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Structural Design Analysis of Thrust Controlled Solid Motor

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Abstract:

Towards demonstration of thrust control in solid rocket, Thrust Controlled Motor (TCM) is configured with Hot Gas Flow Control Valve (HGFCV) to vary throat area for thrust modulation. Prototype TCM is developed for repetitive ground testing to fine tune the propellant formulation and finalize material technologies for high temperature and dynamic sealing applications of HGFCV.

The present report deals with the design and structural analysis of Thrust Controlled Motor (TCM) being developed at RCI/DRDO, HYD.The Thrust Control Motor (TCM) design is carried out as per ASME pressure vessel code for MEOP of 200.0 bar. The flange design is carried out following the Schneider's approach. To meet the functional requirements, igniter, nozzle end dome and nozzle casing has been configured with grooves and 'O'-Ring dimensions are finalized keeping its dialation more than 15% of 'O'-Ring Diameter. Finite element analysis is carried out for the above design to verify the stress levels are within allowable limits and also dialation expected due to internal pressure. The flange joint modeled using contact element method to verify opening of 'O'-Ring due to internal pressure and applying prestress through thermal stress values to verify stress level in bolt.

The result indicates that the maximum stresses and dialation are within allowable limits. Hence the motor design is meeting the ground test requirements.The design of motor is updated using the 3D structural analysis results and drawings are finalized based on the design analysis.

Nomenclature:

A = Minimum area of the bolt
Ac = Effective cross sectional area of the flange undergoing deformation
b_{max} = Half distance between PCD and Outer Diameter
C = Spring Constant of Complete joint
D = Motor Outer Diameter
E = Weld Efficiency
h_g = Half distance between PCD and center of 'O' ring
P = Maximum Effective Operating Pressure
S = Maximum Allowable Stress
L = Crown radius
r = Knuckle radius
N = No. of bolts/mm of bolt circle circumference
t = thickness of shell / flange / dome
σ_b = Preload stress
σ_{bolt} = Yield Strength of bolt
R_m = Mean Radius
l = Half distance between PCD and mean radius

Abbreviations:

3D = Three Dimensional
AMSE = American Society of Mechanical Engineering
CARS = Centre For Aerospace Research Sciences
CAD = Computer Aided Design & Drafting
CAM = Computer Aided Manufacturing
DTMs = Dual Thrust Motors

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DRDO = Defense Research Development Organization
EPP = Effective Pivot Point
FEM = Finite Element Method
GGP = Geometric Pivot Point
HVT = High Velocity Transient
ISRO = Indian Space Research Organization
PCD = Parametric Centre Diameter
PGAD = Programme Air Defence
RSRM = Redesigned Solid Rocket Moor
RCI = Research Centre Imarat
SRM = Solid Rocket Motor
SITVS = Secondary Injection Thrust Vector Control
TVS = Thrust Vector Control

Introduction:

Controllable thrust propulsion technology is being explored by missile industry as a solution to the propulsion requirements for the next generation tactical missiles. Modulating thrust in solid propulsion is one approach for achieving this goal.

Using Thrust Controller (TC) a conventional solid propellant rocket motor can provide variable thrust levels, providing the capability to decrease missile flight time to target, or to increase maximum range capability.Development of Non-Al propellant formulations is in progress at IIT, Madras as part of CARS project of PGAD/RCI. There is a requirement of small scale hot tests towards development of non-Al composite propellant system towards development of minimum smoke propellant for Programme ’AD’ missile applications.

The present report deals with the design and structural analysis of thrust controlled test motor for repetitive ground testing of non-Al composite propellant formulations being developed at IIT,M / HEMRL. The design of motor is updated using the structural analysis results and drawings are developed accordingly.

Configuration & Specification of Motor:

Developmental tests are carried out in straight nozzle configuration accommodating changes in burn rate and grain configurations. The configuration of motor with straight nozzle is shown in Fig. 5.22 It consists of straight nozzle with attached to the motor chamber at nozzle end. The specifications of the motor and geometrical details are given below.

