Nonlinear Dynamic Modeling of a Supersonic Commercial Transport Turbo-Machinery Propulsion System for Aero-Propulso-Servo-Elasticity Research

51st Joint Propulsion Conference
Propulsion and Energy Forum
July 28th, 2015

Joe Connolly

Jan-Renee Carlson, George Kopasakis, & Kyle Woolwine

Joseph.W.Connolly@nasa.gov

Outline

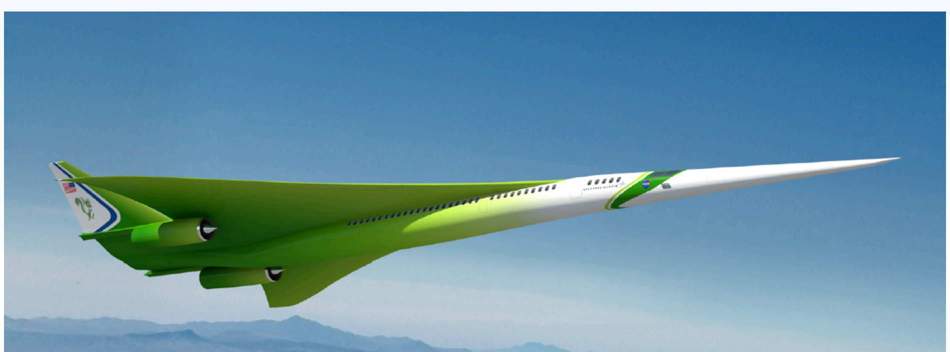
- Introduction and Motivation
- Overview of Commercial Transport & APSE Model
- Quasi-1D Propulsion Modeling
- Coupling Turbo-Machinery with FUN3D
- Results
- Future Work and Conclusions

Introduction and Motivation

- NASA under the Fundamental Aeronautics Program is developing technologies and capabilities to support design of supersonic flight vehicles
- Many technical challenges exists to allow for a commercial supersonic vehicle to be successful
  - New designs for commercial supersonic vehicles are expected to be long and slender
  - It will be imperative to understand the aero-propulso-servo-elastic (APSE) effects
- Two inviscid variations of a propulsion system will be presented to investigate thrust oscillations
  - Quasi-1D model in MATLAB/SIMULINK: Controls Focus
  - The turbo-machinery of the Quasi-1D model coupled with 3D CFD

Supersonic Commercial Transport Vehicle

- N+2 concept vehicle for a low sonic boom configuration
- Two wing mounted engines and one fuselage mounted engine



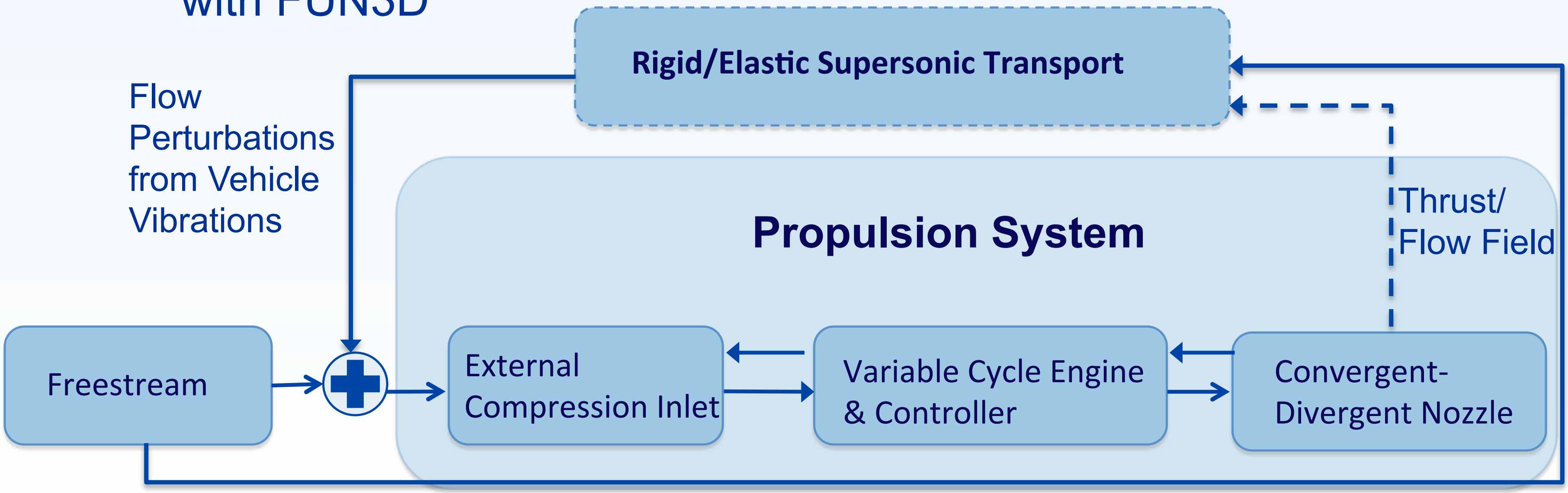
Concorde Comparison

- 21% Longer, 15% Slower

Geometry		
Length	Span	Height
244 ft	84 ft	30.5 ft
Cruise Operating Condition		
Altitude	Mach	Angle of Attack
50,000 ft	1.7	2.25 deg.

