Dynamic analysis of rocket motor case

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Abstract: Rocket Motor Case (RMC) is a major component of Rockets and other Satellite launching vehicles. So, these structures should be of low weight, i.e. Low weight to high strength ratio materials, i.e., composite and alloys materials are used for main components. In the present analysis, 3-Dimensional finite element based static structural analysis and modal analysis are performed on the rocket motor case using aluminum alloy, titanium alloy, alloy steel, carbon epoxy and e glass epoxy. The problem is modeled in student version of ANSYS software. Stresses under radial, hoop, longitudinal directions are calculated with cylindrical coordinate system and list of natural frequencies and mode shapes are noted with respect to pre-stressed constrained and free-free boundary conditions. Later rectangular, semicircular, semi hexagonal and triangular types of stiffeners are introduced to the rocket motor case to perform static structural and modal analysis. The effect of stiffeners to the rocket motor case has studied for different materials under static and dynamic loading conditions. Best stiffener for rocket motor case is recommended based on the results, i.e., rectangular section having higher natural frequencies and semi hexagonal shape having less stresses in their respective directions.

Keywords: FEM, Static Structural Analysis, Modal Analysis, Rocket Motor Case.

Nomenclature: σ_{yt} = Yield Strength, ρ = Density, E = Young’s Modulus, G = Shear Modulus & µ = Poisson’s ratio.

1 Introduction
Rocket Motor Case [RMC] provides the pressure shell for propellant as well as the structural shell for the missile. General Dynamics Ordnance and Tactical Systems produce both metal and composite rocket motor cases. They are the leaders in the industrial world in designing, analysis, testing and manufacturing consumer required solid propellant rocket motor cases. Today, as the advancement in carbon fiber technology and high temperature resin offer advantages in performance and cost effectiveness. General Dynamics Ordnance and Tactical Systems produce products based on customers in the design, development and production of rocket motor cases. Rocket motors don’t require additional oxygen from atmosphere for combustion of the fuel. In a rocket motor, the chemical energy inside the fuel is converted to the thermal energy by a combustion process. The simple configuration of rocket motor consists of a dome, Igniter, motor case, insulation, propellant and nozzle [1] as shown in figure 1.
A solid-fuel rocket is a rocket with a motor that uses solid propellants (fuel/oxidizer). Solid rockets are still used today in model rockets and on larger applications for their simplicity and reliability. V Ramanjaneyulu [1] performed static structural analysis on the composite rocket motor case (CRMC) under realistic conditions. He stated that there is a gradual increase of Hoop stress from outer layer to inner layer in all parts of the CRMC. Eswara Kumar A [2] performed static and dynamic analysis on cylinder with various stiffeners; he stated that the helical stiffener shaped design has the higher specific structural stiffness, lower von mises and hoop stress. Eswara Kumar A [3] performed buckling analysis on the cylinder with varying atmospheric temperatures. It was observed that there is no considerable change of buckling load with convective heat transfer coefficient. But buckling load is decreasing with increase in temperature of inner surface of cylinder. Rakesh Potluri [4] Successful optimization using the response surface optimization procedure for a hybrid laminate has been performed. Bettiet al [5] has successfully performed the Design and Development of VEGA Solid Rocket Motors Composite Cases which has become major support for the development of the CRMC. Sayman [6] studied analysis of multi-layered composite cylinders under hygro thermal loading. In this study, he stated that under hygro thermal loadings condition stress analysis is developed for thick or thin multi-layered composite cylinders. Xia et al. [7] performed multi-layered filament-wound composite pipes under internal pressure.

2. Problem Description

2.1 Problem Statement

The main aim of the problem is to study the dynamic analysis of rocket motor case with different materials and effect of cylinder thickness on the stresses. The problem can be divided into two cases as discussed below.

2.2 Problem Modelling

The geometry of rocket motor case contains many components like igniter end dome, nozzle end dome, cylinder straight end dome, igniter end polar boss insulation, nozzle end polar boss insulation, igniter end bulk head, nozzle end bulk head, flexible rubbers at nozzle end and igniter end bulk heads, nozzle end closure and igniter end closure. The dimensions of the rocket motor case are taken from the Research Article [1] and it is shown in the figure 2.
Figure 2. Cross-sectional Dimensions of the Rocket Motor Case.

