ME302: 2024-25 - II

COURSE PROJECT REPORT

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PROBLEM DESCRIPTION

The objective of this project is to develop and test a scaled model of a turbomachine component that will ultimately be incorporated into a future gas turbine engine. The full-size prototype has a characteristic length of 0.2 meters. In order to analyze its performance, the component must be tested in a smaller, high-pressure, closed-loop test facility.

Two major constraints, however, must be kept in mind during testing:

- The highest pressure at any point in the facility should not exceed 250 kPa.

- The exit stagnation pressure (P_{05}) should be equal to or higher than the inlet stagnation pressure (P_{01}) for continuous closed-loop operation.

Besides meeting these requirements, the scaled model should have similarity of flow conditions with the prototype. More precisely, both the Mach number (target value = 0.55) and Reynolds number (target value = 3×10^6) should be replicated. The challenge is to determine the largest possible scale (model size divided by prototype size) that meets both the similarity of flow and facility constraints.

METHODOLOGY

In order to solve the problem, a step-by-step procedure was employed:

Create Flow Similarity

Isentropic flow and ideal gas behavior equations were utilized to correlate the flow characteristics such as pressure, temperature, density, and velocity at various locations within the system.

Mass Flow Rate Modeling

The real mass flow rate was modeled in terms of a reference mass flow rate and the ratio of stagnation conditions through a general scaling formula.

Reynolds Number Matching

The Reynolds number equation ($\text{Re} = \frac{\rho C L}{\mu}$) was used to match the dynamic conditions of the model with the prototype. This yielded one of the geometrical scale constraints.

Facility Constraints

For each scale considered, the corresponding pressures at different stations (particularly P_{02}, P_{04}, and P_{05}) were determined to ensure that:

- No component of the system exceeds 250 kPa.

- The flow remains closed-loop ($P_{05} \geq P_{01}$).

Calculate Feasible Scale

With the relations and constraints provided above, the maximum feasible geometric scale was calculated.

Software and Tools

Python was utilized throughout the analysis. Computations included fluid property calculations, scaling relations, and checks for constraints. Compressor map data were used to ensure that the operating point of the selected scale falls within acceptable bounds.

   This technique ensured that the selected scale maintained flow similarity while adhering to the safe operating ranges of the test facility.

RESULTS AND DISCUSSION

Mass Flow Rate Relation

$$\dot{m} = \rho_4 A_4 C_4$$

$$\dot{m} = \dot{m}_{ref} \left(\frac{P_{01}}{101.325 \times 10^3} \right) \left(\sqrt{\frac{T_{01}}{293}} \right) = \frac{\rho_4 \pi D_4^2 C_4}{4}$$

$$D_4 = 2 \cdot L_{model} \Rightarrow A_4 = \pi L_{model}^2$$

$$\Rightarrow \dot{m} = \dot{m}_{ref} \left(\frac{P_{01}}{101.325 \times 10^3} \right) = \rho_4 \pi L_{model}^2 C_4 \tag{1}$$

Where $\rho_4 = \frac{P_4}{RT_4}$

Temperature at Station 4 (T_4)

$$\frac{T_{02}}{T_4} = 1 + \frac{(\gamma - 1)}{2} M^2 = 1 + (1.4 - 1) \cdot \frac{(0.55)^2}{2} = 1.0605$$

$$T_4 = \frac{T_{02}}{1.0605} \tag{2}$$

Pressure at Station 4 (P_4)

$$\frac{P_{04}}{P_4} = \left(1 + \frac{(\gamma - 1)}{2} M^2 \right)^{\frac{\gamma}{\gamma - 1}} = 1.228 \tag{3}$$

Given:

$$\Delta P_{023} = P_{02} - P_{03} = 0.015 P_{02} \Rightarrow P_{03} = 0.985 P_{02}$$

$$\Delta P_{045} = P_{04} - P_{05} = 0.05 P_{04} \Rightarrow P_{05} = 0.95 P_{04}$$

$$P_{03} = P_{04} \Rightarrow P_{04} = 0.985 P_{02}$$

$$\Rightarrow P_4 = \frac{P_{04}}{1.228} = 0.8021 P_{04} \tag{4}$$

Velocity at Station 4 (C_4)

$$T_{04} = T_4 + \frac{C_4^2}{2C_p}$$

$$C_p = \frac{\gamma R}{\gamma - 1} = \frac{1.4 \cdot 287}{0.4} = 1004.5$$

$$T_{02}\left(1 - \frac{1}{1.0605}\right) = \frac{C_4^2}{2C_p}$$

$$\Rightarrow C_4 = \sqrt{114.611 \cdot T_{02}} \tag{5}$$

Density at Station 4 (ρ_4)

$$\rho_4 = \frac{P_4}{RT_4} = \frac{0.8021 P_{02} \cdot 1.0605}{T_{02} \cdot 287} = \frac{2.9638 \cdot 10^{-3} P_{02}}{T_{02}} \tag{6}$$