Aero-Propulso-Servo-Elasticity (APSE) Model

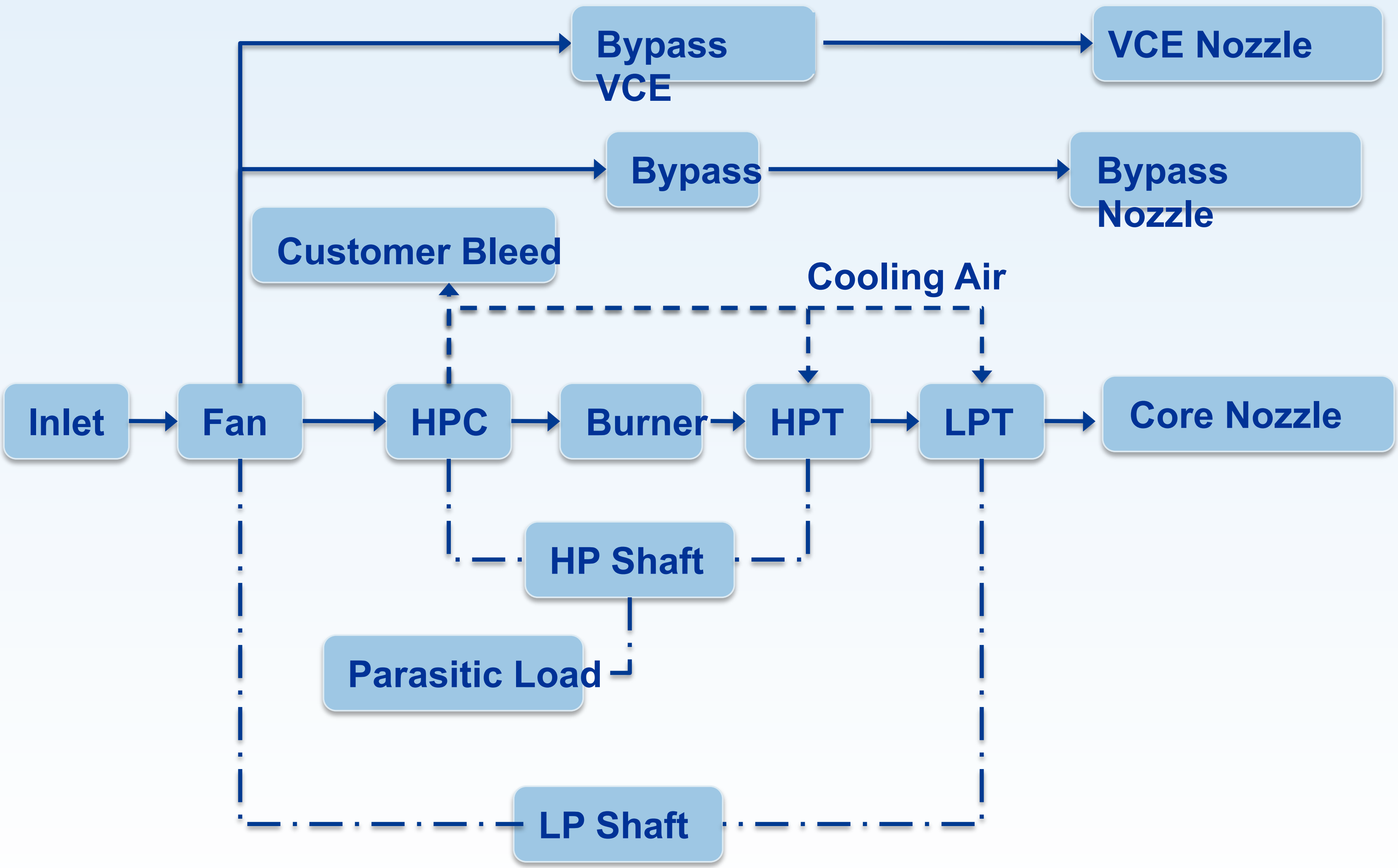
- The ultimate goal of the propulsion model is to develop an accurate thrust estimate for an overall APSE simulation
  - Fully Unstructured Navier-Stokes in Three Dimensions is a code being used for CFD based aero-elastic studies using structural modes shapes
  - Focus of this work is on developing a Quasi-1D model to be used for propulsion system dynamic and control studies and interfacing with FUN3D



