Stage-by-Stage Component Modeling

Fundamental Aeronautics – Supersonics Project
AeroPropulsoServoElasticity Task

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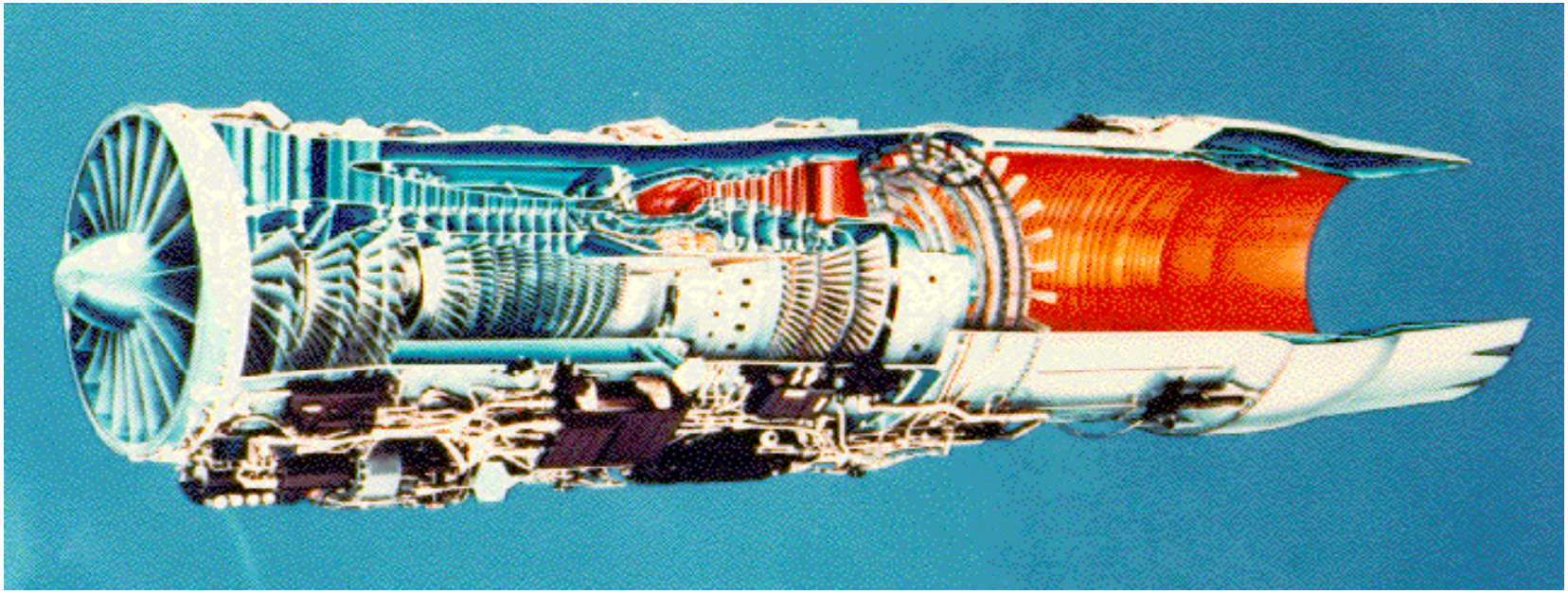

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Stage-by-Stage Component Modeling