The 3D geometry model of the rocket motor case with skirt is modeled in the FEA software i.e., ANSYS 2020 R2 Academic version. The geometry of the model is shown in the figure 3.

Figure 3. Rocket Motor Case

2.3 Materials:
In this research work, 2 types of materials are used, i.e., metals and composite materials. Aluminum is assigned to the Igniter end bulk head, Nozzle end bulk head, igniter end polar boss and nozzle end polar boss. Rubber is assigned to the igniter end and nozzle end rubber portion. Steel is assigned to the igniter end and nozzle end closures. The main objective of the problem is to increase the stiffness and strength of the rocket motor case. The list of the materials used for the rocket motor case and skirt is listed in the below table 1.
Table 1. Isotropic Materials used for rocket motor case with skirt.

| Material Name                  | ρ  (g/cm³) | E  (MPa) | μ  | σyt |
|-------------------------------|------------|---------|----|-----|
| Aluminum Alloy 2024 (Heat Treated) | 2.79       | 72000   | 0.33 | 455 |
| Titanium Alloy                | 4.60       | 110000  | 0.36 | 1240|
| Alloy Steel (Heat Treated)    | 7.84       | 207000  | 0.3  | 1400 – 2000 |
| Rubber                        | 0          | 3.2     | 0.45 | -   |
| Aluminum                      | 0.0013     | 70000   | 0.32 | -   |
| Steel                         | 7.85       | 210000  | 0.3  | -   |

The main parts of the assembly i.e., cylindrical motor case with skirt is too focused mainly. The orthotropic conditions of the composite materials which were assigned to the motor case and skirt for the static and Dynamic analysis are as shown below in the table 2.

Table 2. Orthotropic properties of the composite materials.

| Material          | ρ (g/cm³) | EX (MPa) | EY (MPa) | EZ (MPa) | µXY | µXY | µXY | GXY, (MPa) | GYZ, (MPa) | GXZ, (MPa) |
|-------------------|-----------|----------|----------|----------|-----|-----|-----|------------|------------|------------|
| Carbon Epoxy      | 1.6       | 36600    | 46800    | 30300    | 0.04| 0.289| 0.21| 4900       | 4500       | 4900       |
| E-Glass Epoxy     | 1.98      | 19980    | 19640    | 14210    | 0.204| 0.312| 0.288| 5800       | 5600       | 5800       |

**Note:**
The longitudinal tensile and compressive strength of the carbon epoxy is 640 MPa
The longitudinal tensile and compressive strength of the E Glass epoxy is 428 MPa

2.4 Connections
Connections are given to the components of the rocket motor case to stick together. Bonded contacts are given between the parts of the rocket motor case assembly.

2.5 Mesh
Meshing is defined as conversion of geometric entities into the finite elements. Meshing is properly done on the rocket motor case for convergence of the applied load. Here two types of elements are used for the analysis i.e., solid 186 and solid 187. Solid 186 is a 20-node quadratic element which is applied for the central dome and skirt components. Solid 187 is a 10 node tetrahedron element which is applied for the igniter end and nozzle end domes.

2.6 Loads and Boundary Conditions
The structure of the rocket motor case is analyzed under static load of 9 MPa of internal pressure which is applied on the inside of the surface of the rocket motor case. Igniter end bulk head is fixed in all degrees of freedom i.e., fixed support is given to the igniter bulk head faces which are shown in the figure 4.
Figure 4. Loads and Boundary Conditions

3. Static Structural Analysis
The structure of the rocket motor case is analysed under static structural loads i.e., internal pressure load of 9 MPa and the maximum stresses in radial direction, hoop direction and longitudinal direction using aluminium, titanium, steel alloy, carbon epoxy and E Glass epoxy are calculated and listed in the table 3.0. The maximum radial stress of the motor case using aluminium alloy is shown in the below figure 5.