Turbo-Machinery Engine Model Overview

- All of the Component level models are developed in MATLAB/SIMULINK
- Common model across Quasi-1D and FUN3D
- Modeled using Quasi-1D volume dynamics, where each component is considered a volume
  - Compressor, combustor, turbine, and ducts
  - Numerically integrate the three conservation equations using a technique by Seldner
    - Engine Face Boundary – Subsonic Inflow:
      - Define Total Pressure and Total Temperature
    - Engine Exit Boundary – Subsonic Outflow
      - Nozzle choked mass flow equation assuming ideal expansion
- NPSS simulation results initialized the dynamic model

Variable Cycle Engine (VCE) Model



Inlet/Nozzle Model Overview

- The MacCormack Method is used for both inlet and nozzle internal ducts
  - The CFD approach for this study is geared towards having as simple of an approach as possible while still capturing the relevant thrust dynamics.

- External Compression Inlet Model
  - Focus is on the internal duct dynamics, but steady state solution can be obtained for the external compression using Taylor-Maccoll and method of characteristics

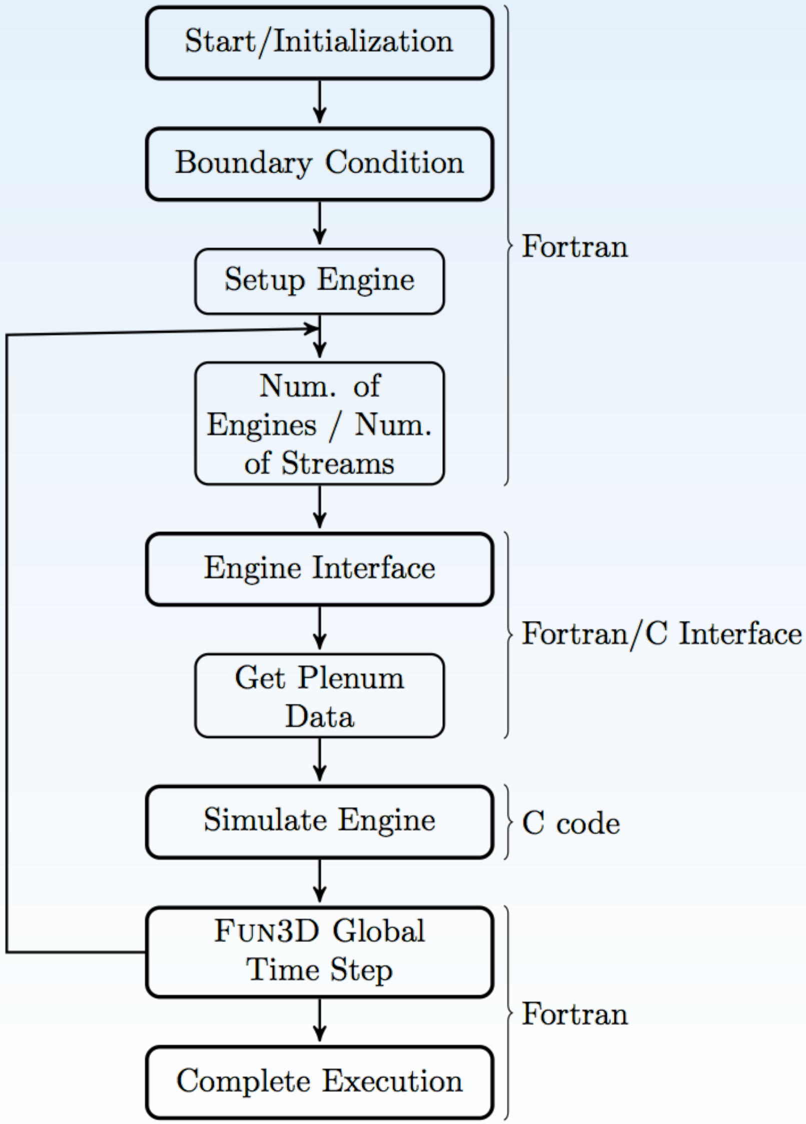
- Convergent – Divergent Nozzle
  - A CD nozzle is modeled to investigate the dynamic thrust behavior caused by upstream flow perturbations.
  - Nozzles are modeled the same way, only geometric differences.

