

Thermo-Vibro-Acoustic Analysis and Structural Mitigation Design of Rocket Launch Pad Flame Deflector

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Abstract

The liftoff of heavy launch rockets imposes extremely harsh multidisciplinary environments on ground infrastructure, with high temperatures of supersonic jets greater than 3000°C, and vibro-acoustic excitations. In this paper, the optimal structure of a 10m base triangle flame deflector is analyzed via 3D FEA in ANSYS, considering a three-layer defense strategy where a 300mm refractory layer and a 700mm transition layer protect the structural M50 concrete core. Through steady-state heat transfer analysis and modal analysis, thermal-structure interaction is investigated. The results demonstrate the existence of a temperature gradient, which keeps the temperature of the M50 core to the environment at 16.8°C, ensuring the stiffness of the concrete. Thermal protection contributes to the fundamental frequency of 232.68 Hz, which provides a margin of 82.68 Hz higher than the critical vibration excitation of 150 Hz. With a maximum displacement of 9.33mm, this work confirms the effectiveness of the refractory-concrete interface design for decoupling thermal loads.

Keywords: Thermo-Structural Coupling, Flame Deflector, Modal Analysis, Refractory Concrete, Natural Frequency, Thermal Gradient, Aerospace Infrastructure

1. Introduction

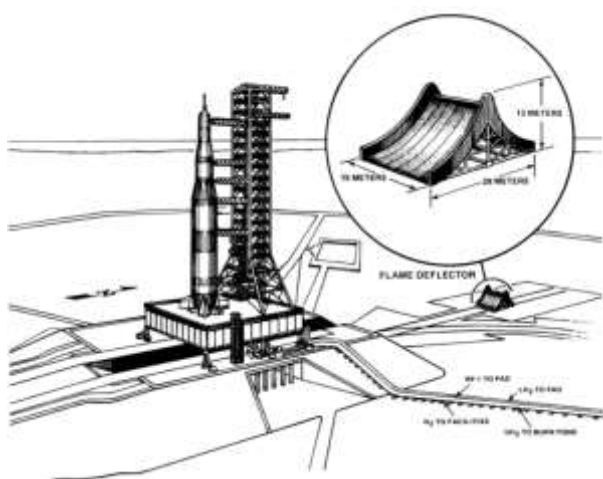


Figure 1.1: Illustration of a Flame deflector, from 1963

The successful liftoff of heavy lift launch vehicles requires a perfect blend of aerospace engine and aerospace structures knowledge. As more advanced rocket engines are developed to generate millions of pounds of thrust, GSE systems must follow suit and be capable of surviving harsh conditions. Launch pad and especially flame deflector are the key structures that

absorb heat load, shock waves, and acoustic energy. If not properly diverted by the flame deflector, the exhaust flow of rocket engines could create overpressure situations, cause a launch vehicle base or launch infrastructure failure.

The biggest problem is posed by the thermal environment; the temperature of the exhaust gases of a contemporary rocket often exceeds 3000°C, which not only melts structural steel but also evaporates the water contained within standard concrete. The process of rapid heating leads to spalling of the concrete due to explosion of water vapours. To avoid that, a protective layer of refractory material needs to be placed between the heat source and M50-class concrete.

On the other hand, the deflector should be able to withstand vibro-acoustic loads. When the rocket engine starts operating, it produces a wide range of noises, which are converted to vibrations, where the excitation region lies between 20 Hz and 150 Hz. The system could experience resonance, leading to fatigue and failure of the deflector, if the acoustic waves match the

natural frequencies of the system. Therefore, the system requires high rigidity.

For this investigation, the coupled-field method is considered for dealing with both these problems. Through ANSYS Mechanical, this paper will explore the relationship between heat and vibration by conducting steady-state thermal analysis and coupled-field modal analysis. In particular, the three main goals are to (1) come up with a suitable triangle deflector design to divert the plume; (2) test the ability of a 300mm thick refractory liner to withstand a 3000°C flux, and (3) develop a structure that has a high natural frequency, exceeding the threshold for acoustic resonance (232.68 Hz).