Solving for L_{model}

From Eqns. (1), (5), and (6):

$$\dot{m}_{ref}\left(\frac{P_{01}}{101.325 \cdot 10^3}\right) = \frac{2.9638 \cdot 10^{-3} \cdot P_{02} \cdot \pi \cdot L_{model}^2 \cdot C_4}{T_{02}}$$

$$L_{model}^2 = \dot{m}_{ref} \cdot \sqrt{\frac{T_{02}}{T_{01}}} \cdot \frac{1}{(P_{02}/P_{01})} \cdot 589.759$$

$$= \dot{m}_{ref} \cdot \sqrt{\frac{T_0 ratio}{P_0 ratio}} \cdot 589.759$$

$$\Rightarrow L_{model} = \sqrt{\frac{\dot{m}ref}{P_0 ratio}} \cdot T_0 ratio^{1/4} \cdot 0.0412$$

Scale Determination

$$\text{Scale} = \frac{L_{model}}{L_{prototype}} = \sqrt{\frac{\dot{m}ref}{P_0 ratio}} \cdot T_0 ratio^{1/4} \cdot \frac{0.0412}{0.2} = \sqrt{\frac{\dot{m}}{P_0 ratio}} \cdot T_0 ratio^{1/4} \cdot 0.206$$

Maximum scale from compressor map = 0.619
Data Point:

$$\dot{m}_{ref} = 10.55028375 \tag{7}$$

$$P_0 \text{ ratio} = 1.210453952 \tag{8}$$

$$T_0 \text{ ratio} = 1.068519008 \tag{9}$$

Reynolds Number Relation

$$Re = \frac{\rho_4 C_4 L_{model}}{\mu_4} \tag{10}$$

$$\rho_4 = \frac{\dot{m}}{A_4 C_4} = \frac{\dot{m}}{\pi D_4^2 C_4} = \frac{\dot{m} P_{01}}{318.322 \cdot 10^3 C_4 L_{model}^2} \tag{11}$$

Given: $Re = 3 \times 10^6, \mu_4 = 1.83 \times 10^{-5}$

$$\Rightarrow L_{model} = \frac{\dot{m}_{ref} P_{01}}{17.476 \cdot 10^6}$$

Using $L_{model} = \text{scale} \cdot L_{prototype} = 0.619 \cdot 0.2 = 0.1238$ m:

$$0.1238 = \frac{10.55028375 \cdot P_{01}}{17.476 \cdot 10^6}$$
$$\Rightarrow P_{01} = 205.068 \text{ kPa} \tag{12}$$

Pressure Calculations

$$P_{02} = 1.210453952 \cdot P_{01} = 248.225 \text{ kPa} \tag{13}$$
$$P_{04} = 0.985 \cdot P_{02} = 244.502 \text{ kPa}$$
$$P_{05} = 0.95 \cdot P_{04} = 232.277 \text{ kPa}$$

Constraints Check

- $P_{05} = 232.277$ kPa $> P_{01} = 205.068$ kPa

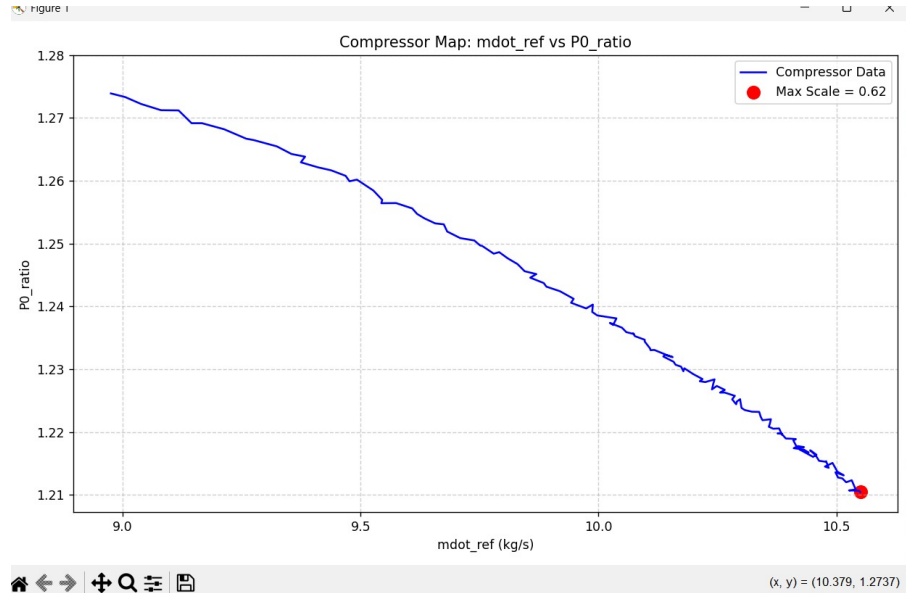- maximum allowable pressure, $P_{02} = 248.225$ kPa < 250 kPa

Discussion

Figure 1: Compressor operation map (P0 ratio vs. $\dot{m}$ref) showing the chosen operating point in red.

