Dynamic Modeling of Supersonic Propulsion Systems for Aero-Propulso-Servo-Elasticity Analysis

NASA Advanced Air Vehicles Program – Commercial Supersonic Technology Project - AeroServoElasticity

George Kopasakis

NASA Glenn Research Center
Cleveland Ohio

NASA Propulsion, Controls and Diagnostics Workshop
Sept. 16-17, 2015, Cleveland, OH

Team Members

GRC
George Kopasakis
Joseph W. Connolly
Noulie Theofylaktos
Jonathan Seidel

LaRC
Walter Silva & team

Outline

- **APSE Goals**
- **AeroServoElastic System Dynamic Modeling**
- **Propulsion System Dynamic modeling**
- **APSE Integration**

AeroPropulsoServoElasticity (APSE) Goals

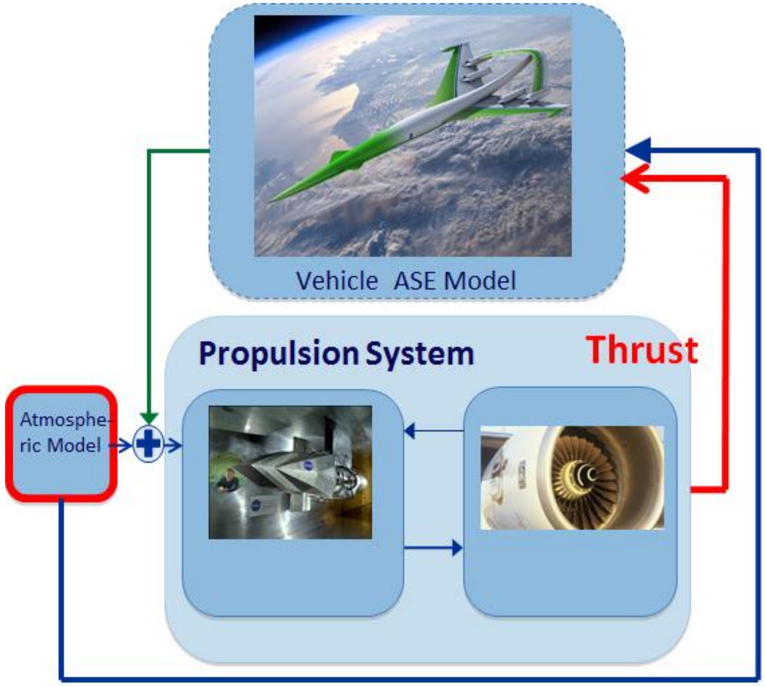
- **Develop dynamic propulsion system and aero-servo-elastic/aerodynamic models, and integrate them together with atmospheric turbulence to study the dynamic performance of supersonic vehicles for ride quality, vehicle stability, and aerodynamic efficiency.**

- **Supersonic vehicles are slender body with more pronounced AeroServoElastic (ASE) modes, which can potentially couple with propulsion system dynamics under various flight conditions to present performance challenges.**

- **<u>Approach for Propulsion System:</u>**

  ○ **Develop 1-Dimensional (1D) component models and 2D models where appropriate to be comparable in frequency range to ASE models.**

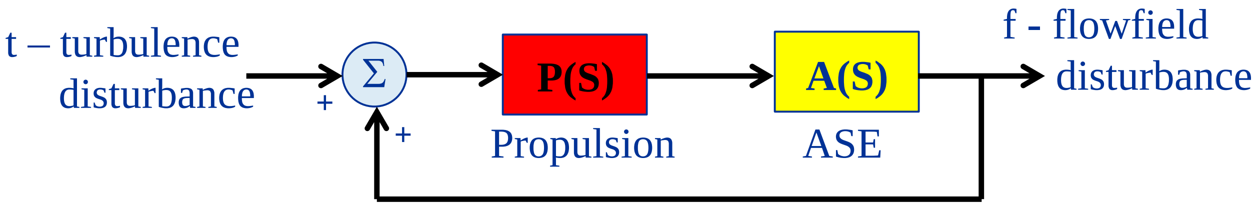
  ○ **Integrate Propulsion with ASE to form a closed-loop dynamic system model to study performance.**