Table 3. Stresses of the Rocket Motor Case under Static Load.

| Material       | Radial Stress (MPa) | Circumferential Stress (MPa) | Longitudinal Stress (MPa) |
|----------------|---------------------|-----------------------------|--------------------------|
| Aluminum Alloy | 320.74              | 456.91                      | 336.16                   |
| Titanium Alloy | 324.59              | 458.04                      | 334.63                   |
| Alloy Steel    | 317.5               | 456.41                      | 337.89                   |
| Carbon Epoxy   | 288.65              | 478.7                       | 332.2                    |
| E Glass Epoxy  | 304.37              | 460.13                      | 315.24                   |

From the above table, it is noticed that the maximum stresses are coming in circumferential direction of the rocket motor case using titanium alloy in metals and carbon Epoxy in composites. The stresses which are obtained in the static analysis are within the limit of the respective material strength.
4. Modal Analysis

The modal analysis of the rocket motor case using Aluminium Alloy, Titanium Alloy, Alloy Steel, Carbon Epoxy and E-Glass Epoxy is performed under free-free and pre-stressed boundary conditions. The natural frequencies of the RMC using aluminium alloy and mode shapes of the rocket motor case are shown in the below figure 6.

The natural frequencies of the rocket motor case with different materials under free-free boundary conditions are listed in the below table 4.

Table 4. Natural frequencies of the structure under free - free boundary conditions.

| Material  | Mode No | Aluminium (Hz) | Titanium Alloy (Hz) | Alloy Steel (Hz) | Carbon Epoxy (Hz) | E Glass Epoxy (Hz) |
|-----------|---------|----------------|---------------------|------------------|------------------|--------------------|
|           | 1       | 0.             | 0.                  | 0.               | 0.               | 0.                 |
|           | 2       | 0.             | 0.                  | 0.               | 0.               | 0.                 |
|           | 3       | 0.             | 0.                  | 0.               | 0.               | 0.                 |
|           | 4       | 6.953          | 6.7499              | 6.9859           | 4.9313           | 3.7338             |
|           | 5       | 7.2463         | 7.0326              | 7.2832           | 5.4714           | 3.9058             |
|           | 6       | 7.9235         | 7.5826              | 8.0699           | 5.6368           | 4.4128             |
|           | 7       | 226.6          | 218.73              | 228.69           | 184.7            | 132.19             |
|           | 8       | 226.96         | 219.07              | 229.06           | 185.04           | 132.4              |
|           | 9       | 429.2          | 412.72              | 434.73           | 298.52           | 234.79             |
|           | 10      | 429.4          | 412.92              | 434.92           | 298.63           | 234.88             |
|           | 11      | 448.89         | 433.89              | 452.46           | 316.02           | 247.95             |
|           | 12      | 448.93         | 433.93              | 452.5            | 316.24           | 247.97             |
From the above table, it is observed that the first six natural frequencies of the structure of the rocket motor case is nearly equal to zero implies that the structure is free to vibrate in linear X, Y, Z direction and rotate about X, Y, Z Axis. It is recommended to consider the natural frequencies from the seventh mode of the structure.

From the above table it is observed that the structure of the rocket motor case with alloy steel has having higher natural frequencies compared to the other materials. The natural frequency is mainly dependent on the mass and stiffness of the structure. Alloy steel better stiffness results for the higher natural frequencies under free – free boundary conditions.

The natural frequencies of the rocket motor case with different materials under pre-stressed boundary conditions are listed in the below table 5.

Table 5. Natural frequencies of the structure under pre-stressed boundary conditions.

| Material Mode No | Aluminium Alloy (Hz) | Titanium Alloy (Hz) | Alloy Steel (Hz) | Carbon Epoxy (Hz) | E Glass Epoxy (Hz) |
|------------------|----------------------|---------------------|-----------------|------------------|-------------------|
| 1                | 316.01               | 291.72              | 284.57          | 187.39           | 170.43            |
| 2                | 316.02               | 291.95              | 284.86          | 187.4            | 170.43            |
| 3                | 323.60               | 301.82              | 322.41          | 286.95           | 245.73            |
| 4                | 323.82               | 301.83              | 322.42          | 287.01           | 245.76            |
| 5                | 492.23               | 462.92              | 477.67          | 298.46           | 299.39            |
| 6                | 492.47               | 463.16              | 477.9           | 385.92           | 323.3             |

From the above table it is observed that the structure of the rocket motor case with aluminium alloy is having higher natural frequencies compared to the other materials. The natural frequency is mainly dependent on the mass and stiffness of the structure. Aluminium with low mass and better stiffness results for the higher natural frequencies under pre stressed constrained boundary conditions.