The graph illustrates the compressor performance with `mdot_ref` on the x-axis and `P0_ratio` on the y-axis. A clear downward trend is observed, where increasing the mass

flow rate results in a gradual drop in pressure ratio. The curve reflects stable operation with minimal fluctuations, except near the highest flow rate. The red marker highlights the point where the scale value is maximum, indicating a performance peak. This point could be useful for identifying the most efficient operating condition of the compressor.

FUTURE WORK

1. Smarter Diffuser Shapes for Better Performance

The Challenge:
Diffusers act as the "exit ramps" for airflow in turbomachinery. Poorly designed shapes can result in flow separation or take up excessive space, leading to energy losses. The aim is to identify an optimal diffuser angle that balances compactness with aerodynamic efficiency.

How We Plan to Test This:

- Fabricate multiple diffuser geometries with angles ranging from 5° to 15°.

- Use Particle Image Velocimetry (PIV) systems to visualize and analyze airflow behavior.

- Validate results through Computational Fluid Dynamics (CFD) simulations.

Industry Relevance:

- Energy firms could achieve 2–3% compressor efficiency improvements, resulting in substantial cost savings.

- Aerospace companies (e.g., Pratt & Whitney) are continuously seeking more compact and efficient designs.

Real-World Examples:

- NASA's report #TP-2005-213934 outlines similar diffuser optimization research.

- Modern wind turbine technology also benefits from enhanced diffuser designs to increase power output.

2. Active Airflow Control Systems

The Big Idea:
Introduce dynamic control systems that adjust airflow actively using jets or vibrating surfaces—similar to how sails are continuously adjusted on a boat.

Proposed Implementation:

- Embed miniature air injectors in the test section.

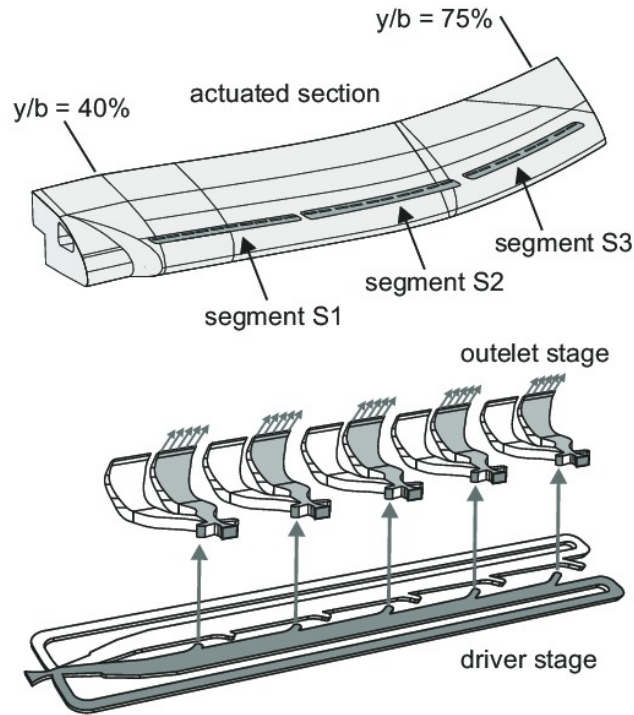- Experiment with various pulsing frequencies and patterns.

Figure 2: Active Airflow Control Systems

- Use high-sensitivity pressure sensors to quantify flow improvements.

Potential Applications:

- Enhance jet engine performance in turbulent or unsteady conditions.

- Minimize wear and tear in power plants by ensuring uniform flow profiles.

Cutting-Edge Context:

- Techniques similar to these are patented by companies like GE (e.g., US20180023421A1).

- However, this research seeks to develop simpler and more cost-effective alternatives.

3. Tougher Materials for Harsh Conditions

The Problem:
Turbomachinery components are exposed to extreme environments, including sand, muddy water, and other particulates—similar to driving through a sandstorm daily.

Our Proposed Solution:

- Test advanced materials such as 3D-printed titanium alloys and ceramic coatings.

- Simulate real-world wear using controlled dirty flow test setups.

