uPSP Test Technology Capability Challenge

Spectral Proper Orthogonal Decomposition of uPSP Measurements in Recent NASA Ames Wind Tunnel Test

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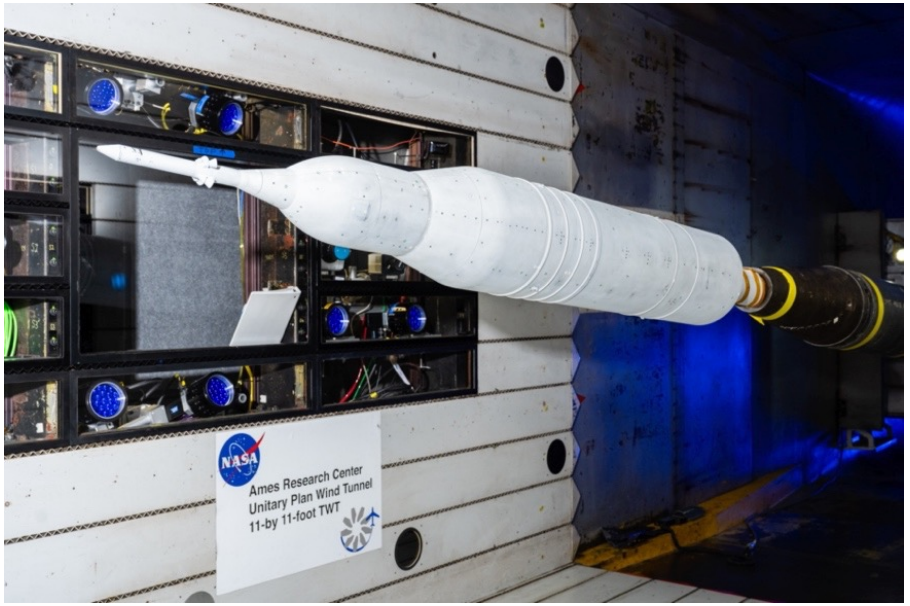
Introduction

- This paper discusses Spectral Proper Orthogonal Decomposition (SPOD) of the Unsteady Pressure-Sensitive Paint (uPSP) measurements in the Launch Vehicle Demonstration Test (LVDT).
- The uPSP measurements were collected with Phantom high-speed cameras as a part of the LVDT in the 11-by 11-foot transonic wind tunnel at NASA Ames Research Center.



SPOD Algorithm

- SPOD is derived from a space-time proper orthogonal decomposition problem for statistically stationary flows.
- SPOD of uPSP measurements consists of two steps:
  - Full timeseries of uPSP measurements are partitioned into a set of smaller blocks, and each block is converted from the time domain to the frequency domain with the Discrete Fourier Transform (DFT);
  - At each frequency, the Cross Spectral Density (CSD) matrix is estimated with Welch's method, and the SPOD modes are determined as the eigenvectors of the estimated CSD matrix.
- SPOD can be viewed as an extension of the DFT decomposition and the Dynamic Mode Decomposition (DMD).

[1] Towne, A., Schmidt, O. T. and Colonius, T., "Spectral Proper Orthogonal Decomposition and Its Relationship to Dynamic Mode Decomposition and Resolvent Analysis", *Journal of Fluid Mechanics*, Vol. 847, pp. 821-867, 2018.

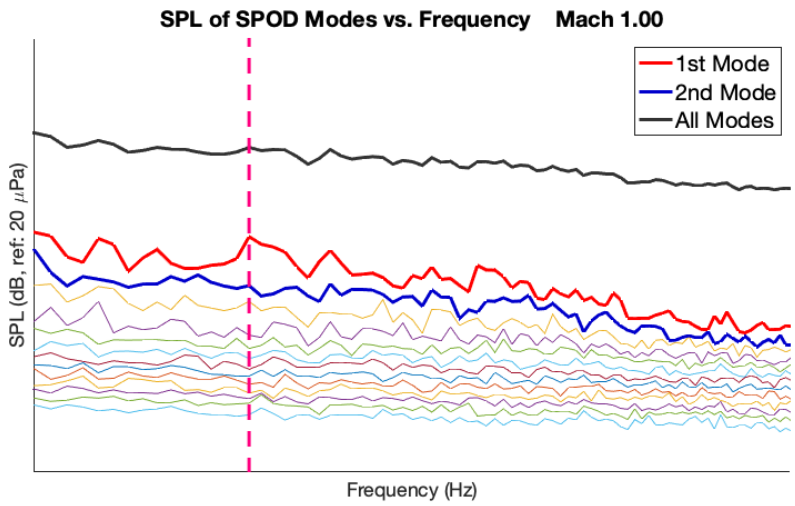
[2] Schmidt, O. T. and Colonius, T., "Guide to Spectral Proper Orthogonal Decomposition", *AIAA Journal*, Vol. 58, No. 3, pp. 1023-1033, 2020.

