ME302: 2024-25 - II
Course Project Report

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September 4, 2025

Problem Description

The project involves scaling a turbomachine component for laboratory testing in a closed-loop high-pressure facility. The key objectives are:

1. **Determine the maximum scale factor** ($l_{\text{model}}/l_{\text{prototype}}$) that satisfies:
   - Matching prototype conditions (Mach = 0.55, Re = 3.0×10^6)
   - Facility constraints:
     - Maximum pressure $\leq 250\,\text{kPa}$
     - Closed-loop flow condition ($p_{05} \geq p_{01}$)
2. **Identify the compressor operating point**:
   - Required pressure ratio (p_{02}/p_{01})
   - Reference mass flow rate ($\dot{m}_{\text{ref}}$)
3. **Report the corresponding inlet stagnation pressure** (p_{01}).

Methodology

Theoretical Basis

- **Scaling Requirements**:
  - Mach number matching ensures dynamic similarity of compressible flow
  - Reynolds number matching ensures viscous effects are properly scaled
- **Pressure Constraints**:

$$
\begin{aligned}
p_{05} &= 0.95 p_{04} \quad (\Delta p_{045} = 5\% \text{ loss}) \\
p_{04} \approx p_{03} &= 0.985 p_{02} \quad (\Delta p_{023} = 1.5\% \text{ loss}) \\
\Rightarrow p_{02}/p_{01} &\geq 1/(0.95 \times 0.985) \approx 1.068
\end{aligned}
$$

Computational Approach

- **Platform**: MATLAB
- **Algorithm**:
  - Adaptive scale search:
    - Coarse pass (0.01 steps) to identify viable scale range
    - Refinement passes (100 steps) near the best candidate
  - Flow calculations using isentropic relations for Mach 0.55 flow
  - Compressor matching by interpolating tabulated data
- **Key Equations**:

$$Re = \frac{\rho_4 C_4 l_{\text{model}}}{\mu}, \quad \rho_4 = \frac{p_4}{RT_4}$$
$$\dot{m} = \dot{m}_{\text{ref}} \left(\frac{p_{01}}{101.325\,\text{kPa}} \right)$$

Results and Discussion

Key Results

Parameter	Value
Maximum scale	0.6328
Inlet pressure (p_{01})	219.01 kPa
Mass flow rate	$21.829\,\text{kg}\,\text{s}^{-1}$
Compressor pressure ratio	1.2344 ($\geq$1.068)
Temperature ratio	1.0729
Reference $\dot{m}_{\text{ref}}$	$10.099\,\text{kg}\,\text{s}^{-1}$

Discussion

- The maximum scale (0.6328) ensures all constraints are met while maintaining similarity
- Compressor operates at $\dot{m}_{\text{ref}} = 10.099\,\text{kg}\,\text{s}^{-1}$ with sufficient pressure ratio margin
- Solution balances testability and prototype fidelity

Conclusion

The analysis successfully identifies:

- A scaled model (63.28% of prototype size) meeting all constraints
- Compressor settings for stable closed-loop operation
- Inlet conditions ($p_{01} = 219.01\,\text{kPa}$) for testing

