

uPSP Test Technology Capability Challenge

Aeroacoustic Analysis using Dynamic Mode Decomposition of Unsteady Pressure-Sensitive Paint Measurements

Jie Li¹, Nettie H. Roozeboom², E. Lara Lash², Marc A. Shaw-Lecarf², Jennifer K. Baerny², Theodore J. Garbeff²,
Lawrence A. Hand², Christopher E. Henze², David D. Murakami², Nathaniel T. Smith²

¹Metis Technology Solutions, Inc., Moffett Field, CA 94035

²NASA Ames Research Center, Moffett Field, CA 94035

2024 AIAA SciTech Forum, Orlando Florida

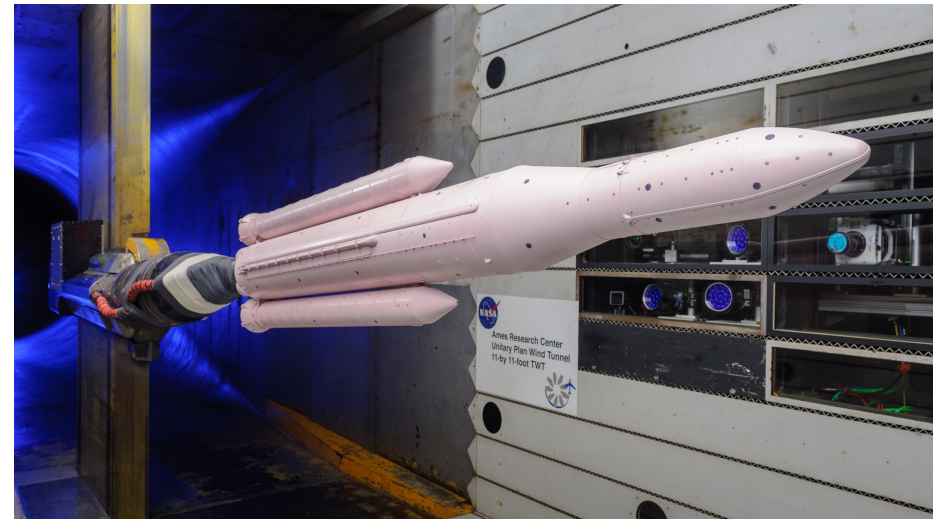
January 8-12, 2024



Introduction



- A new method for the diagnosis and analysis of aeroacoustic phenomena is presented, based on the visualization and analysis of the outputs of Dynamic Mode Decomposition (DMD) of the Unsteady Pressure-Sensitive Paint (uPSP) measurements.
- uPSP measurements were collected with Phantom high-speed cameras in the Space Launch System (SLS) Ascent Transient Aerodynamics Test (ATAT) with the 11-by-11-foot transonic wind tunnel at NASA Ames Research Center.



DMD of uPSP Measurements



- The method is demonstrated by investigating the vortex shedding tone generated by the forward attachment of the Solid Rocket Booster (SRB).
- As examples, the DMD outputs of the uPSP measurements in a subsonic test (freestream Mach number 0.73) in the SLS ATAT are presented.

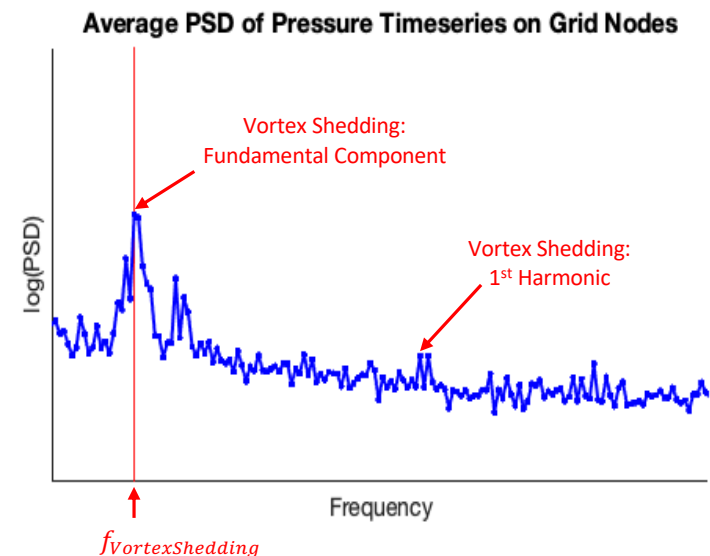


Estimation of Vortex Shedding Frequency



- Estimated vortex shedding frequency (in Hz), $f_{VortexShedding}$, is determined as the frequency corresponding to the peak of the average Power Spectral Density (PSD)
- Uncertainty of estimated vortex shedding frequency (in Hz)

$$\begin{aligned}\Delta f_{VortexShedding} &= 10000 \text{ Hz} / 1024 \\ &= 9.7656 \text{ Hz}\end{aligned}\quad (1)$$