Coupling of Inlet/Engine/Nozzle Quasi-1D

- Inlet-Engine Interface:
  - At the inlet exit a static pressure boundary is defined with the velocity and temperature being extrapolated
  - The Engine duct before the fan is expecting a defined total pressure and temperature and calculates the mass flow upstream
  - The coupling is accomplished by using the extrapolated values at the boundary to obtain the total conditions expected by the engine and an update to the defined static pressure at the inlet exit
- Engine-Nozzle Interface
  - The same basic approach from the inlet-engine is used here
  - The choked flow boundary condition is replaced with a very small duct volume that can be added to the engine simulation.
  - This duct volume serves as the VCE-nozzle interface used to calculate the states and the static density and temperature required for the nozzle model.

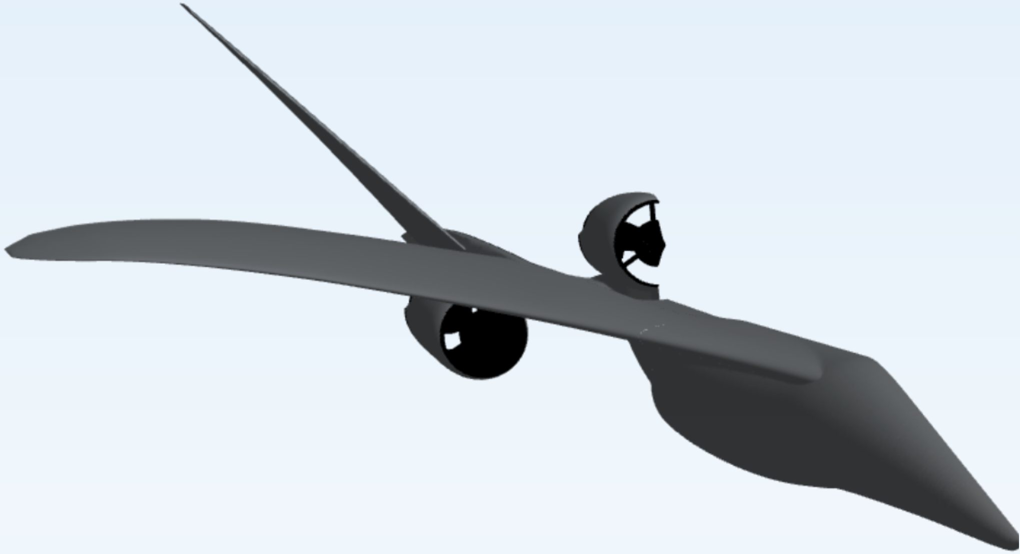
Interfacing with FUN3D

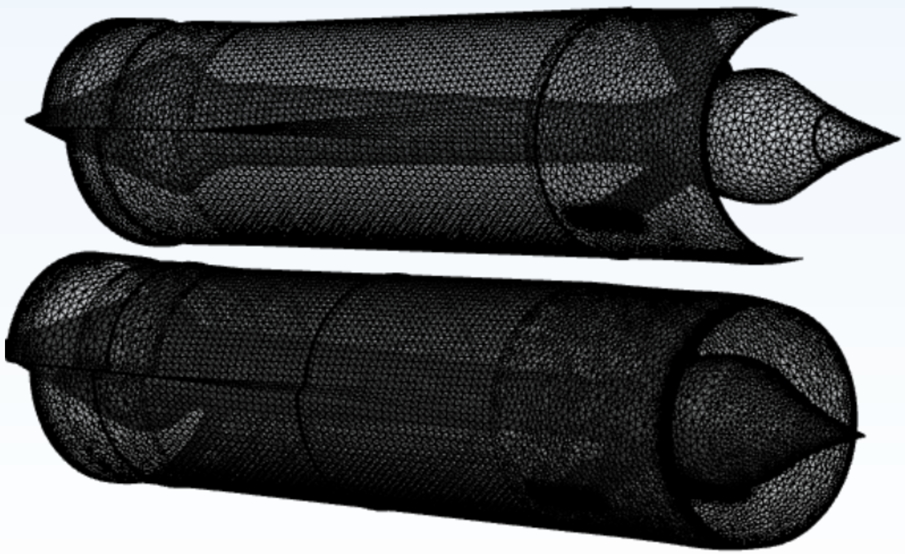
- The MATLAB/SIMULINK engine model is converted to auto generated C-code
- The C-code is wrapped into the FUN3D Fortran code as a shared library
- 3D flow at the inlet-engine boundary is averaged to 1D
- Uniform 3D flow is provided at the engine-nozzle boundary