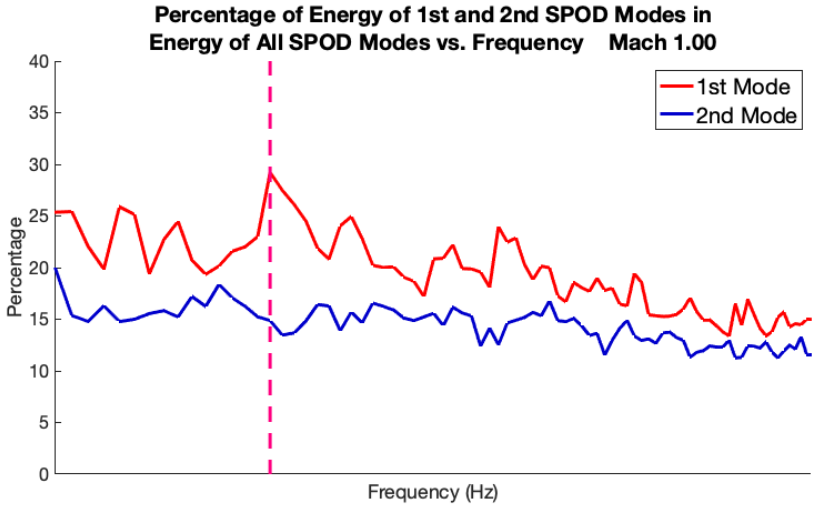
[3] Nekkanti, A. and Schmidt, O. T., "Frequency-Time Analysis, Low-Rank Reconstruction and Denoising of Turbulent Flows using SPOD", *Journal of Fluid Mechanics*, Vol. 926, A26, 2021.

Parameters of SPOD of uPSP Measurements

Parameter	Value
Number of Grid Nodes	633,743
Number of Total Frames	28,672
Number of Frames per Block	4,096
Number of Overlapped Frames	2,048
Number of Blocks	13
Number of SPOD Modes	13
Windowing Function (time)	Hanning window
Sample Frequency (Hz)	10,000
Frequency Resolution (Hz)	2.44