Outline

Introduction

Model Overview

Stage-by-Stage Modeling Technique Results

Conclusions

Future Work

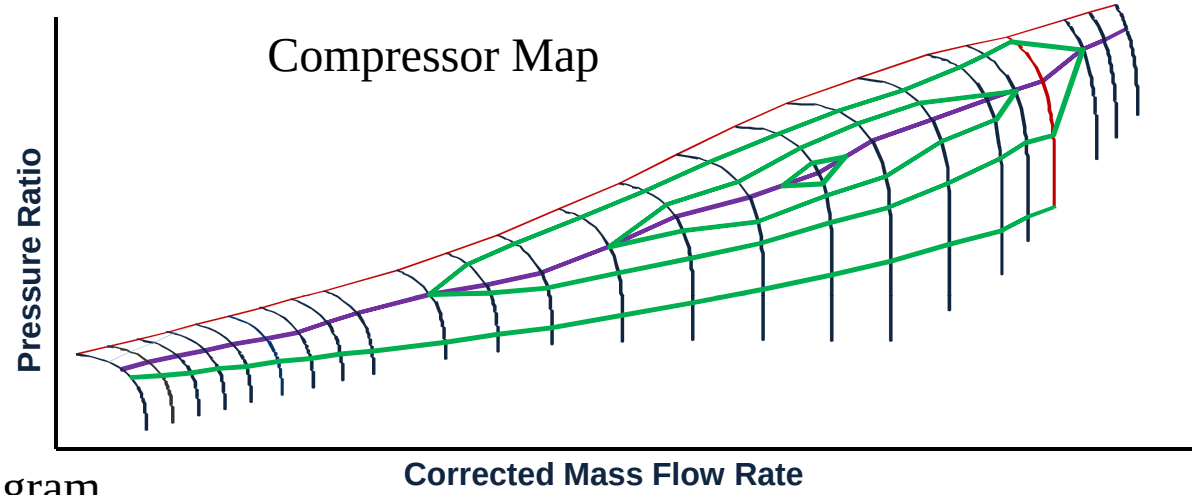
Stage-by-Stage Component Modeling

Introduction

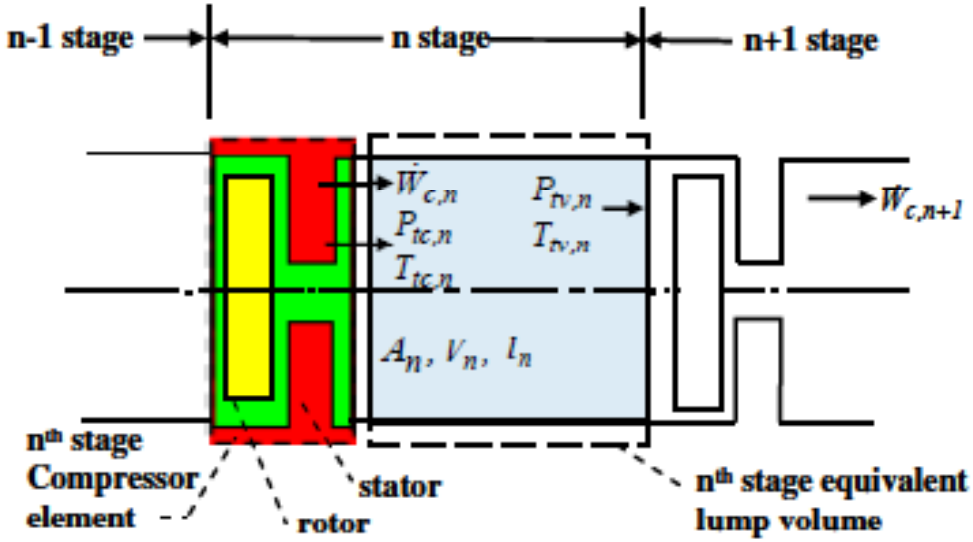
- Objective is to develop Stage-by-stage component models to improve model fidelity for Thrust Dynamics
- Also to learn the process so that stage-by-stage models can be developed for any engine
- The lumped volume generic compressor and turbine models are used as the starting point
- Work was done with support of Summer Co-op Student

Stage-by-Stage Model

- The lumped volume compressor and turbine models w/ derived compressor bleed schedule are used as the starting point