Integrated APSE Model

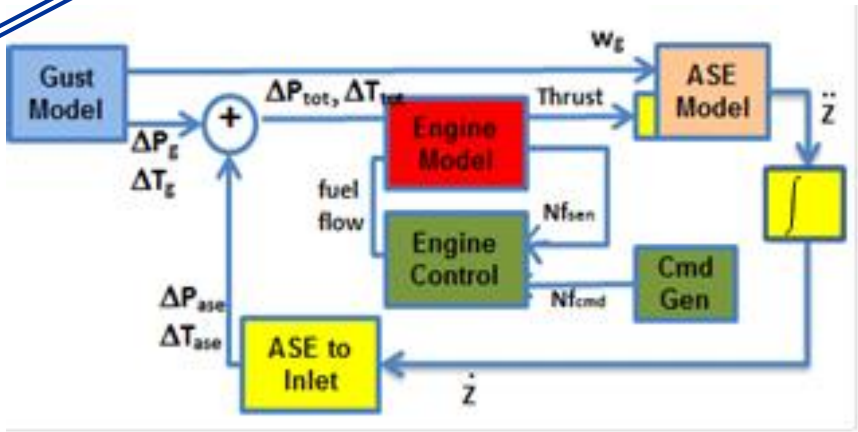
APSE Dynamics - Frequency Range

- **ASE modes extend to about 60 HZ when about half the modes are included in the model.**
- **For that reason propulsion system dynamics need to extend up to approximately 600 Hz in order to also take into account the phase contribution of the propulsion dynamics for the closed-loop system.**



$$\frac{F(s)}{T(s)} = \frac{P(s)A(S)}{1 - P(s)A(s)}$$

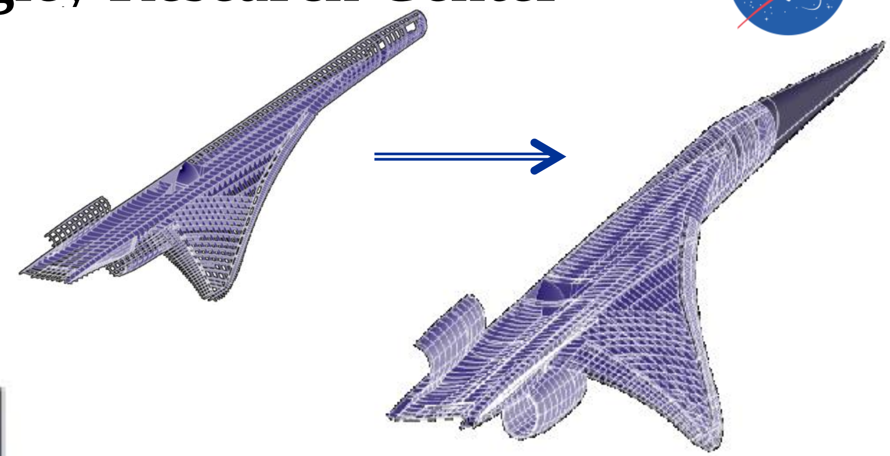
Simplified Closed-loop representation of APSE dynamic coupling