SPOD Outputs of uPSP Measurements at Mach 1.00

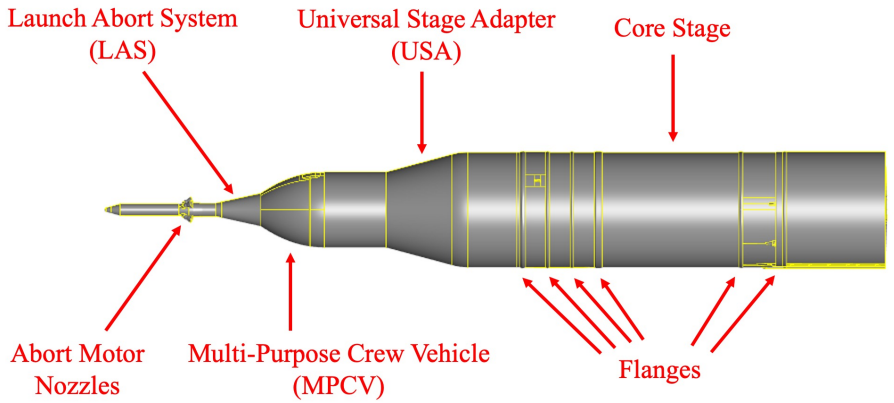




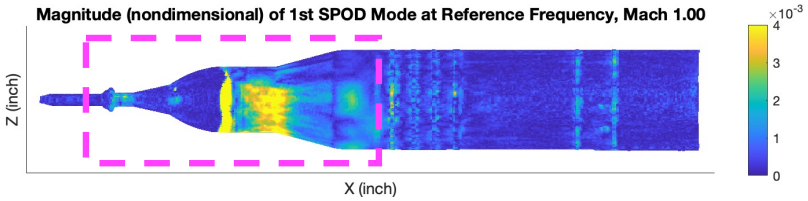
SPOD Mode	Percentage of Energy of the SPOD Mode in Energy of All SPOD Modes at Reference Frequency
1st SPOD Mode	29.2%
2nd SPOD Mode	14.9%
Sum	44.1%

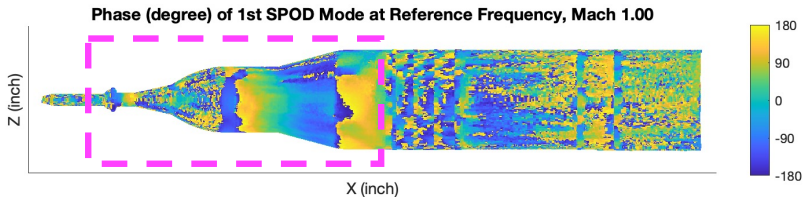
1st and 2nd SPOD Modes of uPSP Measurements at Mach 1.00

- 1st and 2nd SPOD modes of uPSP measurements at the reference frequency
  - Magnitude: nondimensional
  - Phase: ranging from -180º to +180º