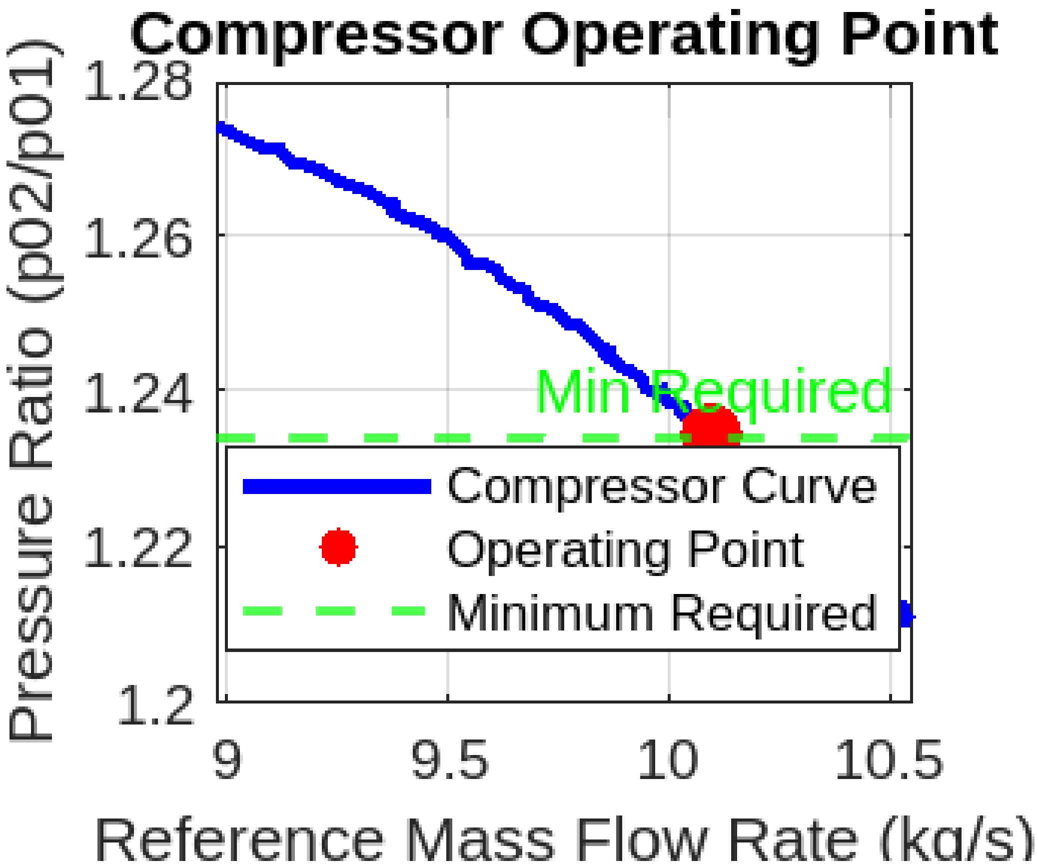

Figure 1: Compressor performance curve with operating point (red) and minimum requirement (dashed green)

Part (b) Future Work

Three proposed research studies:

- **Diffuser Efficiency Optimization** (Beneficiary: Aerospace companies).
- **Noise Reduction Techniques** (Beneficiary: Urban air mobility firms).
- **Thermal Management Studies** (Beneficiary: High-performance engine manufacturers).

FUTURE WORK

Research Proposal 1: Smart Diffuser Configurations for Adaptive Flow Control

This experimental study will investigate variable-geometry diffusers with servo-actuated vanes for gas turbine applications, collaborating with MTU Aero Engines and Honeywell Aerospace. The research focuses on optimizing pressure recovery across different operational regimes, particularly crucial for hybrid-electric propulsion systems operating at off-design conditions. By testing adaptive control algorithms in our facility, we aim to demonstrate 3-5% fuel savings in jet engines, which would help manufacturers meet stringent EU emission targets. The technology could be licensed for next-generation military turbines.

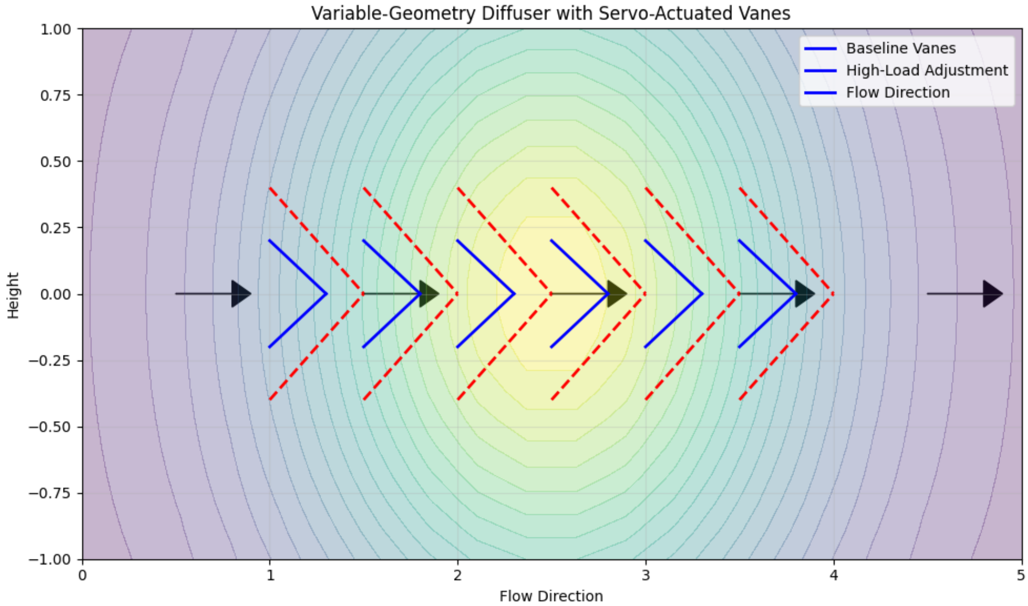

Figure 2: Variable-geometry diffuser concept with servo-actuated vanes showing (a) baseline position and (b) high-load configuration. CFD pressure contours illustrate the improved flow uniformity achieved through vane adjustment.