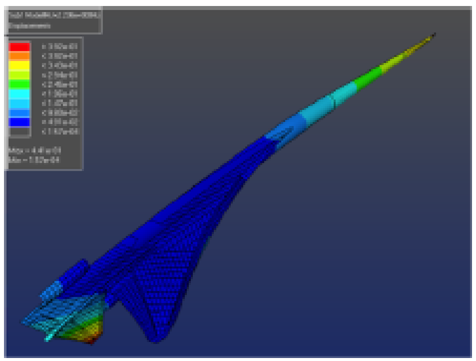


Closed-loop diagram of APSE simulation

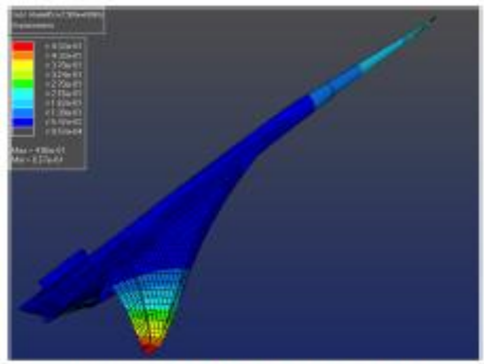
ASE Dynamic Model – Langley Research Center

- **Constructing 3D models to analyze ASE modes and assess flutter conditions.**
- **Utilizing 3D model to develop state space models to integrate with propulsion system.**