5. Rocket Motor Case with Stiffeners

The design of the rocket motor case is modified by adding stiffeners for improving the strength and stiffness of the structure with respect to the static and dynamic loads. Here four types of stiffeners are used i.e., Rectangle, Semi Circle, Semi Hexagon and Triangular shapes. The volume of the structure is constant with different stiffeners. The type of stiffeners is discussed below and shown in the figure 7.

![Figure 7. Rocket Motor Case with Stiffeners](image-url)
Static Structural Analysis are performed and results with rectangular, semicircular, semi hexagonal and triangular sections using aluminium are noted in the below table 6.

| Stress | Rectangular | Semi Circular | Semi Hexagonal | Triangular |
|--------|-------------|---------------|----------------|------------|
| Radial Stress | 297.73 MPa | 297.47 MPa | 297.64 MPa | 297.29 MPa |
| Circumferential Stress | 441.44 MPa | 441.25 MPa | 440.87 MPa | 441.11 MPa |
| Longitudinal Stress | 362.50 MPa | 369.45 MPa | 357.31 MPa | 361.18 MPa |

From the above table, the maximum stresses are located in the circumferential direction and minimum stresses are located in radial direction.

From the above table, it is observed that the minimum radial stress is produced with the triangular shape. The minimum circumferential stress is produced with the semi hexagonal shape. The minimum longitudinal stress is produced with the semi hexagonal shape.

The static structural analysis of the rocket motor case with stiffeners are performed with remaining materials (Titanium Alloy, Alloy Steel, Carbon Epoxy and E Glass Epoxy) and it is noticed that the obtained stresses are within the limits of respective material strength.

Dynamic Analysis (Modal Analysis) is performed on the rocket motor case with rectangular, Semi Circular, semi hexagonal and triangular sections using aluminium under pre-stressed constrained boundary conditions and respective natural frequencies with respect to the mode number are listed in the below table 7.

| Shape | Rectangular (Hz) | Semi Circular (Hz) | Semi Hexagonal (Hz) | Triangular (Hz) |
|-------|------------------|--------------------|---------------------|-----------------|
| Mode 1 | 320.01          | 309.92             | 314.21              | 311.02          |
| Mode 2 | 320.06          | 310.08             | 314.74              | 311.9           |
| Mode 3 | 336.48          | 315.31             | 316.29              | 317.07          |
| Mode 4 | 336.82          | 315.39             | 316.61              | 317.16          |
| Mode 5 | 503.97          | 490.15             | 496.03              | 499.68          |
| Mode 6 | 504.8           | 490.4              | 497.13              | 500.51          |

From the above table, it is observed that the higher natural frequencies are obtained with rectangular section, followed by the triangular, semi hexagonal and semi circular under pre-stressed constrained boundary conditions.

The modal analysis of the rocket motor case with stiffeners is performed with remaining materials (Titanium Alloy, Alloy Steel, Carbon Epoxy and E Glass Epoxy) and it is noticed that the maximum value of natural frequencies is obtained with the rectangular section.

The volume of the rocket motor case with and without stiffeners are listed in the below table 8.

| Rocket Motor Case | Rocket Motor Case with stiffener |
|-------------------|---------------------------------|
| Volume (mm³)      | 1.8222e+008 mm³                |
|                   | 2.01E+08 mm³                   |

The percentage increment of volume with stiffener is listed below.

\[
\frac{2.01E+08 - 1.8222e+008}{1.8222e+008} \times 100 = 10.12
\]
From the above calculation, the total weight of the RMC with stiffeners is increased by 10.12% of its total weight without stiffener.

6 Conclusions
From the present work, the following observations and conclusions are drawn from the analysis of Rocket motor case.

1) Higher stresses are obtaining in circumferential direction compared to the radial and longitudinal directions.
2) The stresses which are produced from the rocket motor case using different materials are within the limits of respective material strength.
3) Rocket motor case using Aluminum having higher natural frequencies than the other materials.
4) The stresses of the rocket motor case with semi hexagonal shape stiffener having less value compared to the other stiffeners.
5) The natural frequencies of the rocket motor case with rectangular shape stiffener are higher compared to the other stiffeners.
6) It is recommended to use rectangular or semi hexagonal shape stiffeners to the rocket motor case for static and dynamic loads.

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