Harmonic Analysis of Flex Seal of Rocket Nozzle

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Abstract: A flex seal in a rocket nozzle provides directional change of the rocket and acts as a pressure tight seal. In the present analysis, ground test conditions and forced vibration test are simulated using 3D finite element method to check the effect of number of pads and shims on the flex seal, to study the effect of isotropic material and composite material on the flex seal for shims. The problem is modeled in ANSYS Workbench 2020 R2 student version. 3D analysis is performed for flex seal with varying design parameters (shims and pads) to perform the harmonic analysis. The constraints and loading are given as per the ground test conditions followed in industry. A maximum extended operating pressure of 9MPa is applied. Proper mesh refinement is done for reasonably acceptable finite element solution. From the design parametric study, model 5 with 9 shims and 10 pads shows better deformations and better stress values. The remaining models (1, 2, 3 and 4) are showing maximum deformations and peak stresses which are going to failed in the resonance conditions. Model 5 under harmonic analysis does not allow the structure to fail in the resonance conditions.

Keywords: Finite Element Method, Flex Seal, Rocket Nozzle, Flex Nozzle, Pivot point, Actuator, Flex seal sub assembly, ANSYS and Finite Element Method.

1 Introduction

The Flex Nozzle System mainly consists of
- Flex seal
- Pivot point
- Actuator

The detailed structure of above mentioned components are as shown below in the Fig 1.
The Flex Nozzle System consists of 4 sub assemblies i.e., Convergent sub assembly, Divergent sub assembly, Intermediate dome sub assembly and Flex seal sub assembly. John T. Herbert et al [1] invented the flexible joint. This flexible joint is invented for coupling of shafts, conduits, and more particularly to an annular joint means comprising of alternate layers of rigid reinforcing and resilient material. E.Y.Wong [2] in this a solid rocket motor with an inner diameter of 260 inch is designed, fabrication, and test of a large diameter, flight weight, and omnidirectional flexible seal meeting their requirements are presented. Form this simplified flexible seal was designed which consists of uniform, conical shapes of rubber and steel layers. Donat, James R [3] the solid rocket motors, direction are controlled by controlling the thrust vector from the nozzle. In this the flex seal core geometry is estimated. The core is analyzed for performance characteristics such as stress, weight, and the torque required vectoring the core based on the requirements/constraints. Fredrick R. et al [4]. This invention related to liquid propellant reaction engines for controlling the direction of rocket and amount of thrust required. Vector control of the craft, pitch and yaw changes, has been obtained by deflecting the exhaust stream in a desired direction by installing vanes or jetavators in the exhaust stream. Louis E. Miltenberger [5] invented a system providing a rocket powered vehicle with complete thrust vectoring capabilities including a convergent-divergent nozzle attached to a motor casing by a flexible joint member. Gerald F. Kobalter [6] told that a flexible nozzle consists of conically shaped body with alternative layers of pads and shims bonded together in a fluid tight manner. The studies regarding misalignment and thermal growth in the system due to redirect flow of applied forces due to pressure integrity are elaborated. Stanley P. Desjardins, et al [7]. The present invention represents a further advance in the art by incorporating the flexible bearing not as a separate component, but as an integral, annular portion of the divergent cone of the thrust nozzle. Gary M. Wendel [8] a thrust nozzle of the hollow-cone type fixed to a stationary shell having external insulation on the nozzle is invented. The extended part with lining of a thin light weight insulation made of carbon-epoxy liner provides more efficient energy conversion. John T. Herbert [9] the swivelled type rocket motor joint and the purpose of its exhaust guidance are presented in this paper. James R. Johnston, et al [10] in this performance of Rocket nozzle throat insert materials were investigated using three small-scale solid-propellant rocket engines. The graphite nozzles performed well with the least oxidizing 5600°F propellant but generally eroded severely with the other propellants. Fibre reinforced plastic nozzles as a class was the least erosion resistant materials.
2 Problem Description

2.1 Problem Objective & Scope of the work

To simulate the structure of the flex seal of a rocket nozzle under harmonic loads using finite element analysis with reference to the ground test conditions by varying number of shims and elastomeric pads. The scope of the work is to develop and verify 3D finite element models in ANSYS software and performing non-linear static analysis for studying the normal stresses (Axial & Radial) and directional deformations (Axial & Radial).