Estimated Wavelengths from Plot of Phase

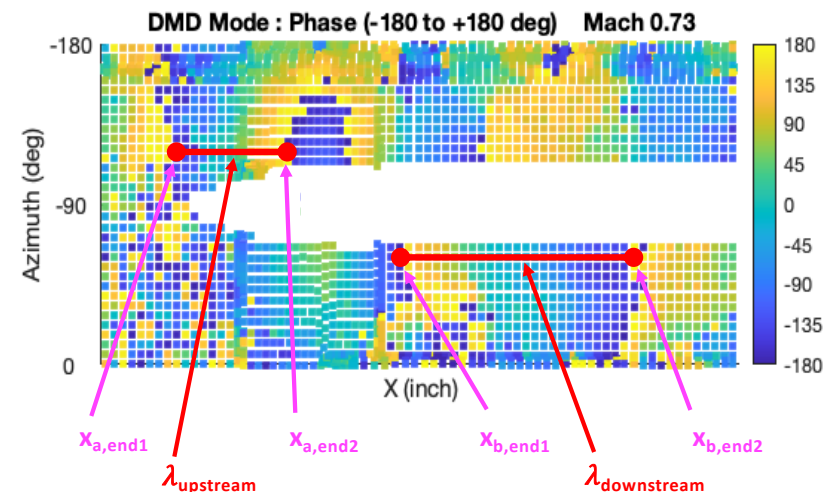


- Estimated wavelengths (in ft)

$$\lambda_{upstream} = (x_{a,end2} - x_{a,end1})/12 \quad (2)$$

$$\lambda_{downstream} = (x_{b,end2} - x_{b,end1})/12 \quad (3)$$

- Uncertainties of estimated wavelengths (in ft): $\Delta\lambda_{upstream}$ and $\Delta\lambda_{downstream}$



Estimated Wavelengths from the Slope (1)



- Linear Model

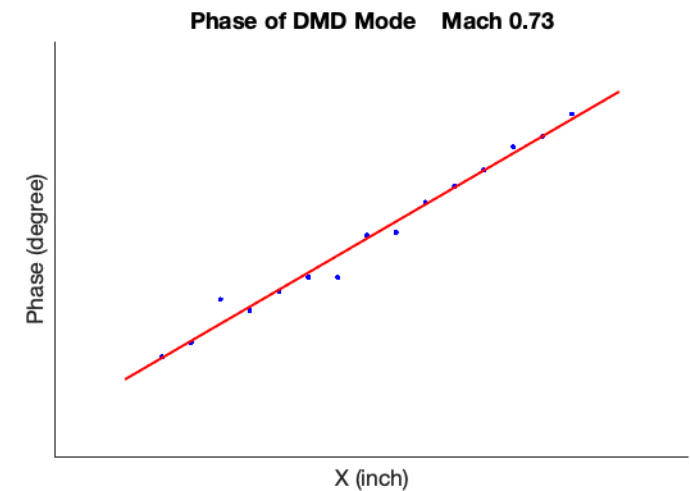
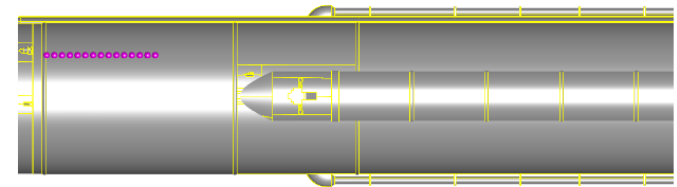
$$\Phi_a = H_a \theta_{upstream} + E_a \quad (4)$$