Stage Model Diagram



Conservation Equations

$$\frac{d}{dt}(\rho_{sv}) = -\frac{1}{V}\Delta\dot{W}$$

$$\frac{d}{dt}(\dot{W}) = -\frac{A}{l}\Delta P_{tv}$$

$$\frac{d}{dt}(\rho_{sv}T_{tv}) = -\frac{\gamma}{V}\Delta(T_{tv}\dot{W})$$

Scaling Process

Overall Scaling Process

1) Scaling Variables for Compressor Generic model

$$PR_{st} = \sqrt[J]{PR_{lmp}}$$ pressure ratio

$$\eta_{st} = \sqrt[J]{\eta_{lmp}}$$ efficiency

$$l_{st} = \frac{1}{J} l_{lmp}$$ length

$$\dot{W}_{st} = \dot{W}_{lmp}$$ mass flow rate

$$\dot{W}_{Bst} = \frac{1}{J} \dot{W}_{Blmp}$$ bleed rate

$$OL_{st} = OL_{lmp}(\dot{W}_{lmp}, PR_{st}, N_{lmp})$$ operating line

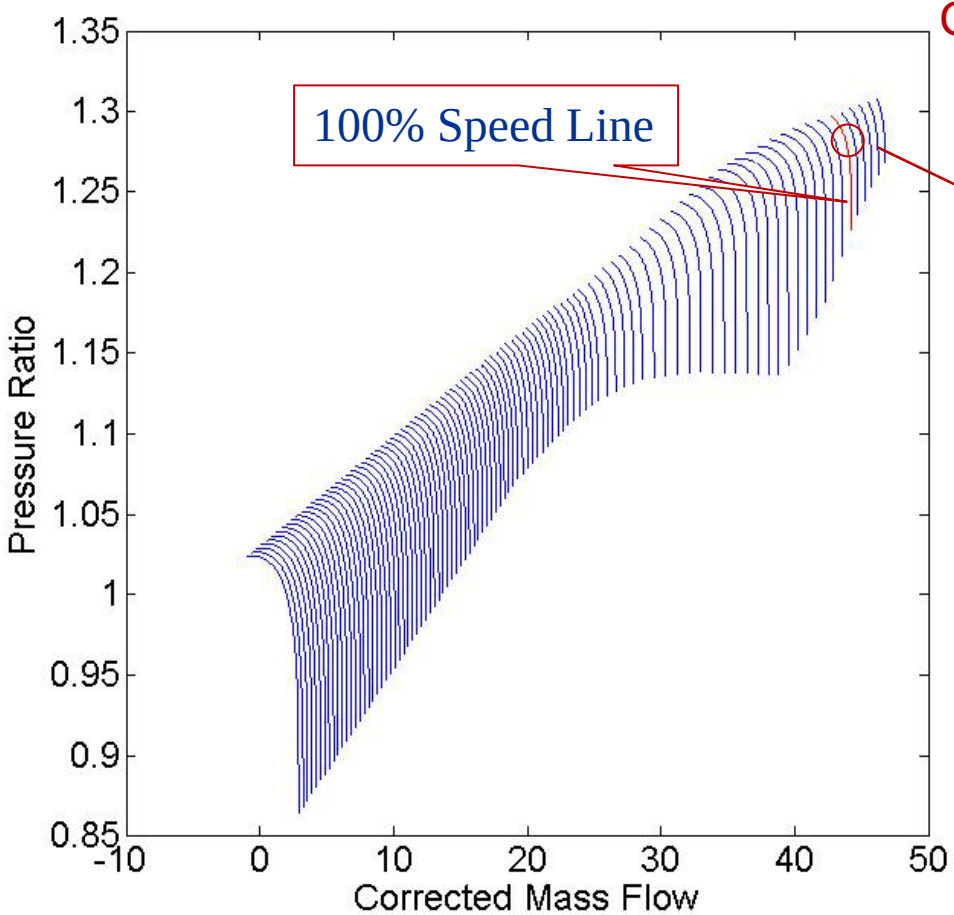
2) Construct a single stage model with initial stage bleed, adjust bleed schedule to operate on the operating line for a given speed

3) Stack single stage models to generate component stage-by-stage model

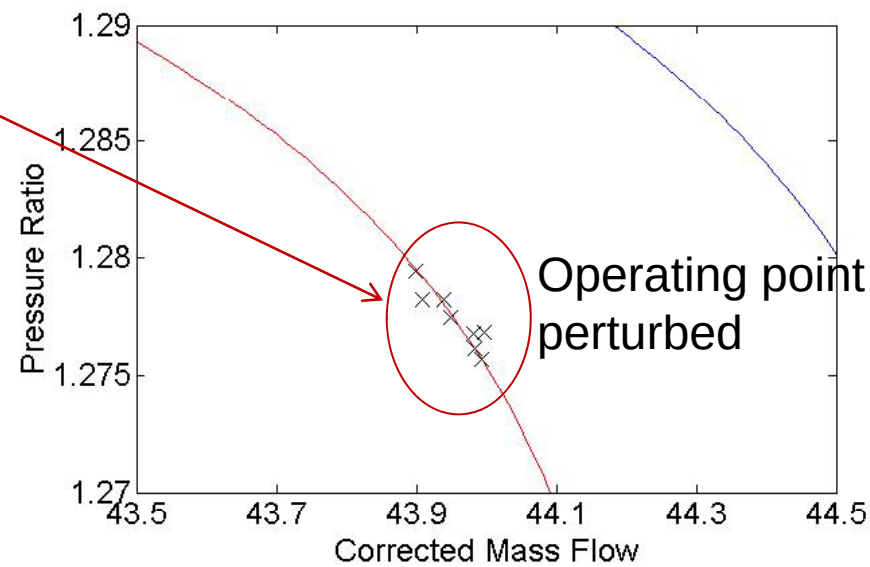
Scaling Process

4) Similarly for turbine scaling

5) Construct engine model using stage-by-stage models. Verify it operates on compressor operating line and overall turbine choked region