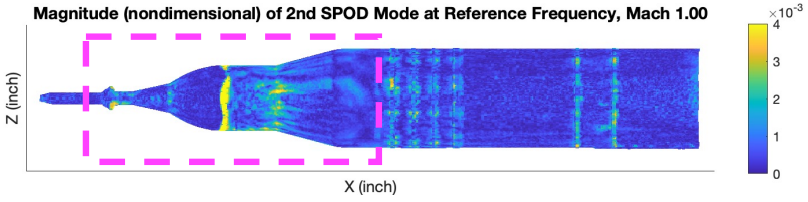


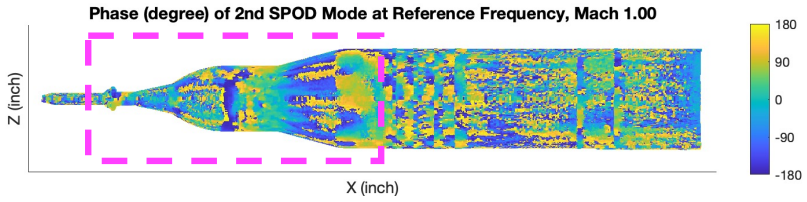
1st SPOD Mode, Mach 1.00





2nd SPOD Mode, Mach 1.00

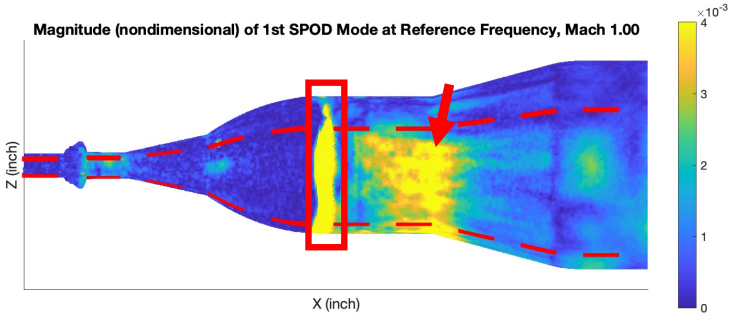


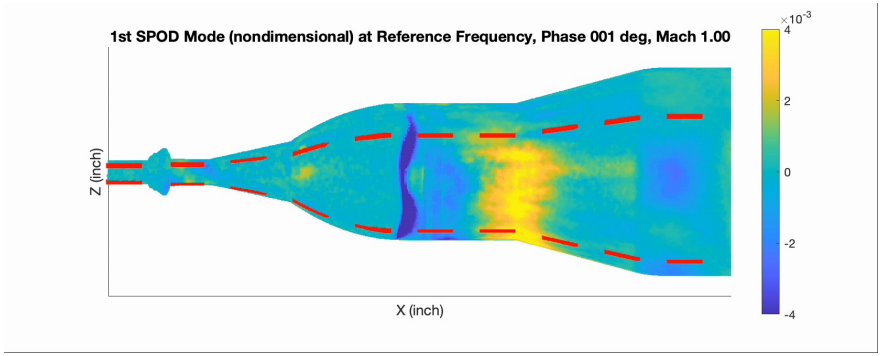


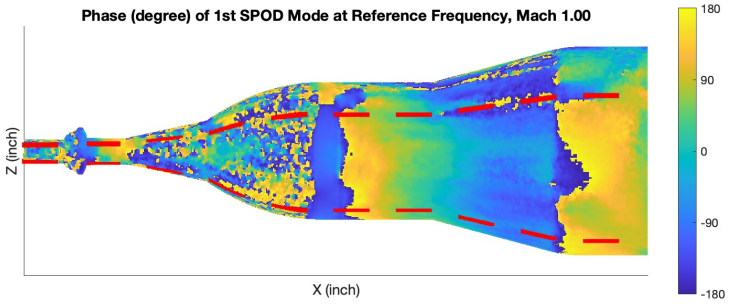
1st SPOD Mode of uPSP Measurements at Mach 1.00

- A bulk turbulent flow, generated by the shock-induced separation of the boundary layer, is observed in the 1st SPOD mode of the uPSP measurements at the reference frequency.

1st SPOD Mode, Mach 1.00



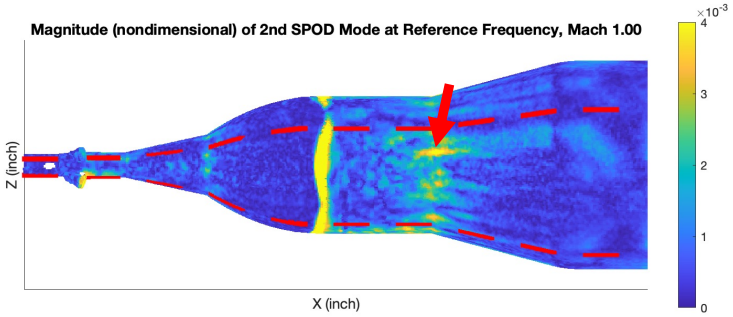


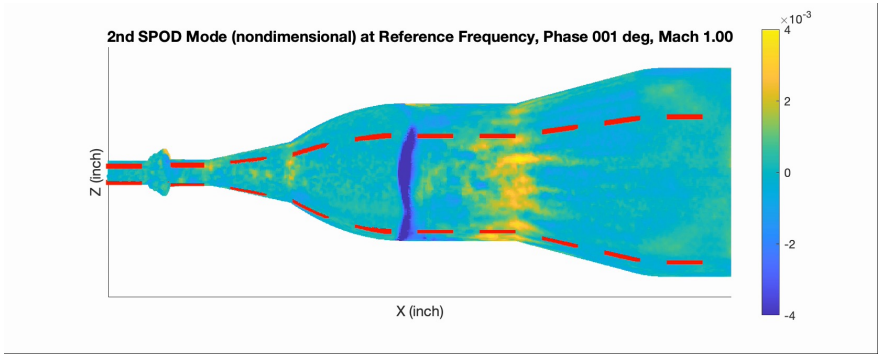


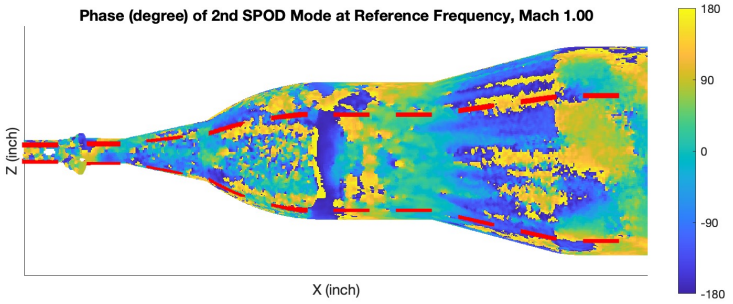
2nd SPOD Mode of uPSP Measurements at Mach 1.00

- Flows separated by the abort motor nozzles are observed in the 2nd SPOD mode of the uPSP measurements at the reference frequency.
- The less energetic mode, shadowed by the dominant mode in the DFT decomposition and the DMD, can be effectively identified with SPOD.