- Least-Squares Fit

$$\hat{\theta}_{upstream} = (H_a^T H_a)^{-1} H_a^T \Phi_a \quad (5)$$

$$P_{\hat{\theta},upstream} = \sigma^2 \cdot (H_a^T H_a)^{-1} \quad (6)$$

- Estimated Slope $\hat{k}_{upstream}$
and Uncertainty $\Delta\hat{k}_{upstream}$
(in deg/inch)



Estimated Wavelengths from the Slope (2)



- Estimated Slope $\hat{k}_{downstream}$ and Uncertainty $\Delta\hat{k}_{downstream}$ (in deg/inch)

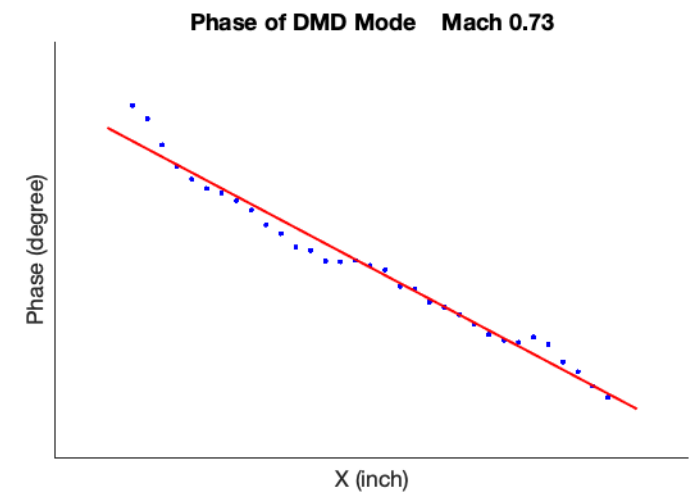
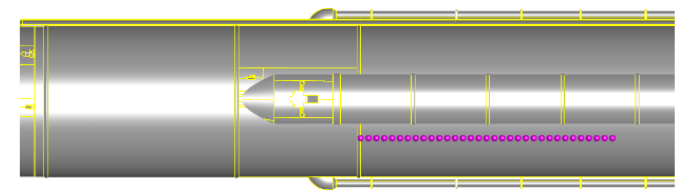
- Estimated Wavelengths and Uncertainties (in ft)

$$\lambda_{upstream} = 360/\hat{k}_{upstream}/12 \quad (7)$$

$$\lambda_{downstream} = 360/|\hat{k}_{downstream}|/12 \quad (8)$$

$$\Delta\lambda_{upstream} = 360/12 \cdot \Delta\hat{k}_{upstream}/\hat{k}_{upstream}^2 \quad (9)$$

$$\Delta\lambda_{downstream} = 360/12 \cdot \Delta\hat{k}_{downstream}/\hat{k}_{downstream}^2 \quad (10)$$



Estimated Speeds of the Waves (1)



- Estimated Speeds of the Waves and Uncertainties (in ft/s)

$$U_{upstream} = \lambda_{upstream} \cdot f_{VortexShedding} \quad (11)$$

$$U_{downstream} = \lambda_{downstream} \cdot f_{VortexShedding} \quad (12)$$

$$\Delta U_{upstream} = \Delta \lambda_{upstream} \cdot f_{VortexShedding} + \lambda_{upstream} \cdot \Delta f_{VortexShedding} \quad (13)$$

$$\Delta U_{downstream} = \Delta \lambda_{downstream} \cdot f_{VortexShedding} + \lambda_{downstream} \cdot \Delta f_{VortexShedding} \quad (14)$$

Estimated Speeds of the Waves (2)



Test Parameters	Values
Measured Mach Number, M	0.7296
Speed of Sound (ft/s), c	1076.7
Speed of Freestream Flow (ft/s), U_{∞}	785.6

Waves	Variables	Estimated Values from Phase Plot	Estimated Values from Phase Slope
Wave traveling in upstream direction	Speed of the Wave (ft/s), $U_{upstream}$	299.7 ± 26.8	301.9 ± 14.5
	Ratio of Speed of the Wave to Speed of Sound, $U_{upstream}/c$	0.28 ± 0.02	0.28 ± 0.01
	Ratio of Speed of the Wave to Speed of Freestream Flow, $U_{upstream}/U_{\infty}$	0.38 ± 0.03	0.38 ± 0.02
Wave traveling in downstream direction	Speed of the Wave (ft/s), $U_{downstream}$	587.6 ± 31.5	598.9 ± 25.6
	Ratio of Speed of the Wave to Speed of Sound, $U_{downstream}/c$	0.55 ± 0.03	0.56 ± 0.02
	Ratio of Speed of the Wave to Speed of Freestream Flow, $U_{downstream}/U_{\infty}$	0.75 ± 0.04	0.76 ± 0.03