Research Proposal 2: High-Temperature Fiber-Optic Sensor Integration

In partnership with Siemens Energy and the InnoTurbinE Consortium, we propose embedding fiber-optic sensors in ceramic matrix composite (CMC) turbine blades to monitor strain and temperature at extreme conditions exceeding 1,500°C. This study will validate sensor durability under simulated engine environments while providing critical data for predictive maintenance systems. Successful implementation could extend turbine lifespan by 20%, significantly reducing maintenance costs for power plants.

Research Proposal 3: Hybrid Experimental-CFD Validation for Compressor Design

Collaborating with ANSYS and Texas A&M's EPRC, this project will bridge the gap between wind tunnel testing and computational fluid dynamics for compressor cascades. Our facility will provide experimental validation data to refine turbulence models in ANSYS Fluent, particularly for transonic flow separation prediction. This hybrid approach has the potential to reduce compressor R&D costs by 30% through more accurate virtual prototyping, with ANSYS potentially commercializing the validated simulation packages. Key results will be presented in comparative tables:

Table 1: Experimental vs. CFD Pressure Ratio Validation

Blade Profile	**Experimental**	**CFD**	**% Diff.**	**Key Findings**
NACA 0010	1.3235	1.3846	+4.5	Shock at leading edge
NACA 8410	1.4535	1.5147	+4.1	Better high-β match
Centrifugal	8.16	8.446	+3.6	81.4% efficiency

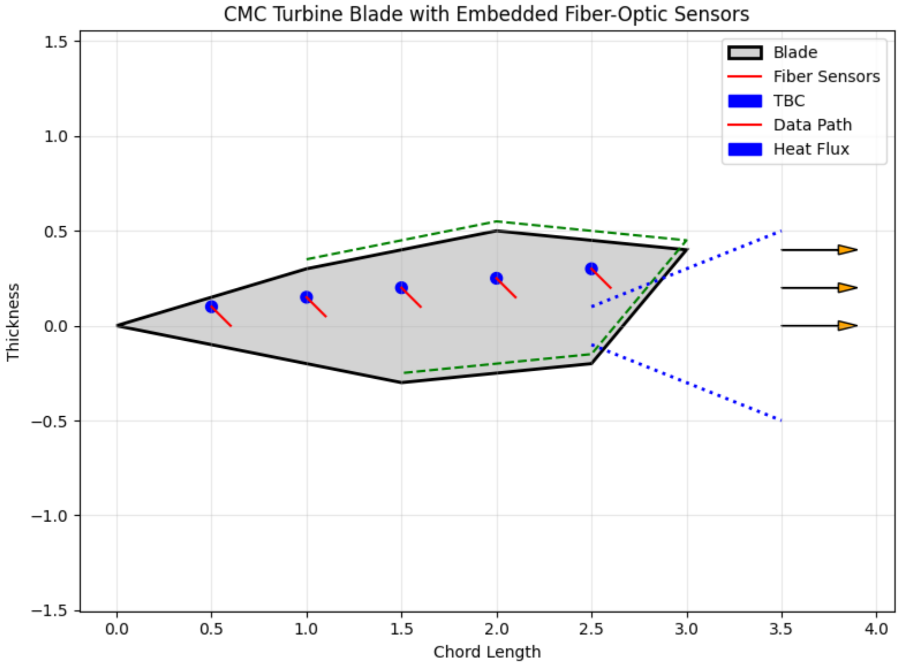

Figure 3: Cross-section of CMC turbine blade showing (1) embedded fiber-optic sensor network, (2) thermal barrier coating, and (3) data acquisition pathways. Arrows indicate heat flux directions during operation.

SUPPLEMENT

- **MATLAB code File**: `ME302_Project.m`
- **Python File**: `ME302_project_part(b).ipynb`
- **Data File**: `Compressor_operation_map.xlsx`
- **Report Source**: `ME302_Report.tex` (LaTeX)