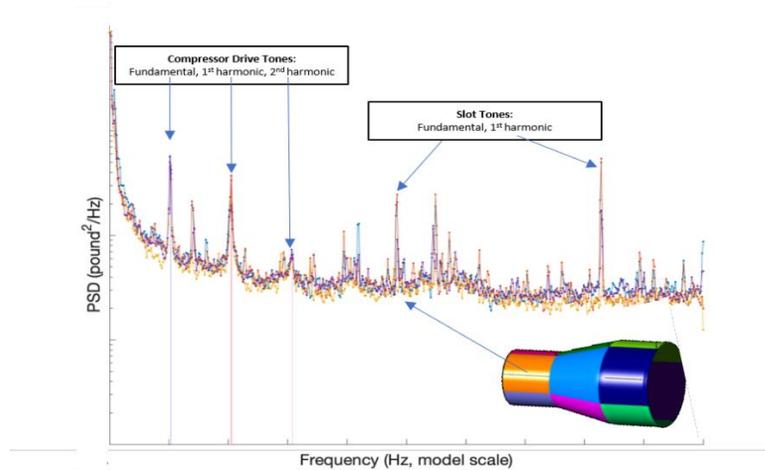

Figure 2: uPSP Panel Integration for Wind Tunnel Diagnostics

Previous acoustic surveys at the NASA ARC UPWT have documented, but recent studies have shown these results are sufficient for subsonic conditions[8,9]. This is not a critique of the previous work, but rather, a proposal for complimentary acoustic surveys to be conducted while employing the uPSP technology, and other optical technologies, to support the need for advanced aerospace vehicle testing. Powerful analysis tools like the DMD and wavenumber-frequency spectra can be used to show phase and direction of an acoustic or turbulent feature. With the boom in launch vehicles in design and development to support NASA and other public and private space industry needs, there is a surge in wind tunnel testing to assess low-frequency buffet loads. The uPSP can be applied to walls of the facility to act as an acoustic survey to collect this required data. For determining buffet loads, it is crucial to know what tones acoustic (facility generated) and what tones are turbulent (model-generated). Oftentimes, lower frequency acoustic tones overlap, the buffet frequencies of greatest interest.

2. Processing Pipeline

The uPSP processing pipeline has been seen several operational improvements allowing for uPSP data from multiple high-speed cameras for a single wind tunnel condition to be processing in minutes, rather than hours. This software[10] has been in development since 2016.

The uPSP has team further developed an operational data processing pipeline capability to process dense uPSP surface pressure measurements (1000x higher resolution than traditional pressure transducers) at a speed 10,000x faster than the initial baseline capability from 2018. This notable achievement leverages the NASA HECC resources to store, process, and transfer the high-spatial resolution surface pressure data in near real-time. The software is modular and flexible to handle multiple wind tunnel events. The team also completed the design of a novel, networked software application for remote access and visualization of output uPSP datasets. The solution complies with stringent NASA network security policies and simplifies how customers will securely access, and gain insight into, dense uPSP data products from anywhere in the world.

Intrinsic and extrinsic camera calibrations[11] have leveraged open-source software, like OpenCV[12], and off-the-shelf tools, like Calib.io Calibrator Software to decrease external calibration uncertainty.

Operational Efficiencies

The operational capability has been demonstrated multiple times at the ARC UPWT[13,14] and has shown, even in its infancy, the uPSP capability does not have significant impacts on tunnel productivity. More work has been done to achieve a sustainable, secure, reliable, fast connection between the NASA ARC UPWT and the NASA Advanced Supercomputer (NAS) (under NASA's HECC project). One of the goals of the uPSP Capability Challenge project is to imagine what ground testing looks like 10-20 years from now and start executing those ideas. There are several technical and sociotechnical benefits, as well as obvious financial benefits, by connecting the two facilities and having the experimental data available to a larger group of individuals.

- Technical benefit:
    o Directly enable technologies with large experimental data sets (>100 GB), like uPSP and some buffet test with 200+ unsteady pressure transducers) by making large storage and compute resources available that are severely limited on personal workstations
    o Accelerate scientific discovery by allowing processing the raw data and make results available as quickly as it is generated[15].
    o Allow a broader group of analysts to view the data while wind tunnel test is being conducted
    o Shares more information with more technical experts quicker
    o Allow for test matrix decisions from all the stakeholders while wind tunnel test is being conducted
    o Reduce the design cycle time
    o Quicker diagnostics of unexpected results
    o Consolidate experimental results and computational simulations to one location

- Sociotechnical benefits:
  - o Allows employees with any travel restrictions to make positive contribution to wind tunnel test without the requirement to travel since data is available through secure connection.

A couple caveats to highlight:

  - o Decrease travel cost does not imply no travel cost. There is an essential staff required to execute any wind tunnel test successfully, however, this connection between ground test facilities and high-end computing allows for more people to analyze the data and offer feedback than before.
  - o If the test is running multiple shifts, a customer will probably desire a complementary group back home on the same shift analyzing data.
  - o Version control of preliminary wind tunnel data and final wind tunnel data must be established.
  - o Preparation before the wind tunnel test is key. Access to wind tunnel data while wind tunnel test is being conducted is only as good as the preparations before the wind tunnel test starts.

Lastly, in order to produce an absolute pressure, a steady-state pressure measurement must be acquired. The steady-state pressure is used to set the gain[16] for the uPSP data. Traditionally, this is done using cameras, paint, and separate processing hardware. However, the current mythology requires the installation of two systems. A new methodology[17] and capability is in development and will increase in operational efficiency and decrease uncertainty but acquiring the steady-state pressure via the high-speed cameras and processed in the uPSP processing pipeline decreases the operational complexity and contains the technology to one system.

3. **Uncertainty Quantification**
   The uPSP team has increased confidence in uPSP measurements via end-to-end uncertainty quantification (UQ). The team developed a digital twin of the uPSP system leveraging a high-performance, physics-based scene renderer to simulate the physical wind tunnel model, light sources, and camera sensor output images. The digital twin maintains "ground-truth" physics-based parameters and enables the team to support wind tunnel customers with analyses such as Monte-Carlo-based UQ studies.

Future Work

The uPSP technology has been accelerated by leveraging industry-standard, opensource tools. To enable other facilities, whether large-scale production facilities or small academic research facilities, the processing software will be released as an opensource project within the next year.

It will be crucial to deploy the uPSP system on a launch-vehicle-like model to have an open data set that demonstrates the panel integration analysis and direct input to finite-element analysis. This has been shown the greatest interest from the launch vehicle community.

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