2nd SPOD Mode, Mach 1.00

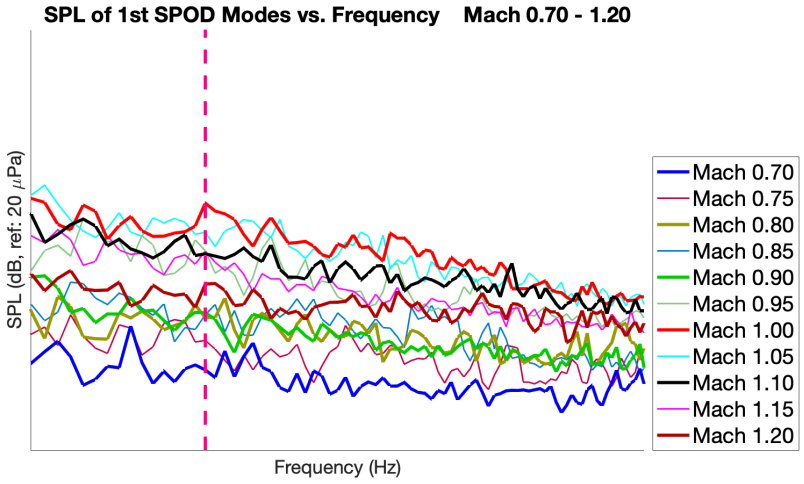


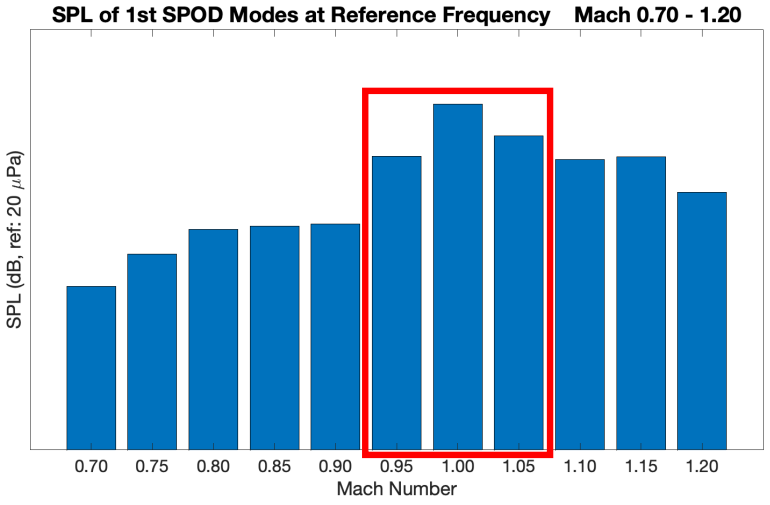




SPOD Outputs of uPSP Measurement in a Mach Sweep

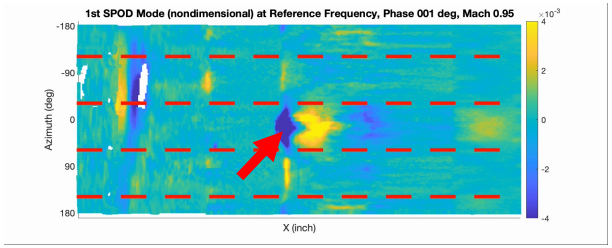
- SPOD outputs of uPSP measurements in a Mach sweep from LVDT
  - Mach numbers were 0.70 through 1.20 in increments of 0.05