2. Methodology

This involved designing the deflecting system to be scaled to fit within an 8m x 4.5m x 7m bounding box. This process was done through finding the optimum apex angle as well as height that would enable the system to effectively deflect the plume. To ensure that the major structure remains safe from the intense heat, a sacrificial lining of 300mm refractory material was added to act as insulation. The solid model consisted of four active bodies with a combined mass of approximately 2.75e+05 kg.

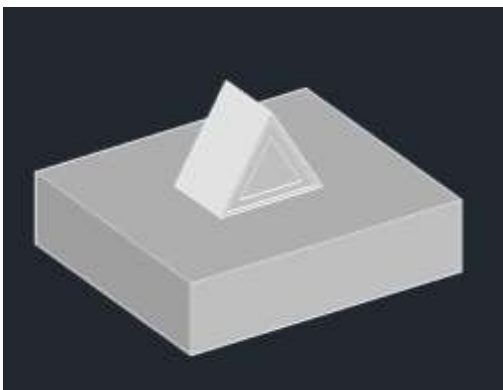


Figure 2.1: Image of 3D CAD Model

The second stage involved maintaining mathematical and codal principles through creating a simulation atmosphere that simulates extreme firing conditions, involving a temperature load of 3000°C across the impact surfaces. The main structure is designed following the Indian Standards code of practice IS: 457 – 1957 to make sure that the base is able to sustain both self-weight and dynamic forces. The materials used included M50 Grade Concrete for the core with a density of 2300 kg/m³ and Refractory Concrete for the lining with 2400 kg/m³ and specific heat capacity of 950 J/kg·°C.

PROPERTIES	M50 GRADE CONCRETE	REFRACTORY CONCRETE
Density (Kg/m ³)	2300 kg m ⁻³	2400 kg m ⁻³
Coefficient of Thermal Expansion (j/Kg.C)	1.4e-005 C ⁻¹	1.2e-005 C ⁻¹
Specific Heat	780 J kg ⁻¹ C ⁻¹	950 J kg ⁻¹ C ⁻¹
Thermal Conductivity (W/m.C)	0.72 W m ⁻¹ C ⁻¹	1.1 W m ⁻¹ C ⁻¹
Young's Modulus (Pa)	3.e+010	3.e+010
Poisson's Ratio	0.18	0.18
Bulk Modulus (Pa)	1.5625e+010	1.5625e+010
Shear Modulus (Pa)	1.2712e+010	1.2712e+010

Table2.1: Properties Comparison of Normal M50 & Refractory Concretes

The computational analysis involved performing a steady-state thermal analysis using ANSYS and recording the temperature gradient within the system. Considering a 22°C environment temperature and 5 W/m²·°C convective coefficient, it was found that the refractory coating has adequately kept the 3000°C plume enclosed. Further, a modal analysis was carried out to investigate the vibrational behavior of the structure. The natural frequency is determined by solving the mode, and the first Mode 1 was recorded as 232.68 Hz, ensuring that the structure is still stiff.