Grid Development for Full Vehicle

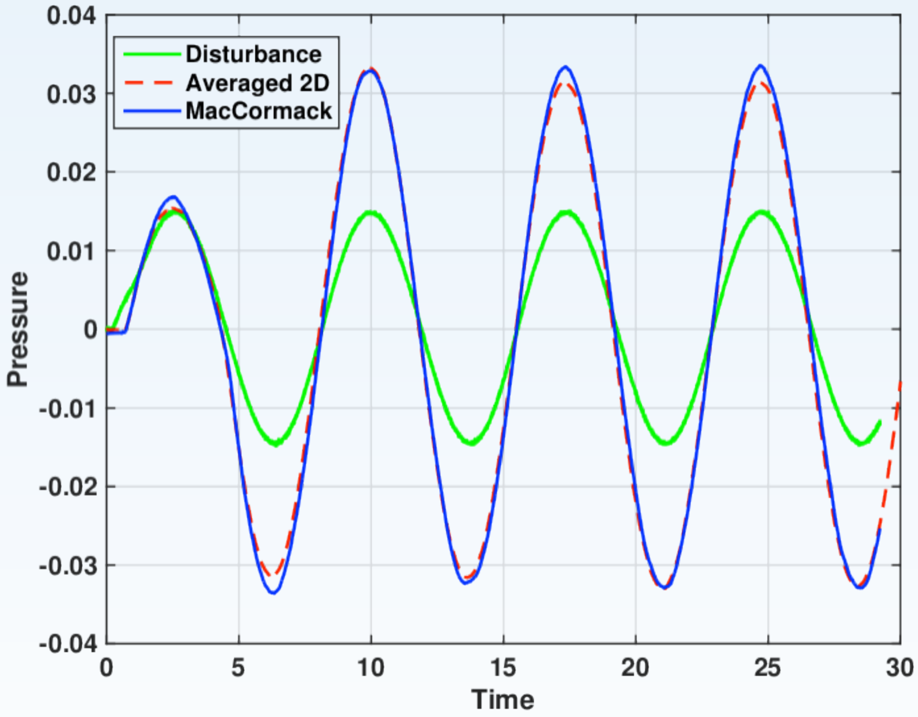
- Aero-elastic vehicle studies are being conducted, but typically they have neglected the propulsion system
  - For this work the external portion of the inlet and nozzle are included in the grid
- The grid provided currently only has a single exit nozzle, which caused some engine redesign



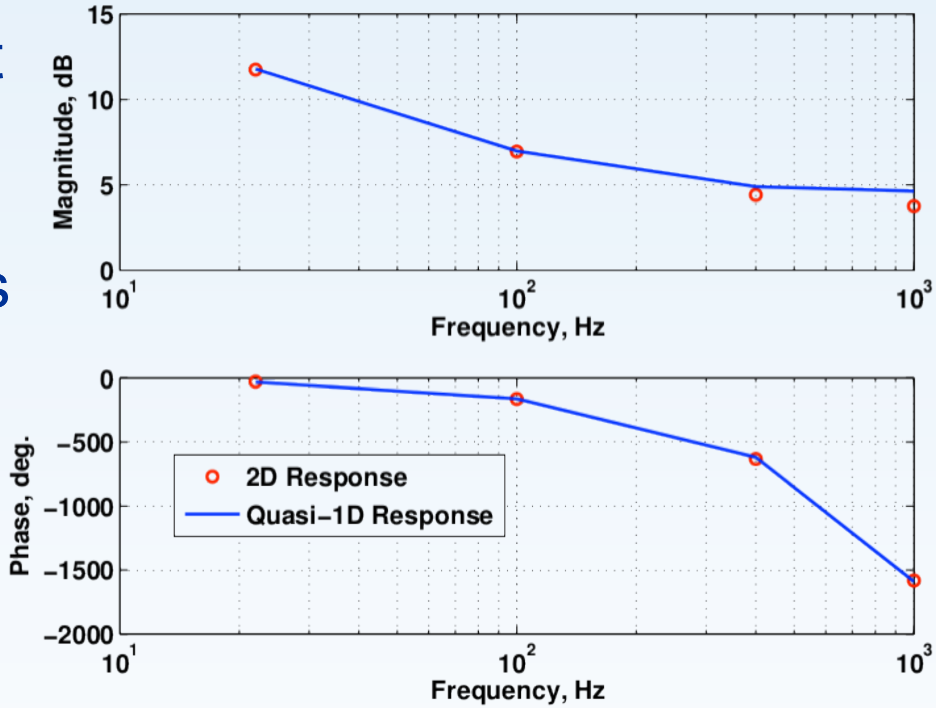


Inlet Component Model
Dynamic Study – Pressure Sinusoid

- A 1% amplitude disturbance on the pressure freestream condition is compared to the pressure at the inlet exit at 22Hz
  - The highest expected frequency due to atmospheric turbulence at the desired cruise condition of Mach 1.7 is about 20Hz.
  - However, the resulting aero-elastic disturbances due to the vehicle vibrations could get as high as 60Hz.