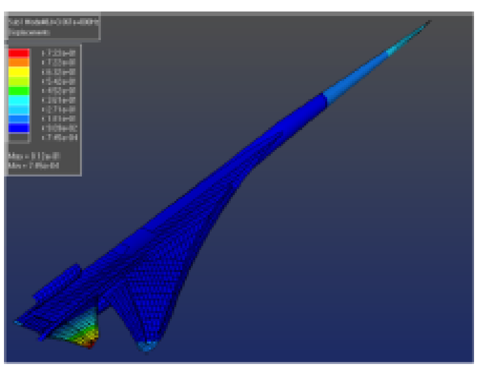




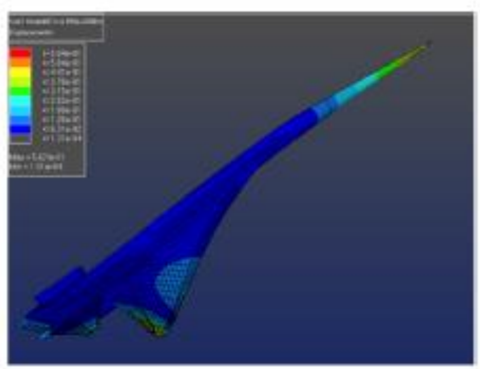
(a) Mode 4, Fuselage Bending, 2.24 Hz



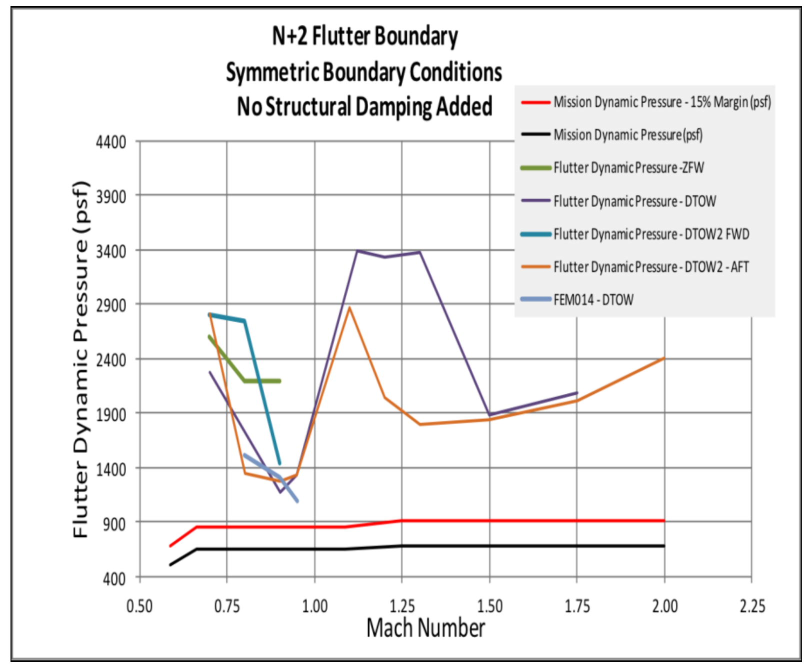
(b) Mode 5, Wing Bending, 2.50 Hz



(c) Mode 6, Tail Bending, 3.06 Hz



(d) Mode 7, Wing Tip Bending-Torsion-Fuselage 2nd Bending, 4.46 Hz

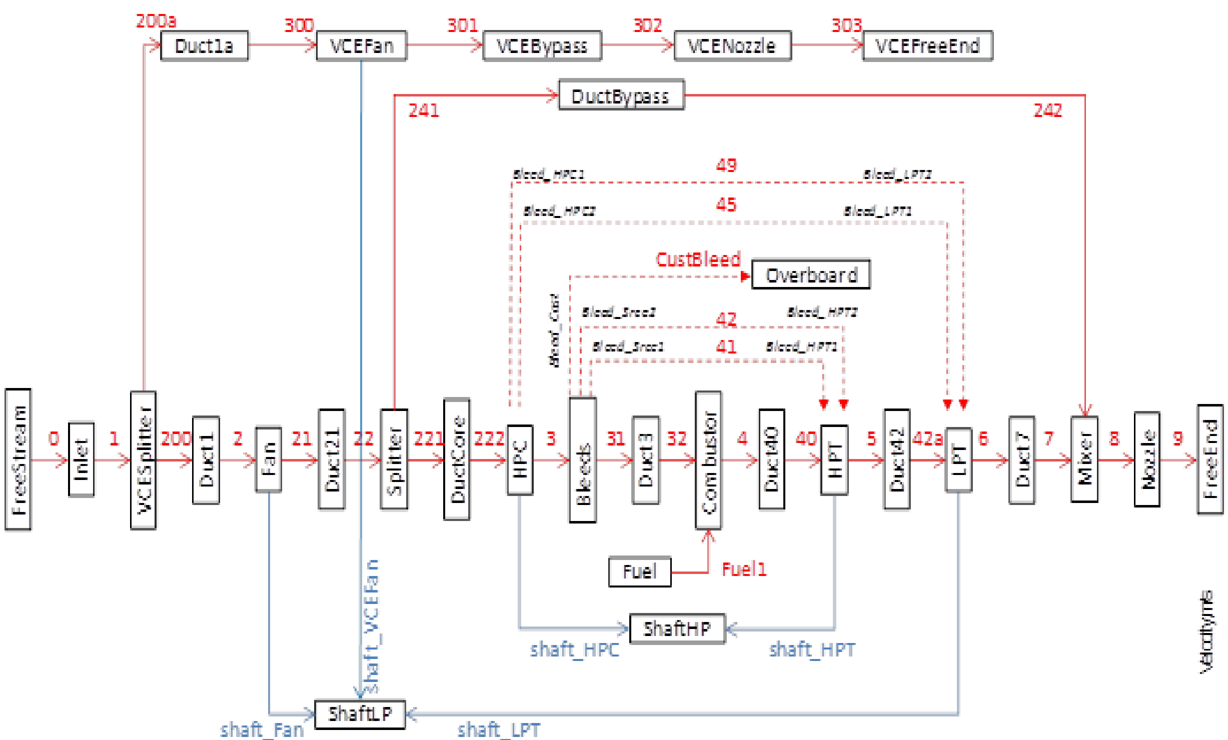


Silva, W. A., et al; "The NASA High Speed ASE Project: Computational Analyses of a Low-Boom Supersonic Configuration," AIAA SciTech, Jan. 13-17,2014