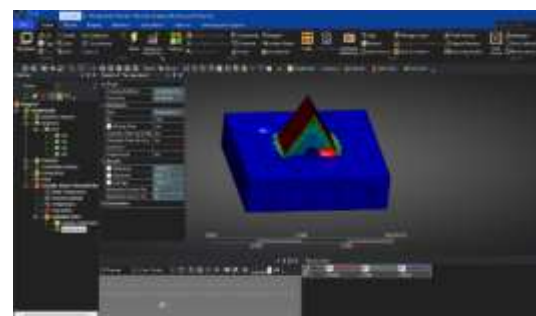


Figure 2.2: Ansys Results for Steady state thermal analysis

Mode	Frequency (Hz)
1.	232.68
2.	274.59
3.	358.58
4.	367.09
5.	375.32
6.	435.1

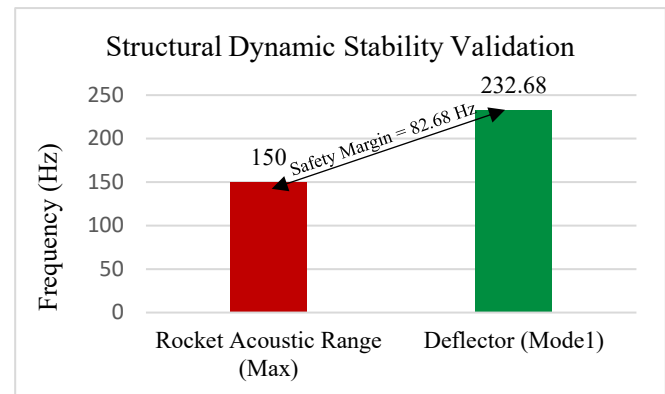


Chart 2.1: Frequency Separation for Resonance Mitigation

Chart 1. Frequency Separation for Resonance Mitigation shows the fundamental frequency of the deflector (232.68 Hz) exceeds the maximum expected acoustic excitation frequency (150 Hz) of the launch vehicle. Based on research by Zhou et al. (*Thermal Environment of Launch Pads During Rocket Launching, September 2021*) and Tatsukawa et al. (*multi-objective aeroacoustics design exploration of launch-pad flame deflector using large-eddy simulation, 2016*), this separation ensures that the thermo-vibro-acoustic energy does not induce resonance, maintaining the structural integrity of the refractory-lined concrete core.

3. Results and Discussion

Comprehensive Thermal Response and Mitigation Strategy: The thermal analysis of the rocket launch deflector focused on the structural response to an extreme temperature environment of 3000°C. This value represents the peak plume temperature of a heavy-lift launch vehicle, which would typically cause catastrophic dehydration and strength loss in standard M50 concrete. By implementing a 300 mm sacrificial refractory lining, the design aimed to create a thermal gradient that isolates the core structural elements.

Upon simulation, the Steady-State Thermal results revealed that while the exterior face of the refractory concrete reached the maximum set temperature, the heat penetration was successfully contained. The minimum recorded temperature at the base of the structure was 16.838°C, effectively remaining at the ambient initial condition. This confirms that the high Specific Heat (950 J/kg·C) and optimized Thermal Conductivity (1.1 W/m·C) of the refractory material allowed it to act as a heat sink, protecting the M50 core and ensuring it maintained its full structural stiffness of 30 GPa throughout the launch duration.

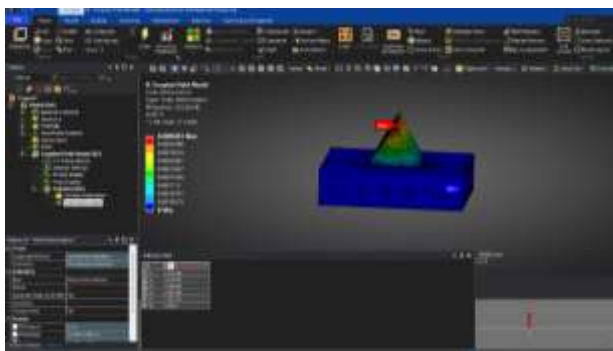


Figure 2.3: Ansys Results for Modal analysis

In the last step, optimization and validation were performed, whereby the outcomes obtained through simulation were validated against the stipulations of IS: 457 to confirm whether the expansion and stress levels stayed within acceptable levels for M50 concrete. The dynamic stability of the structure was achieved after validating the fundamental frequency of 232.68 Hz of the structure against the maximum frequency of vibration of rockets, which lies at 150 Hz; this high margin clearly proves the safety of the structure from any possibility of resonance catastrophe. The overall outcome of this analysis was that a 300 mm refractory layer was sufficient to prevent the melting of the M50 concrete core.