Inlet Component Model
Dynamic Study – Pressure Bode Plot

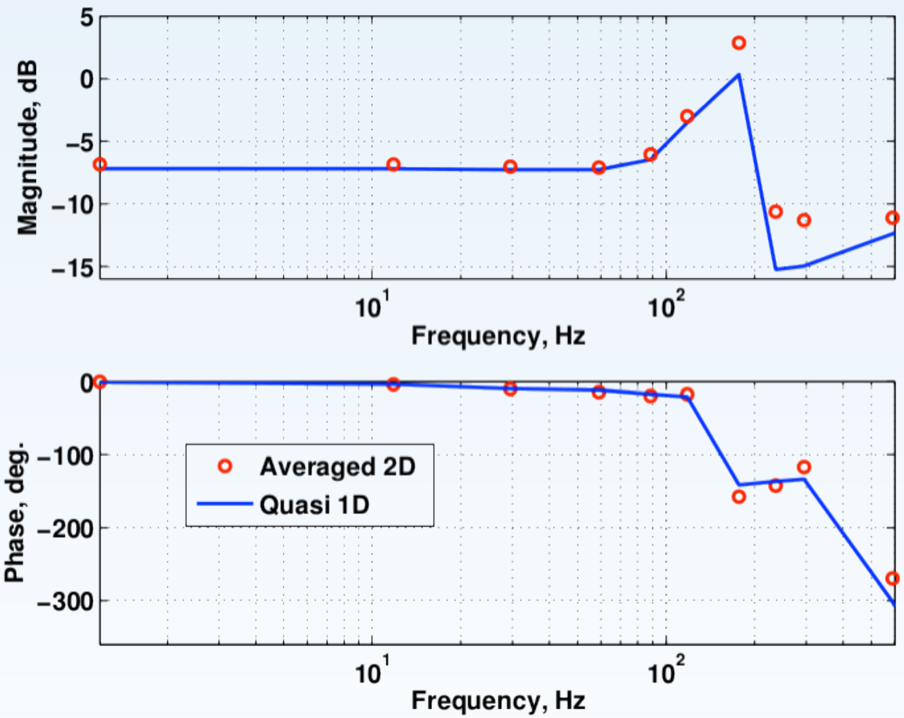


- The disturbance dictates that the frequency range of interest is extended to 600 Hz, since dynamics up to this frequency can still effect the phase at 60 Hz.

- Both the MacCormack and PHASTA 2D results show that the two methods agree very well dynamically

Nozzle Component Model Dynamic Study – Density Bode Plot

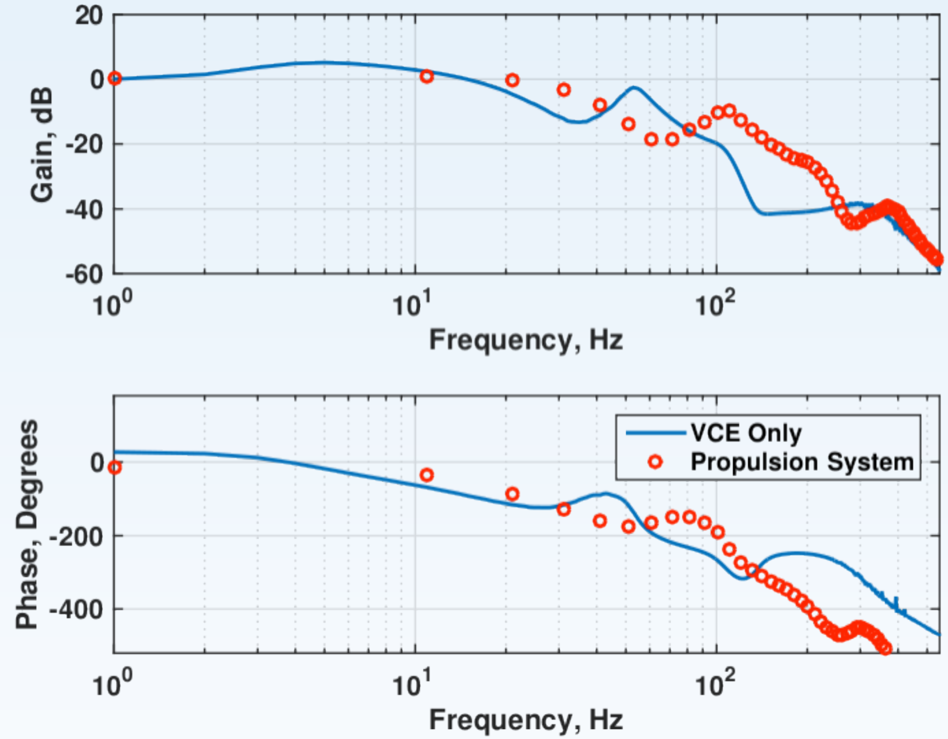
- The input/output density response is used to generate a bode plot.
  - This is done in order to compare the frequency response.
- It can be seen that the two methods agree very well, and provide a higher level of confidence in the nozzle dynamics in the absence of experimental data.