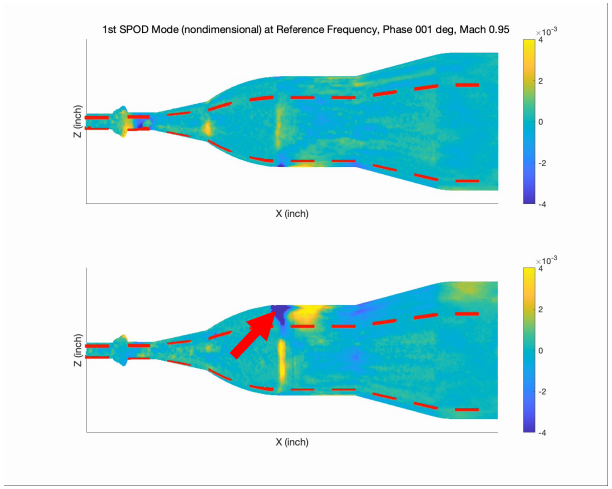




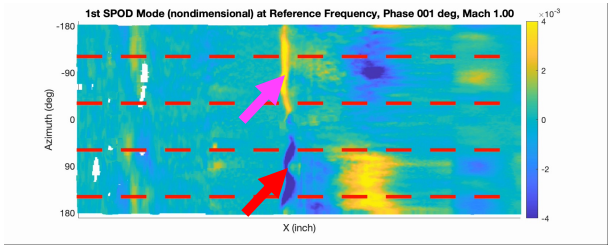
1st SPOD Modes at Mach Numbers 0.95, 1.00 and 1.05

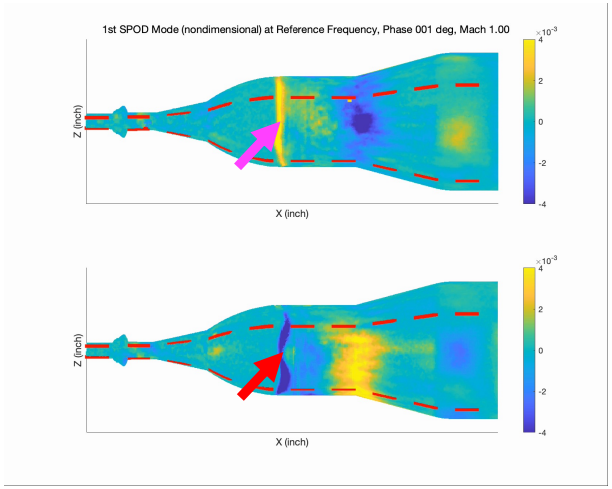
1st SPOD Mode, Mach 0.95



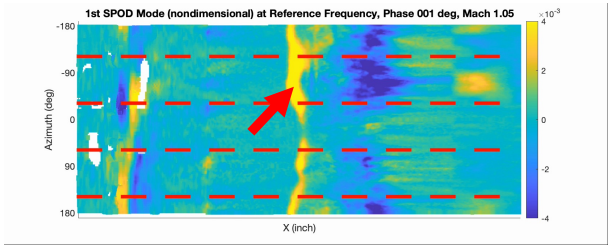


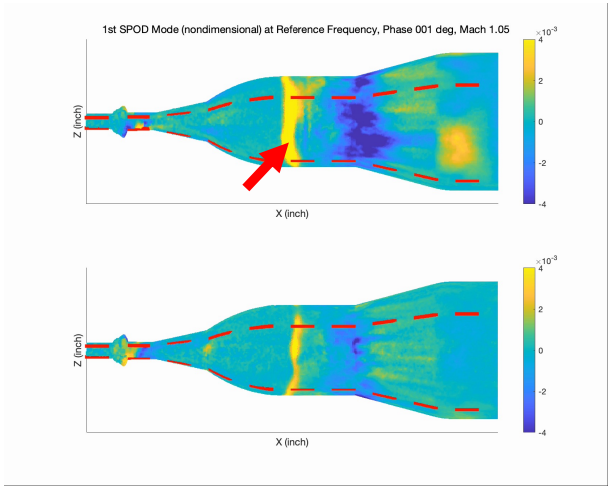
1st SPOD Mode, Mach 1.00





1st SPOD Mode, Mach 1.05





Conclusions

- Preliminary results of SPOD of the uPSP measurements in the LVDT are presented.
- Effectiveness of SPOD in the identification, diagnosis and analysis of the aerodynamic and aeroacoustic phenomena is demonstrated.
  - The measurements of the uPSP have much higher spatial resolution compared to those of the conventional pressure transducers.
- The features of complicated physical processes are effectively identified from the SPOD outputs of the uPSP measurements.
  - Shock
  - Bulk turbulent flow generated by the shock-induced separation of the boundary layer
  - Flow separated by the abort motor nozzles

Acknowledgement

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