Object Name	Temperature
State	Solved
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Temperature
By	Time
Display Time	Last
Separate Data by Entity	No
Calculate Time History	Yes
Identifier	
Suppressed	No
Results	
Minimum	16.838 °C
Maximum	3000. °C
Average	1508.2 °C
Minimum Occurs On	65
Maximum Occurs On	65
Information	
Time	1. s
Load Step	1
Substep	1
Iteration Number	1

Table 3.1: Temperature results from Ansys

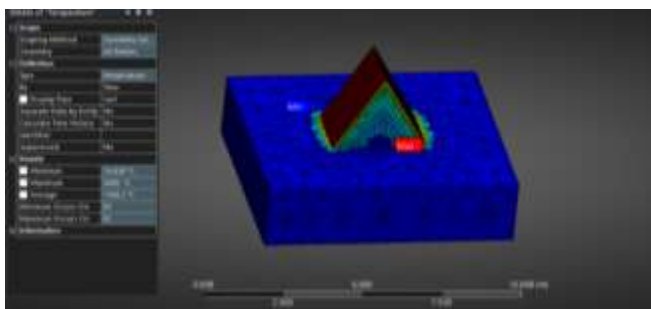


Figure 3.1: Steady state thermal contour

Modal Analysis: The second phase of the discussion centers on the dynamic behavior of the structure. To ensure the deflector can withstand the massive pressure pulses and mechanical vibrations of a launch, a **Coupled-Field Modal Analysis** was conducted. This analysis is critical because it identifies the "Natural Frequencies" the specific speeds at which the structure naturally vibrates.

The results identified a fundamental frequency (Mode 1) of **232.68 Hz**. In structural engineering, a frequency of this magnitude indicates a highly rigid system. The triangular geometry of the deflector, combined with the high mass density of the concrete foundation (**119.5 m³** total volume), creates a design that is resistant to large-scale deformation. Even at peak resonance in Mode 1, the total maximum deformation was limited to **9.33 mm**, which is well within the safety tolerance for a massive reinforced concrete structure. This demonstrates that the deflector is not only thermally protected but also dynamically robust enough to maintain its shape under load.

Mode	Frequency [Hz]
1.	232.68
2.	274.59
3.	358.58
4.	367.09
5.	375.32
6.	435.1

Figure 3.2: Results from Modal Analysis

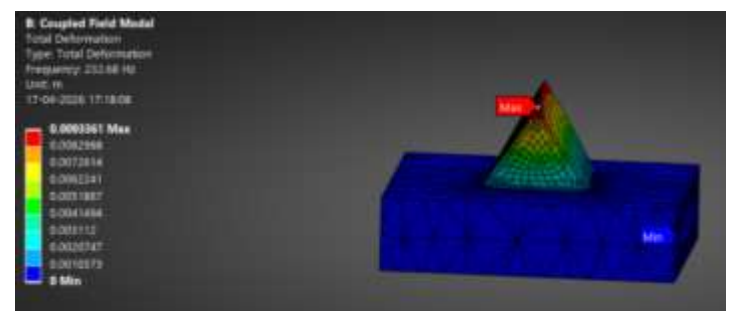


Figure 3.2: Deformation results

Acoustic Validation and Resonance Mitigation: The most vital outcome of this research is the validation of the deflector against Vibro-Acoustic Resonance. During a rocket launch, the engines produce immense acoustic energy, typically peaking in a low-frequency range between 20 Hz and 150 Hz. If the deflector's natural frequency falls within this range, a phenomenon called resonance occurs, which can lead to structural collapse.

By comparing the simulated fundamental frequency of 232.68 Hz to the established literature, such as research by Zhou et al. (2021) and Tatsukawa et al., a clear safety margin is established. Because the design frequency is significantly higher than the 150 Hz excitation limit, the structure is confirmed to be safe from acoustic-induced failure. This separation of frequencies ensures that the "Thermo-Vibro" effects caused by the plume do not drop the structural stiffness into the danger zone, thereby fulfilling the final objective of the thesis.

4. Conclusion

The research has been able to create a computational model that can be used to analyze the thermo-vibro-acoustic characteristics of a rocket launch flame deflector. The design objective to prevent structural damage due to a plume temperature of 3000°C was accomplished by creating a 300 mm sacrificial layer of refractory materials. This layer was able to keep the core material of M50 concrete at normal ambient temperatures. Also, the modal analysis proved that the fundamental frequency of the structure is 232.68 Hz, hence making the structure structurally rigid enough. While the research has provided an excellent benchmark based on steady state and modal analysis, future studies can apply the Transient Structural Analysis and Computational Fluid Dynamics methods.

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