MacCormack 1D compared to CE/SE 2D method

Propulsion System and Engine Thrust Response to Pressure Perturbation

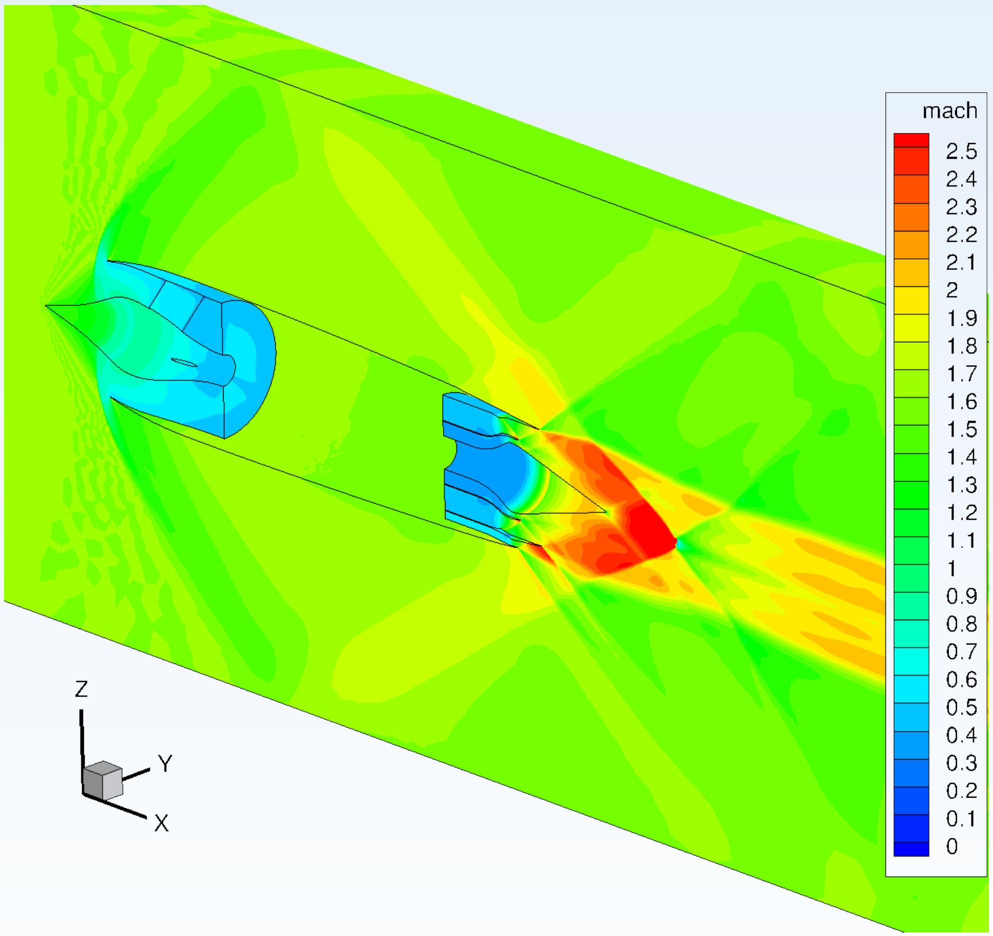
- Results highlight the dynamic response of the integrated propulsion system compared to the engine alone
  - Includes the Inlet, VCE and CD nozzles
- The general response is similar to previous studies with a jet engine



  - The inclusion of a larger volume generally would lower the roll off frequency, however as was seen in the component models of the inlet and nozzle, the roll off in magnitude occurs at a higher frequency than the engine alone.