Target Industries:
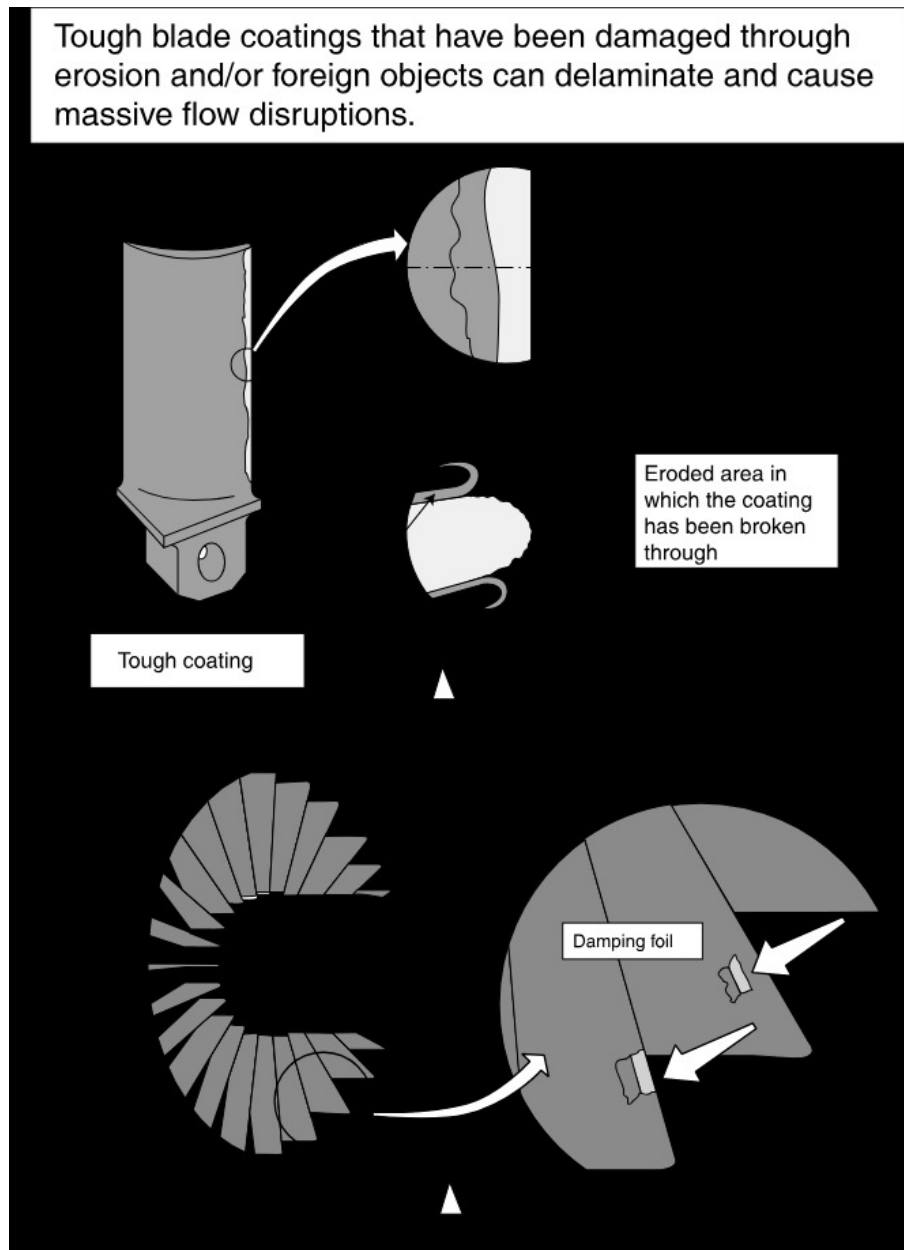
- Oil and gas operations in desert conditions.

Figure 3: Tougher Materials for Harsh Conditions

- Hydropower plants affected by sediment-rich water sources.

Supporting Evidence:

- Coatings can extend component lifespan by up to three times (*Wear Journal*, 2019).

- Testing will follow adapted procedures based on ASTM G76 standards for erosion testing.

Required Python Libraries

- `pandas:`–for reading and handling tabular data

- `matplotlib:`–for plotting graphs

- `numpy:`–for numerical operations

If you do not have these packages installed, you can install them using pip (Python's package manager). Open your terminal or command prompt and execute the following command:

pip install pandas numpy matplotlib

Here are some things that should be in mind:-

1. A Python script is a file with a `.py` extension that contains Python code.

2. It runs step by step to perform tasks like reading data, doing calculations, or showing plots.

3. The data file it uses (like `Compressor_operation_map.txt`) should be in the same folder as the script unless you give the full file path.

4. You can run the script by typing `python script_name.py` in a terminal or Python environment.

References

[1] NASA Technical Paper Available: https://ntrs.nasa.gov/citations/20050172494

[2] GE Patent (US20180023421A1): https://patents.google.com/patent/US20180023421A1/

[3] Wear Journal (2019) Coatings Study: https://www.sciencedirect.com/science/article/abs/pii/S0043