2.2 Geometry

The geometrical dimensions of the flex seal of the rocket nozzle [2] for the present analysis which are considered are shown in Figure 2.

![Figure 2. Flex seal Geometry](image)

- Diameter (Inner): 350 mm
- Diameter (Outside): 420 mm
- Full height: 190 mm
- Joint angle (Inner): 42 degrees
- Joint angle (Outer): 54 degrees
- Joint angle (Mean): 48 degrees
- Radius of pivot: 248 mm
- Diameter (Throat): 160 mm
- Geometry of Shim: Spherical
The cross sectional (2D) view of the Flex Seal (5 Shims and 6 Pads) with parts and 3D view are shown in the below Figure 3. The list of the flex seal models used for the harmonic analysis and their respective quantity of shims and pads and their thickness are as shown in Table 1.

![Figure 3. (a) 2D and (b) 3D Geometry of Flex Seal](image)

### Table 1 Geometric Model Details

| Model Number | Quantity | Thickness (mm) | Weight (Kg) |
|--------------|----------|----------------|-------------|
|              |          | Shim | Elastomeric Pad | Shim | Elastomeric Pad |
| Model 1      | 5        | 6    | 11             | 6.67  | 64.958          |
| Model 2      | 6        | 7    | 10             | 5     | 66.199          |
| Model 3      | 7        | 8    | 9              | 4     | 66.945          |
| Model 4      | 8        | 9    | 8              | 3.45  | 66.958          |
| Model 5      | 9        | 10   | 7              | 3.2   | 67.197          |

2.3. Meshing

Meshing is the process of converting the geometrical entities to finite element entities, such as nodes and elements. Here two types of elements are used for the analysis i.e., solid 186 and solid 187. Solid 186 is used for the flat portions and Solid 187 is used for the curved portions of the flex seal of the rocket nozzle. The three dimensional mesh model of the flex seal of the rocket nozzle having 5 shims and 6 pads are shown in the Figure 4.
A cylindrical coordinate system is assigned to the geometry of the flex seal with all models. X-Axis is assigned to the radial direction, Y–Axis is assigned to the circumferential direction and Z-Axis is assigned to the longitudinal direction.

2.4 Material Properties

Steel and mooney rivlin 2 parameters rubber material are used for harmonic analysis. Fore end ring, aft end ring, throat housing & Shims are assigned with steel material, Elastomeric pads are assigned with mooney rivlin two parameters and shims are assigned with the steel. Steel material has density of 5.68 kg/m$^3$, Young’s Modulus of 2.1e5, poisso’s ratio of 0.3 and yield strength of 1000 MPa and Mooney rivlin parameters are C01 = 1.0 MPa, C10 = 1.85 MPa with density of 0.8 kg/m$^3$.

2.5 Loads and Boundary Conditions

A normal pressure of 9 MPa [1] is applied on external surface of the flex seal of the rocket nozzle and bottom surface of the Aft end ring is fixed in all degree of freedoms, therefore a fixed support constraint is given to the bottom surface of the aft end ring which are shown in the below Figure 5.

2.6 Connection

The individual components of the flex seal are glued together to form an assembly. So, in this analysis bonded contacts are given to the individual parts of the flex seal. As discussed in the previous session elastomeric pads contain material non linearity properties. So solution type of nonlinear analysis is to be performed on the flex seal.
3. Harmonic Analysis

In this paper we perform Harmonic analysis on the flex seal of the rocket nozzle [Model 1] with a harmonic load (Pressure) of 9 MPa within a frequency range of 0 to 1000 Hz. For harmonic analysis, a modal analysis is required to perform to find the natural frequencies of the flex seal within the range of 0 to 1500 Hz and natural frequencies are listed in Table 2.