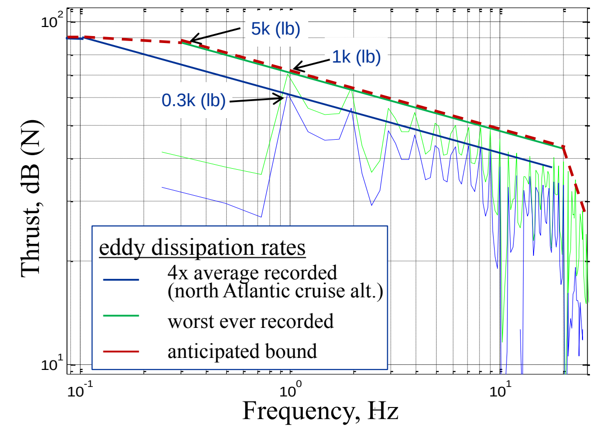
Propulsion System Dynamic Modeling - GRC

- **Modeling all the components with lump volume dynamics and performance characteristics, and adding combustor and shaft dynamics and variable geometry (Inlet Guide Vanes), with lump or quasi-1D inlet and nozzle models**

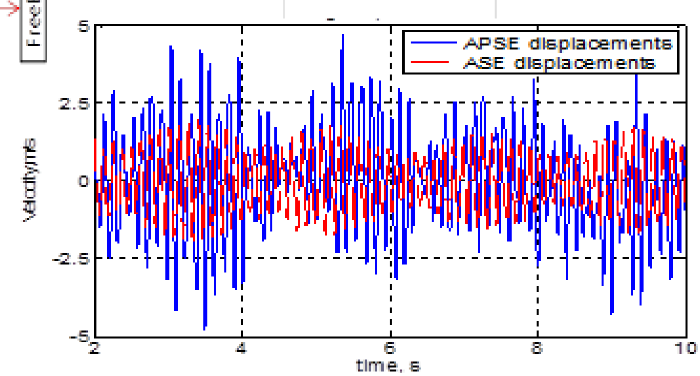
- **Higher fidelity models include 2D/3D inlet & nozzles, stage-by-stage for compressors and turbines, and parallel flow path modeling.**



Variable Cycle Engine (VCE) Model



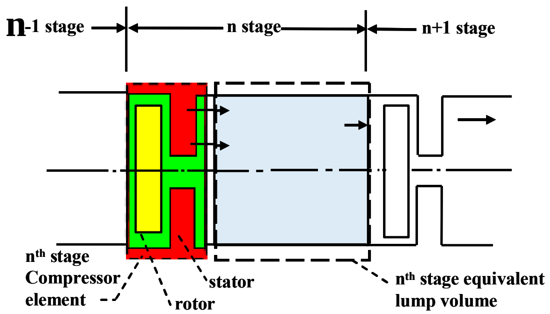
Open Loop thrust spectral Densities



Closed loop vehicle displacements

Engine Component Modeling

1. Lump volume: Component treated as single volume for axial gas dynamics and performance characteristics



Compressor stage

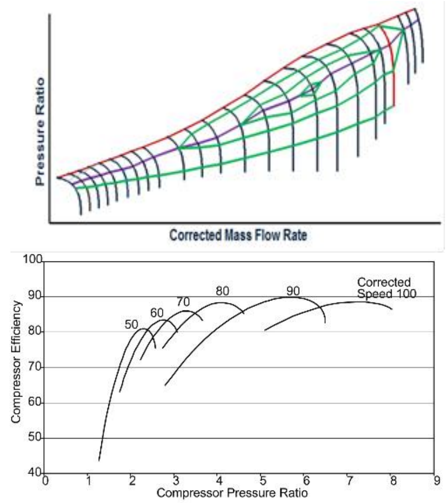
$$\frac{d}{dt}\rho_{sv,n} = \frac{1}{V_n}\left(\dot{W}_{c,n} + \dot{W}_{c,n+1} - \dot{W}_{b,n}\right)$$

$$\frac{d}{dt}\dot{W}_{c,n} = \frac{A_n g}{l_n}\left(P_{tc,n} - P_{tv,n}\right)\left(1 + \frac{\gamma_{cp}-1}{2}M_{mv}^2\right)^{\frac{-\gamma_{cp}}{\gamma_{cp}-1}}$$

