Structural and Design Analysis for a Mach 8 High Temperature Wind Tunnel

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Introduction

The Propulsion & Energy Research Lab operates several testing rigs capable of Mach 0.1 to Mach 6 with a mass flow rate of 2 kg/s. However, these conditions do not fully replicate real-world scenarios. The new Mach 5-8 wind tunnel (HADES) will reach speeds up to Mach 8 with a higher mass flow rate of 30 kg/s. It will also feature a 10-inch nozzle diameter, simulating typical flight conditions. Unlike existing wind tunnels requiring component scaling, HADES will allow true-scale model testing, improving accuracy and providing better insights into supersonic flow. This capability is valuable for the Air Force, defense contractors, and commercial airlines to enhance aircraft designs and advance air travel technologies.

The Mach 5-8 wind tunnel will be a large-scale test system capable of running models at speeds up to Mach 8 and altitudes of up to 45 km. It consists of three sections: the Flow Conditioning Section, Test Section, and Ejector, each designed to achieve the required test conditions. With 50,000 lbf of axial thrust, the system must be mounted on a rigid base to withstand these forces. Finite Element Analysis (FEA) will ensure the structure supports the system's weight while withstanding axial thrust. The system will operate under varied flow conditions, with lower altitudes (below 25 km) not requiring an ejector, while higher altitudes do. This adaptability ensures structural integrity under extreme conditions and optimizes material selection for efficiency, durability, and cost-effectiveness.

Methodology

ASME Standards

Math standards and equations

Design

- CAD designs to accomplish the necessary goals.

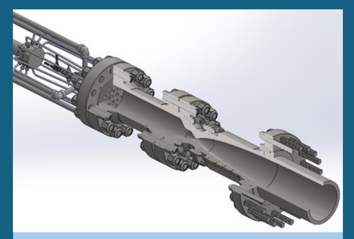

Fig. 1: Current Flow Conditioning Section CAD

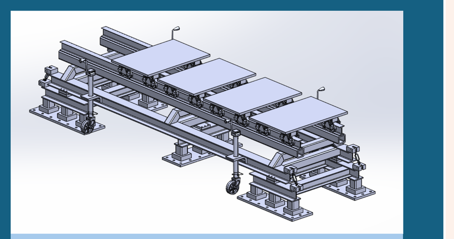

Fig. 2: Current iteration of Skid CAD

Design Loop

FEA

- Computational Analysis

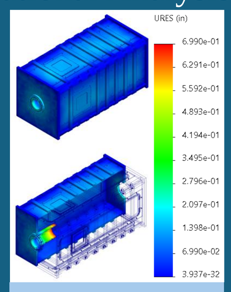

Fig. 3: Test Section Results

Mesh

- Convert CAD design to mesh for computational analysis

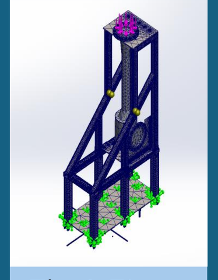

Fig. 4: Ejector Mesh

If design loop is satisfactory

BOM

Bill of materials table after final design

Fabrication

Engineering drawing

Results

Base

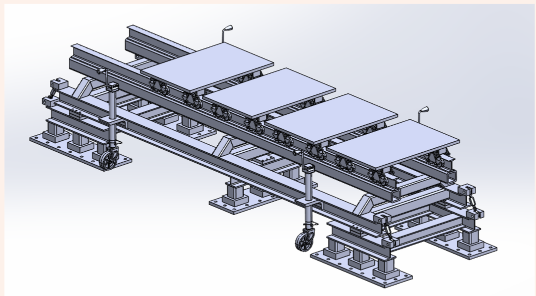

Fig. 5: Base Skid Design

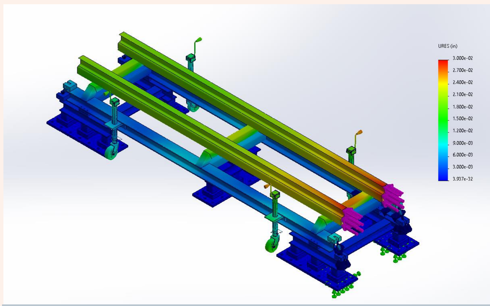

Fig. 6: Base Skid Design Results

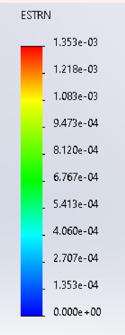

Fig. 7: Strain Results

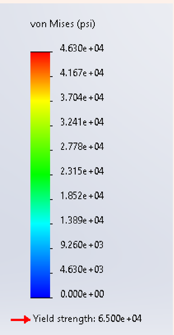

Fig. 8: Pressure Results

Extreme Conditions at 50,000 lbf:

- Stress: $4.63 * 10^4\ psi$
- Maximum displacement: $3.000 * 10^{-2}\ in$
- Minimum displacement: $3.937 * 10^{-32}\ in$
- Maximum strain: $1.353\ * 10^{-3}\ in/in$