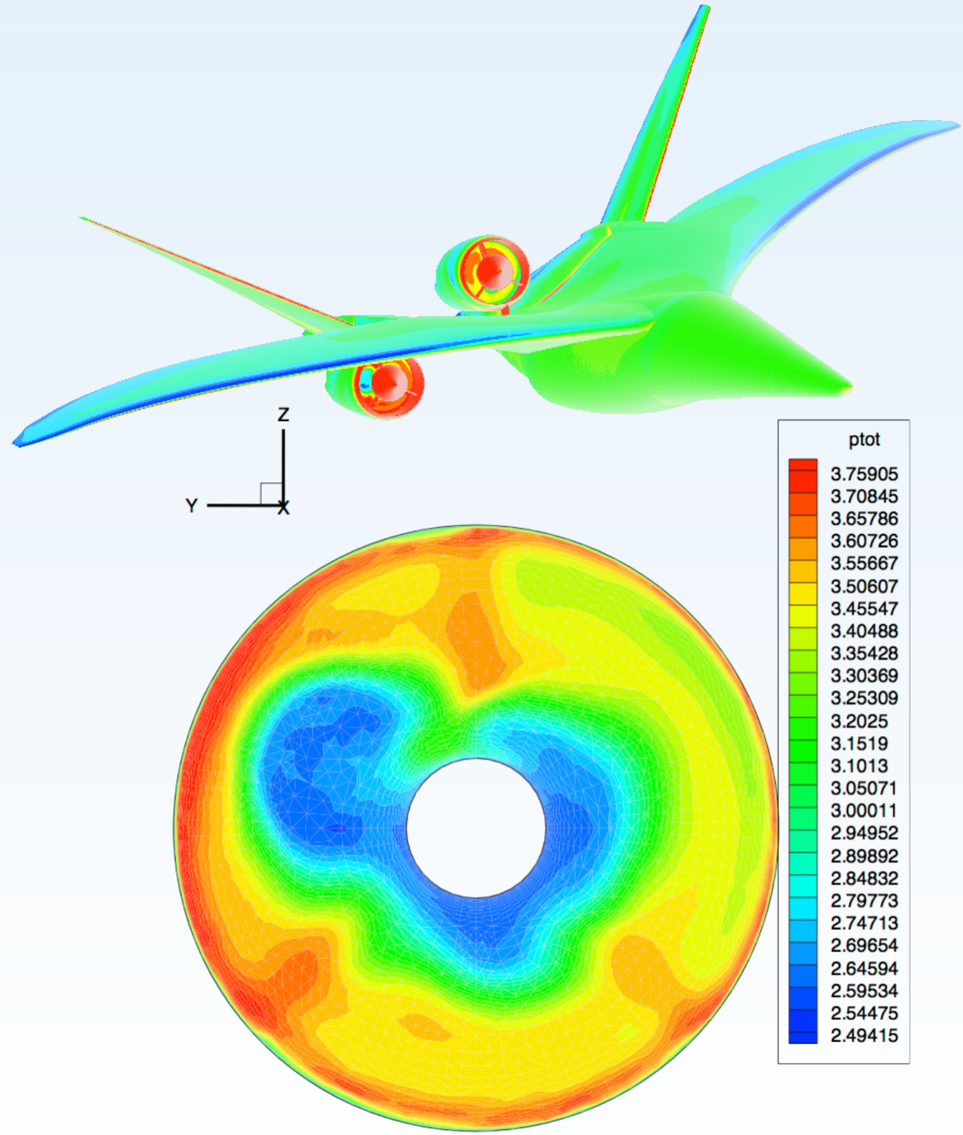
Engine in FUN3D Propulsion Model

- Steady-State simulation with the full propulsion system integrated into FUN3D.
  - The Mach contours provide the basic expected flow pattern with an oblique shock off the inlet cone, a weak normal shock just before the internal cowl portion of the inlet, and supersonic flow out of the nozzle
- Here the engine and flow solvers are passing the required flow information, but operate at their own time



Propulsion System with N+2 Vehicle

- The VCE was integrated into a rigid steady-state simulation with the N+2 vehicle, the cp on the vehicle surface and total pressure at the engine inlet face is shown
  - Close up Inlet-Engine boundary illustrates distortion for the engine under the wing
- The change to the single nozzle flow could be causing some problems with the VCE stability, changes to the VCE could be required



Future Work

- A dynamic thrust comparison of the Quasi-1D and propulsion system in FUN3D is required for a comparative study since no test data is available

- Run the full rigid body N+2 configuration with a grid refinement that includes the propulsion elements and with a viscous grid

- Once confidence is gained in the rigid body model inclusion of the structural modes of the vehicle will need to be included to perform static aero-elastic studies for the full APSE model

Conclusions

- An integrated propulsion system model has been developed and the turbo-machinery component has been coupled with FUN3D in an N+2 supersonic transport.
- While no test data is available the individual component models have been compared favorably to other higher fidelity CFD methods
- The inclusion of the turbo-machinery in FUN3D will enable the traditional aero-elastic studies to include propulsion system impacts, advancing the current state of the art

Questions?