$$\frac{d}{dt}\left(\rho_{sv,n}T_{tv,n}\right) = \frac{\gamma_{cp}}{V_n}\left(T_{tc,n}\dot{W}_{c,n} - T_{tv,n}\dot{W}_{c,n+1} - T_{tv,n}\dot{W}_{b,n}\right)$$

$$P_{tv,n} = \left(1 + \frac{\gamma_{cp}-1}{2}M_n^2\right)^{\frac{1}{\gamma_{cp}-1}}\rho_{sv,n}RT_{tv,n}$$

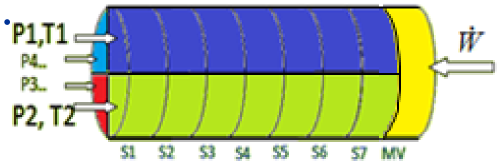
Volume dynamics



Performance maps

2. Stage-by-stage: Component treated as multiple volumes for axial gas dynamics and performance characteristics – new methodology

3. Parallel Flow: Component treated as multiple volumes and multiple flow paths for axial and rotational gas dynamics and performance characteristics – new M.



Parallel flow path compressor model

$$\frac{\partial \rho_s}{\partial t} = -\frac{\partial(\rho_s u)}{\partial x} - \frac{1}{r}\frac{\partial(\rho_s w)}{\partial \varphi}$$

$$\frac{\partial(\rho_s u)}{\partial t} = -u\frac{\partial(\rho_s u)}{\partial x} - \frac{w}{r}\frac{\partial(\rho_s u)}{\partial \varphi} - \frac{\partial P_s}{\partial x}$$

$$\frac{\partial(\rho_s w)}{\partial t} = -u\frac{\partial(\rho_s w)}{\partial x} - \frac{w}{r}\frac{\partial(\rho_s w)}{\partial \varphi} - \frac{1}{r}\frac{\partial P_s}{\partial \varphi}$$

$$\frac{\partial}{\partial t}\left(\frac{P_s}{\gamma-1} + \frac{\rho V^2}{2}\right) = -\frac{\partial}{\partial x}\left[\left(\frac{\gamma P_s u}{\gamma-1} + \frac{\rho u^3}{2}\right)\right] - \frac{1}{r}\frac{\partial}{\partial \varphi}\left[\left(\frac{\gamma P_s w}{\gamma-1} + \frac{\rho w^3}{2}\right)\right]$$

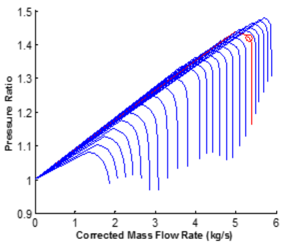
Volume dynamics of stage sector

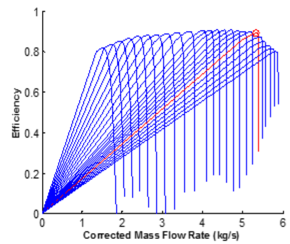
$$\frac{d}{dt}\rho_{s,mv} = \frac{1}{V_{mv}}\left(\dot{W}_{mv} - \dot{W}_{cb}\right)$$

$$\frac{d}{dt}\dot{W}_{mv} = \frac{A_{mv}g}{l_{mv}}\left[\sum_{m=1}^{q}\left(\beta_m P_{tm,n=k}\right) - P_{t,mv}\right]\left(1 + \frac{\gamma_{cp}-1}{2}M_{mv}^2\right)^{\frac{-\gamma_{cp}}{\gamma_{cp}-1}}$$