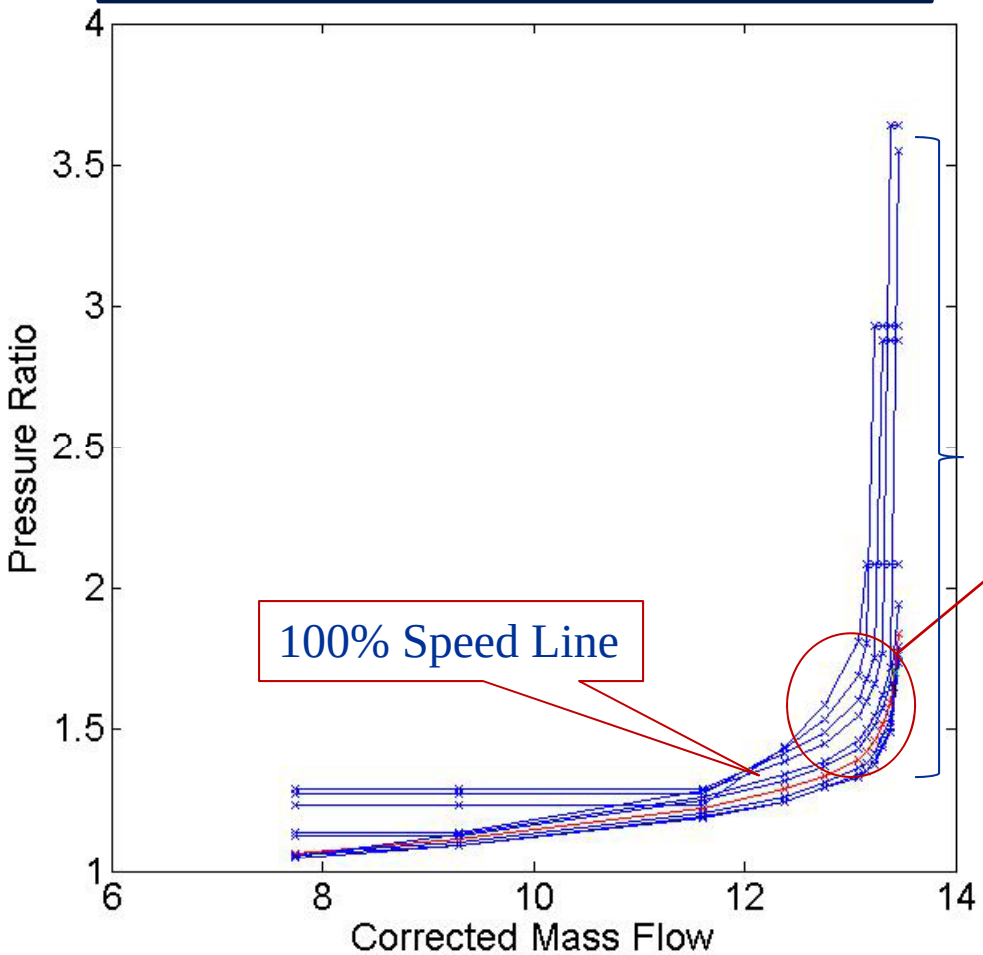
Compressor Operating point

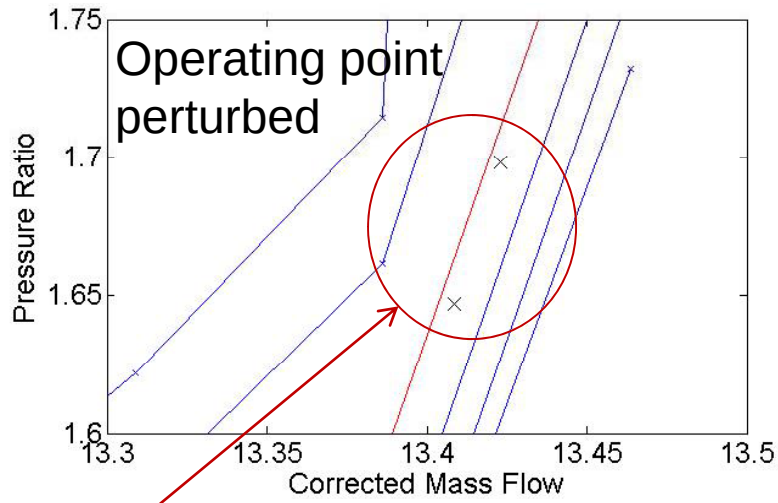


Each stage's map is scaled to enable performance at the operating point

Turbine Operating Point

Each stage's map is scaled to enable performance at the operating point





Scaling Process

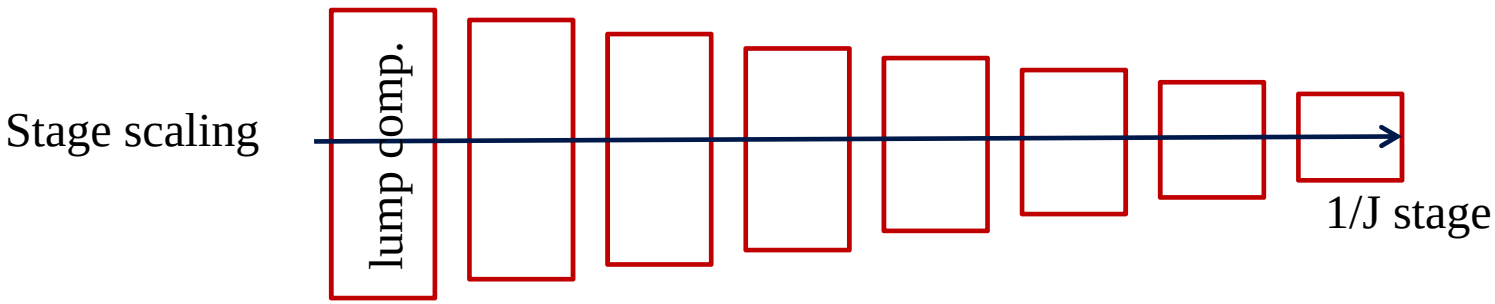
Detail Scaling Process

Step 2 (Construct single stage): Start at some known operating point, fixed $N, \dot{W}$

-- Problem: directly going from lump volume to single stage initial conditions too far off, response unstable

-- Solution

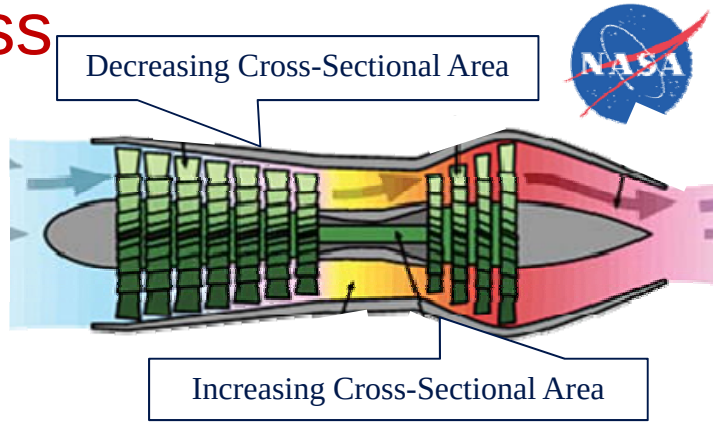
(a) Scale from lump model to ¾ to ½ to ¼ to 1/8 (for 8-compressor stages)



(b) Each step successively substitute final conditions for initial conditions until start up transient dies out, then subdivide again

(c) Each step trim bleed to operate on desired point on the operating line

Scaling Process



Detailed Scaling Process

Step 3 (stack single stage models):

-- Problem: Connecting and running stages causes Mach estimator to vary widely (M depends on T, ρ , A), response unstable

$$M_n = \frac{\dot{W}_{c,n}}{\rho_{cv,n} A_n \sqrt{\gamma_{cp} R T_{s,n}}}$$

-- Solution