Table 2. Natural Frequencies of the Flex Seal [Model 1]

| Mode No | Frequency (Hz) | Mode No | Frequency (Hz) |
|---------|---------------|---------|---------------|
| 1       | 126.45        | 11      | 767           |
| 2       | 126.55        | 12      | 963.67        |
| 3       | 148.05        | 13      | 963.81        |
| 4       | 315.61        | 14      | 985.91        |
| 5       | 339.33        | 15      | 1014.5        |
| 6       | 339.65        | 16      | 1015          |
| 7       | 535.87        | 17      | 1186.2        |
| 8       | 536.03        | 18      | 1224.4        |
| 9       | 546.88        | 19      | 1224.8        |
| 10      | 765.63        | 20      | 1303.4        |

From the above table, it is shown that a total of 20 natural frequencies are obtained between the ranges of 0 to 1500 Hz. The directional deformation of the flex seal [Model 1] shown in the figure 6.0, which is subjected to harmonic load.

From the above Figure 6, it is shown that the directional deformations of the flex seal in longitudinal direction are more than the deformations of the flex seal in the radial direction. The maximum deformations are occurred at the 300 Hz frequency which is very close to the fourth natural frequency of the structure. The normal stresses of the flex seal [Model 1] shown in the Figure 7 which is subjected to harmonic load.
Figure 7. Normal Stresses of the flex seal [Model 1]

From the above figure it is shown that the normal stresses of the flex seal in circumferential direction are more than the stresses of the flex seal in the radial and longitudinal directions. The maximum deformations are occurred at the 300 Hz frequency which is very close to the fourth natural frequency of the structure. Harmonic analysis is performed on the flex seal of the rocket nozzle [Model 2] and natural frequencies are listed in Table 3.

Table 3. Natural Frequencies of the Flex Seal [Model 2]

| Mode No | Frequency (Hz) | Mode No | Frequency (Hz) |
|---------|----------------|---------|----------------|
| 1       | 134.06         | 11      | 771.35         |
| 2       | 134.1          | 12      | 1015.3         |
| 3       | 156.94         | 13      | 1015.8         |
| 4       | 307.92         | 14      | 1015.9         |
| 5       | 332.74         | 15      | 1016.1         |
| 6       | 332.95         | 16      | 1042.8         |
| 7       | 560.35         | 17      | 1165.7         |
| 8       | 560.42         | 18      | 1249.9         |
| 9       | 574.78         | 19      | 1250.1         |
| 10      | 771.09         | 20      | 1273.8         |

From the above table, it is shown that a total of 20 natural frequencies are obtained between the ranges of 0 to 1500 Hz. The directional deformation of the flex seal [Model 2] shown in the fig 8. which subjected to harmonic load.

Figure 8. Directional Deformation of the flex seal [Model 2]
From the above figure it is shown that the directional deformations of the flex seal in longitudinal direction are more than the deformations of the flex seal in the radial direction. The maximum deformations are occurred at the 300 Hz frequency which is very close to the fourth natural frequency of the structure. The normal stresses of the flex seal [Model 2] shown in the fig 9, which subjected to harmonic load

![Normal Stresses](image)

Fig 9. Normal Stresses of the flex seal [Model 2]

From the above figure it is shown that the normal stresses of the flex seal in circumferential direction are more than the stresses of the flex seal in the radial and longitudinal directions. The maximum deformations are occurred at the 300 Hz frequency which is very close to the fourth natural frequency of the structure. Harmonic analysis is performed on the flex seal of the rocket nozzle [Model 3] and natural frequencies are listed in table 4.

**Table 4. Natural Frequencies of the Flex Seal [Model 3]**

| Mode No | Frequency (Hz) | Mode No | Frequency (Hz) |
|---------|----------------|---------|----------------|
| 1       | 175.26         | 8       | 881.78         |
| 2       | 175.84         | 9       | 899.87         |
| 3       | 202.55         | 10      | 954.37         |
| 4       | 407.4          | 11      | 954.5          |
| 5       | 414.67         | 12      | 1182.5         |
| 6       | 414.95         | 13      | 1182.6         |
| 7       | 881.55         |         |                |

From the above table, it is shown that a total of 13 natural frequencies are obtained between the ranges of 0 to 1500 Hz. The directional deformation of the flex seal [Model 3] shown in the fig 10, which subjected to harmonic load
From the above Fig 10, it is shown that the directional deformations of the flex seal in longitudinal direction are more than the deformations of the flex seal in the radial direction. The maximum deformations are occurred at the 400 Hz frequency which is very close to the fourth natural frequency of the structure. The normal stresses of the flex seal [Model 3] shown in the fig 11 which subjected to harmonic load.