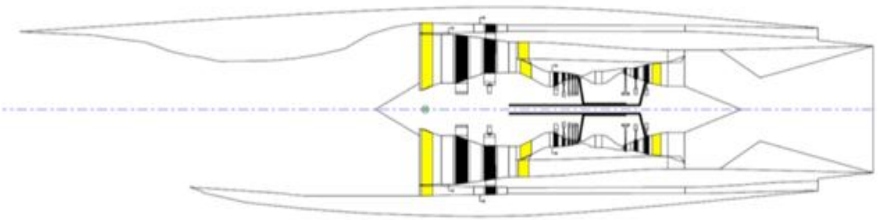
$$\frac{d}{dt}\left(\rho_{s,mv}T_{t,mv}\right) = \frac{\gamma_{mv}}{V_{mv}}\left[\dot{W}_{mv}\sum_{m=1}^{q}\left(\beta_m^2 T_{tm,n=k}\right) - \dot{W}_{cb}T_{t,mv}\right]$$

Mixing volume dynamics

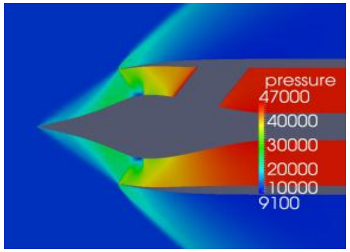




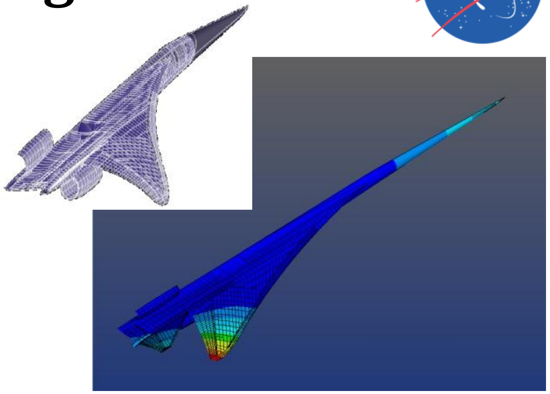
Component Modeling and APSE integration



Propulsion System volume dynamics component modeling (1, 2 & 3)