Test Section without ribs

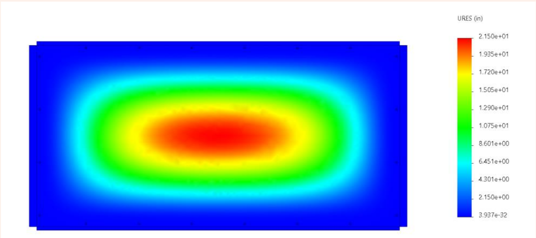

Fig. 9: M_∞ = 8 Worst Case Conditions

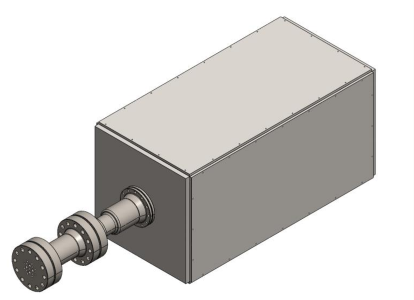

Fig. 10: Test Section without ribs CAD

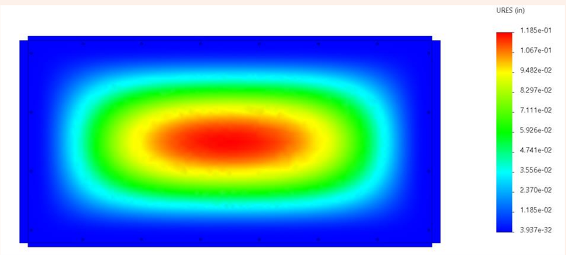

Fig. 11: Negative Pressure Conditions

M_∞ = 8 Stagnation Conditions in Test Section:

- Internal Pressure: $5,400\ psi$
- External Pressure: $14.7\ psi$
- Internal Temperature: $2,381\ K$
- External Temperature: $300\ K$
- Max. Displacement: $2.150 * 10^1\ in$
- Min. Displacement: $3.937 * 10^{-32}\ in$

Negative Pressure within Test Section:

- Internal Pressure: $-14.7\ psi$
- External Pressure: $14.7\ psi$
- Internal Temperature: $300\ K$
- External Temperature: $300\ K$
- Max. Displacement: $1.185 * 10^{-1}\ in$
- Min. Displacement: $3.937 * 10^{-32}\ in$

Test Section with ribs

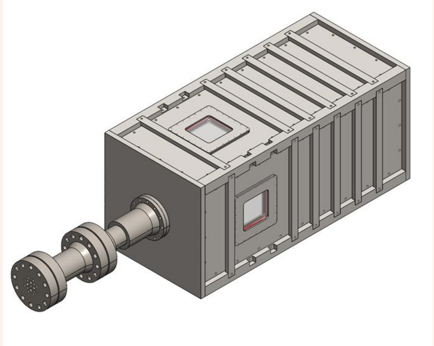

Fig. 12: Test Section Design

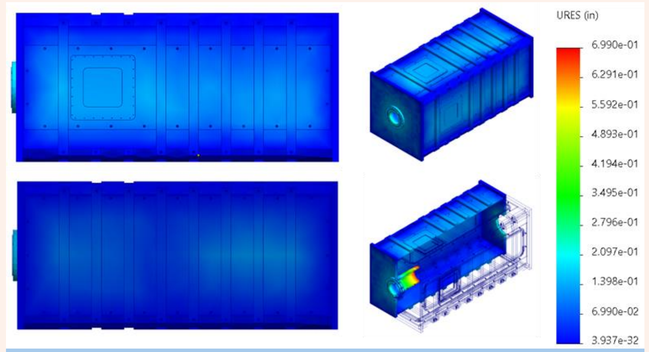

Fig. 13: Test Section Results

M_∞ = 8 Stagnation Conditions in Test Section:

- Internal Pressure: $5,400\ psi$
- External Pressure: $14.7\ psi$
- Internal Temperature: $2,381\ K$
- External Temperature: $300\ K$
- Max. Displacement: $6.990 * 10^{-1}\ in$
- Min. Displacement: $3.937 * 10^{-32}\ in$

Negative pressure within Test Section:

- Internal Pressure: $-14.7\ psi$
- External Pressure: $14.7\ psi$
- Internal Temperature: $300\ K$
- External Temperature: $300\ K$
- Max. Displacement: $1.669 * 10^{-3}\ in$
- Min. Displacement: $3.937 * 10^{-32}\ in$