From the above figure it is shown that the normal stresses of the flex seal in circumferential direction are more than the stresses of the flex seal in the radial and longitudinal directions. The maximum deformations are occurred at the 400 Hz frequency which is very close to the fourth natural frequency of the structure. Harmonic analysis is performed on the flex seal of the rocket nozzle [Model 4] and natural frequencies are listed in table 5.

| Mode No | Frequency (Hz) | Mode No | Frequency (Hz) |
|---------|----------------|---------|----------------|
| 1       | 287.36         | 7       | 1038.1         |
| 2       | 288.02         | 8       | 1038.2         |
| 3       | 338.27         | 9       | 1308.3         |
| 4       | 534.33         | 10      | 1308.5         |
| 5       | 534.61         | 11      | 1326.9         |
From the above table, it is shown that a total of 11 natural frequencies are obtained between the ranges of 0 to 1500 Hz. The directional deformation of the flex seal [Model 4] shown in the fig 12. which subjected to harmonic load,

![Directional Deformation](image1)

**Fig 12. Directional Deformation of the flex seal [Model 4]**

From the above figure it is shown that the directional deformations of the flex seal in longitudinal direction are more than the deformations of the flex seal in the radial direction. The maximum deformations are occurred at the 500 Hz frequency which is very close to the fourth natural frequency of the structure. The normal stresses of the flex seal [Model 4] shown in the fig 13. which subjected to harmonic load

![Normal Stresses](image2)

**Fig 13. Normal Stresses of the flex seal [Model 4]**

From the above figure it is shown that the normal stresses of the flex seal in circumferential direction are more than the stresses of the flex seal in the radial and longitudinal directions. The maximum deformations are occurred at the 500 Hz frequency which is very close to the fourth
natural frequency of the structure. Harmonic analysis is performed on the flex seal of the rocket nozzle [Model 5] and natural frequencies are listed in table 6.

Table 6. Natural Frequencies of the Flex Seal [Model 5]

| Mode No | Frequency (Hz) |
|---------|----------------|
| 1       | 893.37         |
| 2       | 894.41         |
| 3       | 1378.8         |

From the above table, it is shown that a total of 3 natural frequencies are obtained between the ranges of 0 to 1500 Hz. The directional deformation of the flex seal [Model 5] shown in the fig 14 which subjected to harmonic load,

Fig 14. Directional Deformation of the flex seal [Model 5]

From the above figure it is shown that the directional deformations of the flex seal in longitudinal direction are more than the deformations of the flex seal in the radial direction. The maximum deformations are occurred at the 1000 Hz frequency. The normal stresses of the flex seal [Model 5] shown in the fig 15 which subjected to harmonic load

Fig 15. Normal Stresses of the flex seal [Model 5]
From the above fig15. , it is shown that the normal stresses of the flex seal in circumferential direction are more than the stresses of the flex seal in the radial and longitudinal directions. The maximum deformations are occurred at the 1000 Hz frequency.

4. Conclusions

From the present work, harmonic analysis is performed on the flex seal of the rocket nozzle and the results of directional deformations in radial & longitudinal directions and normal stresses in radial, circumferential & longitudinal directions are calculated. The results shows that the directional deformations are higher in the longitudinal direction compared to the radial direction, normal stresses in circumferential directions are higher than the radial & longitudinal directions. The design model 1, 2, 3 & 4 are going to fail in strength point of view under harmonic loads in circumferential direction due to resonance. The design model 5 is in safe position under strength point of view and exhibits better stiffness performance and does not undergo resonance condition.

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