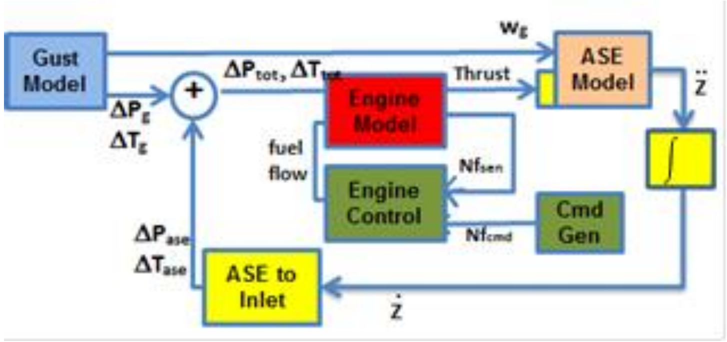


Inlet & Nozzle quasi-1D, 2D/3D Modeling

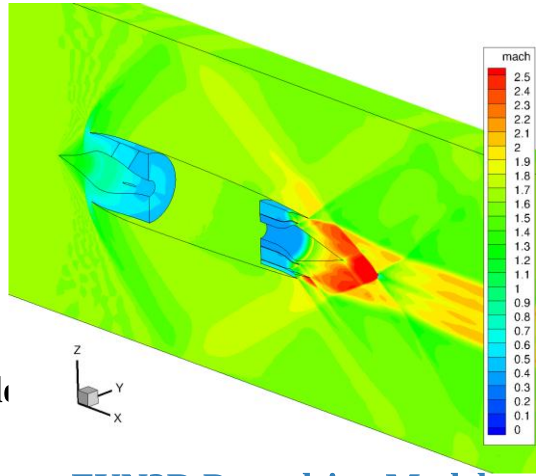


Vehicle Structure – CFL3D/FUN3D & State Space Modeling

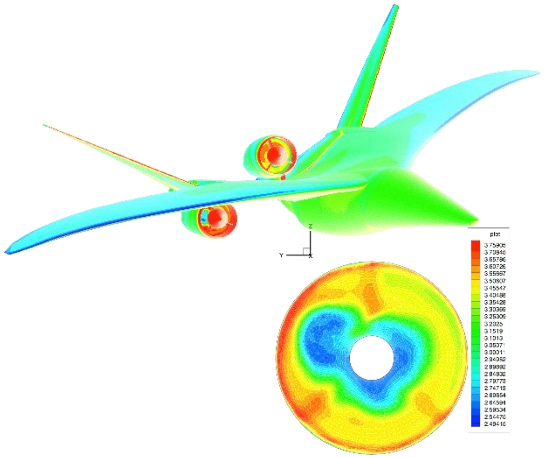
APSE Component Modeling



Integrated APSE (propulsion & structure) vehicle modeling in MATLAB/Simulink



FUN3D Propulsion Model



Integrated FUN3D Vehicle Model

APSE Integrated Modeling

External Disturbance: Atmospheric turbulence modeling – discussed previously

References

1. Silva, W. A., et al. "The NASA High Speed ASE Project: Computational Analyses of a Low-Boom Supersonic Configuration," AIAA 2014-0675, AIAA SciTech Conference, Harbor Maryland, Jan. 13-17, 2014.

2 Kopasakis, G.; Connolly, J. W.; Seidel, J.; "Propulsion System Dynamic Modeling of the NASA Supersonic Concept Vehicle for AeroPropulsoServoElasticity," AIAA 2014-3684, AIAA Joint Propulsion Conference and Exhibit, Cleveland Ohio, July 28-30, 2014.

3 Connolly, J. W.; Jan-Renee-Carlson; Kopasakis, G.; Woolwine, K.; "Nonlinear Dynamic Modeling of a Supersonic Commercial Transport Turbo-Machinery Propulsion System for Aero-Propulso-Servo-Elasticity Research" AIAA 2015-4031, AIAA 2015-4143, 51st AIAA Joint Propulsion Conference and Exhibit, Orlando FL, July 27-29, 2015.

4 Kopasakis, G; Cheng, L.; Connolly, J. W; "Stage-by-Stage and Parallel Flow Path Compressor Modeling for a Variable Cycle Engine" AIAA 2015-4143, 51st AIAA Joint Propulsion Conference and Exhibit, Orlando FL, July 27-29, 2015

5 Connolly, J. W.; Friedlander, D.; Kopasakis, G; "Computational Fluid Dynamics Modeling of a Supersonic Nozzle and Integration into a Variable Cycle Engine Model," AIAA 2014-3687, AIAA Joint Propulsion Conference, Cleveland, Ohio, July 28-30, 2014.

6 Kopasakis, G.; Connolly, J. W.; Kratz, J; "Quasi One-Dimensional Unsteady Modeling of External Compression Supersonic Inlets" 48thst AIAA Joint Propulsion Conference and Exhibit, 2012

7 Kopasakis, G.; Connolly, J. W.; Paxson, D. E.; Ma, P.; "Volume Dynamics Propulsion System Modeling for Supersonic Vehicle Research," GT2008-50524, ASME TurboExpo 2008, Berlin Germany; NASA/TM-215172; Journal of Turbomachinery, Vol. 132, October 2010.

8 Kopasakis, G; "Feedback Control Systems Loop Shaping Design With Practical Considerations," NASA/TM—2007-215007.

9 Kopasakis, G.; "Atmospheric Turbulence Modeling for Aero Vehicles: Fractional Order Fits," NASA/TM—2010-216961/REV1

10 Connolly, J. W; Kopasakis, G; "Loop Shaping Control Design for a Supersonic Propulsion System Model Using QFT Specifications and Bounds" 46th AIAA Joint Propulsion Conference and Exhibit, 2010

Several other references that can be found within the references listed here