Measured Speed of the Acoustic Wave



- First, we assume an observer in a reference frame fixed to the ground

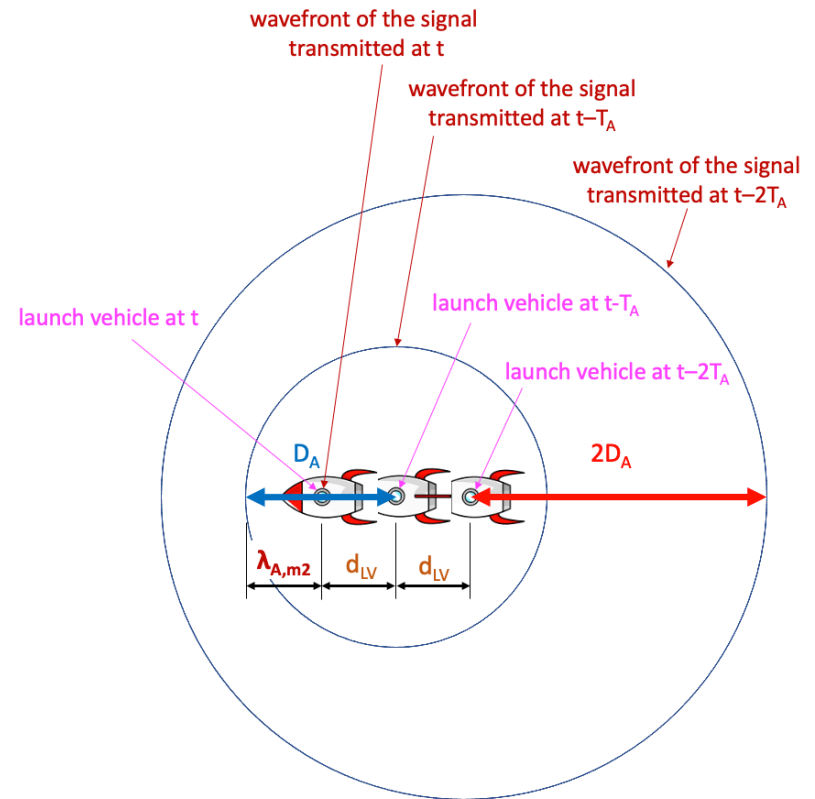
$$\lambda_{A,m2} = D_A - d_{LV} \quad (15)$$

$$U_{A,m2} = c - v_{LV} \quad (16)$$

- Next, we assume the observer is moved to a reference frame fixed to the wind tunnel and the launch vehicle

$$U_{\infty} = v_{LV} \quad (17)$$

$$U_{A,m2} = c - U_{\infty} \quad (18)$$



Conclusions



- A new method for the diagnosis and analysis of the aeroacoustic phenomena is presented in this paper, based on the visualization and analysis of the DMD outputs of the uPSP measurements.
- As examples, the DMD outputs of the uPSP measurements in a subsonic test in the SLS ATAT are presented and used in the estimation of the vortex shedding frequency, the wavelengths and speeds of the traveling waves at the vortex shedding frequency.
- It is demonstrated the information retrieved from the DMD outputs of the uPSP measurements can be effectively used in the identification and diagnosis of the aeroacoustic phenomena.

Acknowledgement



- Funding was provided by the NASA Aerosciences Evaluation and Test Capabilities (AETC) Portfolio Office.
- The authors would like to thank James Bell, Paul Bremner, Nicholas Califano, Bob Ciotti, David Ellsworth, Ross Flach, Patrick Heaney, Jaffar Iqbal, Alan Landman, Bruce Laverde, Kenneth Lyons, Blair Mclachlan, Patrick Moran, Bron Nelson, Jack Ortega, Jayanta Panda, David Piatak, Victoria Pollard, James Ramey, James Ross, Timothy Sandstrom, Martin Sekula, Francesco Soranna, Thomas Steva, Craig Streett, Paul Stremel, Lucy Tang and Thomas Volden for their expertise and advice for the research work of this paper.