Ejector

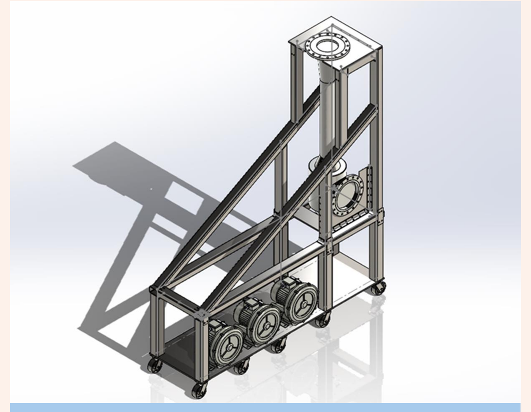

Fig. 14: Ejector Design

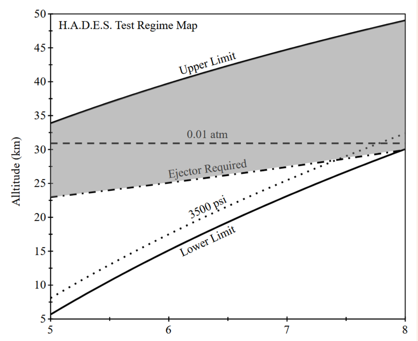

Fig. 15: Test map for Ejector use

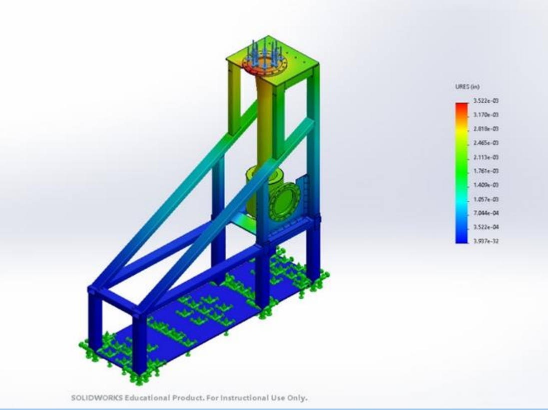

Fig. 16: Ejector Results

Maximum Stress: $2.259\ * 10^3\ psi$
Maximum Displacement: $3.522 * 10^{-3}\ in$
Maximum Strain: $4.435\ * 10^{-5}\ in/in$
Altitude requirement for Ejector Mach 5: **22.5 – 33.8 Km**
Altitude requirement for Ejector Mach 8: **25.1 – 48.6 Km**

Conclusion

1. Base Skid

1. After several revisions and a literature review on wind tunnel skid designs, the latest design was simulated. It incorporates I-beams, rectangular and square tubes, and flat plates to ensure rigidity and structural integrity under thrust loads. Given the test section's weight (~24,000 lbs.), maintenance is best facilitated by making the flow conditioning section and ejector movable. The skid must accommodate alignment errors, allowing both vertical and horizontal movement. Rollers on I-beams enable horizontal adjustments, while lead screws provide fine vertical shifts to prevent displacement during maintenance and testing. The ejector base, supported by casters and lead screws, holds the 2,000-lb ejector and allows controlled movement. Simulation results confirmed the skid can withstand 50,000 lbf axial thrust, with maximum stress occurring near the end section but remaining within the Young's modulus elastic region. Plastic deformation would only occur beyond 6.5 × 10^4 psi.

2. Test Section

1. Two test section designs were considered: one with ribs and one without. The ribs were included to distribute pressure from the continuous airflow. Simulating the ribless design revealed significant displacement at the center, causing uniform deformation. This would be problematic during multiple test runs, as high internal pressure could lead to material expansion. Additionally, the extreme temperatures during Mach 8 tests could intensify deformation through thermal expansion. A second simulation with ribs showed a reasonable reduction in deformation, confirming that ribs are necessary to maintain structural integrity at high Mach numbers. Future considerations for a possible expansion of the wind tunnel would be have a bigger test section to accommodate bigger models in which would allow more types of testing at different criteria. A redesign stage is necessary to determine whether the current base skid would keep its structural integrity holding the new test section and if not, design a new base skid in which can be adapted to the current one.

3. Ejector Selection and Requirements

1. The ejector is a critical component of the wind tunnel, as it enables altitude simulation within the test section. This is essential for testing models at varying altitudes and analyzing the results. The choice of ejector depends on the specific conditions planned for test campaigns. The Mach 5-8 wind tunnel is designed to simulate supersonic speeds at altitudes ranging from 5 to 50 kilometers, establishing the lower and upper limits for testing. Based on mathematical analysis following ASME standards, the minimum altitude required for ejector use is 22.5 kilometers, extending up to 50 kilometers. Another key consideration is whether to use a single-stage or multi-stage ejector, which differs in the number of mixing chambers used to achieve the desired altitude pressure. After a literature review and discussions with lab members, a single-stage ejector was determined to be the most suitable choice. It effectively achieves the required pressures while being simpler to operate, easier to maintain, and allowing for faster test preparation. Future considerations for a possible expansion of the wind tunnel's ejector would be to accommodate higher attitudes. This would require a reevaluation of the capabilities of other ejectors to determine which type of ejector would accomplish the goals of the lab.

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