(a) Disconnecting Mach estimator & assuming SS M_{in} and ΔM across compressor, estimate SS stage Mach no.

$$M_{st,i} = M_{in} + \frac{i}{J} \Delta M$$

(b) Successively substitute final conditions for initial conditions until start-up transient subsides

(c) Using final SS quantities (M, T, ρ), calculate $A_{st,i}$ & connect back M-estimator

(d) Verify model runs stable on operating line (trim $\dot{W}_{Bst,i}$), before connecting next stage

Lumped Volume and Stage-by-Stage Comparison

Compressor	Stage - by - Stage	Lumped	Discrepency
Pressure Out	718380	709240	1.29%
Temperature Out	508.5	530.3	4.11%
Density Out	4.74	4.46	6.32%
Massrate N2	19.23	19.24	0.04%
Massrate N1	19.96	19.96	0.01%
Total Bleed	0.725	0.721	0.65%

Turbine	Stage - by - Stage	Lumped	Discrepency
Pressure Out	269150	268260	0.33%
Temperature Out	937.5	970.4	3.39%
Density Out	1.07	1.03	3.66%
Massrate N2	21.98	21.31	3.14%
Massrate N1	20.68	20.66	0.08%

Lumped volume and stage-by-stage models have equal total volume

Conclusions

- A systematic approach has been developed for the development of stage-by-stage component models

Future Work

- Integration of components into overall model
- More time domain and frequency domain validation
- Thrust dynamics comparisons