Motor Specifications:

Total Impulse :17500.0 ± 1500 Kgf-s
Nominal Thrust:2000.0 Kgf
Nozzle system :one straight nozzle
Nominal burning time :8.00 s
Temperature range: $-20\,^{o}C$ – $+55\,^{o}C$
Altitude of test motor : Sea level
Propellant :Non-Al composite
Ignition System:Pyrotechnic
Propellant Weight: ≈ 60 kg
Space Envelope
Motor Outside diameter: ϕ650mm
Motor length : ≈ 800 mm

Motor Design:

The L/D of the motor casing is less than 1.0. The motor casing is designed as per ASME pressure vessel code [1]. Flange design at head end and nozzle end are designed using Schneider’s approach. Flange thickness is calculated using flat plate closure formula as per ASME pressure vessel code. Tori-spherical dome configuration is selected of easy fabrication for head end and nozzle end domes and thickness is calculated using ASME pressure vessel code [1].

Material Properties:

High strength 15CDV6 steel material is chosen for motor casing and nozzle due to its high strength to weight ratio, availability and well established fabrication procedure. The specification of the material is given below.

Chemical Composition of 15CDV6 (Wt. %):

Cr = 1.5 Max.

Mn	=	1.1	Max.
Mo	=	1.1	Max.
V	=	0.3	Max.
C	=	0.18	Max.
Ni	=	0.25	Max.
Cu	=	0.2	Max.
Si	=	0.2	Max.
P	=	0.02	Max.
S	=	0.015	Max.

Mechanical Properties:

Property	(Tangential)	(Transverse)
Tensile Strength (MPa)	1080 (min.)	1020 (min.)
Yield Strength (MPa)	930 (min.)	880 (min.)
% elongation (on 50mm) min.	10	10
Hardness	290-360	290-360
Impact toughness (J) 2mm charpy 'U' notch)	60 (min.)	60 (min.)
Plain Strain fracture toughness (MPa)	80	80

Factor of Safety Selection Criteria:

The following safety factors have been chosen for the design of rocket motor for repetitive ground tests.

On Yield = 1.5; Allowable = 587 MPa

On UT = 2.0; Allowable = 510 MPa

Operation of Hot Gas Flow Control Valve:

The configuration of the HGFCV is shown in Fig.1. It consists of hot gas generator based on solid propellant attached with convergent-divergent nozzle. The valve pintle is arranged in throat region of the nozzle and area is varied by opening/closing the pintle using BLDC actuator as shown in the figure. Closed loop control of pintle position varies the throat area in real time achieving flow control.

Hot gasses are generated due to burning of the solid propellant at the propellant surface injected into the core region and enter nozzle convergent and divergent regions. Expansion of high pressure and high temperature hot gasses from nozzle inlet to outlet generates high velocity and momentum. The reaction force due to expulsion of gasses generates thrust force.

Thrust is computed at exit plane as an integration of the momentum due to high velocity and pressure difference as follows:

$$\int\{ mV+A(P_e - P_a) \}dr \;.....(1)$$

Varying the flow rate changes the exit momentum thereby changing the thrust force.

Flow rate is varied altering the equilibrium chamber pressure between inlet mass flow due to propellant combustion and out let flow through the choked nozzle.

The inlet flow rate due to hot gas generation is function of burn rate and surface are of the grain as per the following equation:

$$m\ p = A\ b\rho r \;........ (2)$$

Propellant burn rate is function of chamber pressure and it is given by as St. Robert's law:

$$r. = aP_c^{\ n} \;........ (3)$$

where r is the burn rate, a is the pre-exponential factor, P_c is the chamber pressure, and n is the pressure exponent.

The outlet flow rate of the choked nozzle based on 1-D isentropic flow is proportional to the throat area and chamber pressure as follows:

$$m_d = \frac{P_c A_c}{C^*} \;............ (4)$$

The equilibrium pressure of the system is established as per the following continuity equation between inlet flow (2) and out let flow (4).

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$$\frac{dP_c}{dt} = \frac{RT_g}{V}\left(A_b \rho a P_c^n - \frac{P_c A_t}{C^*}\right)$$

Varying the throat area establish new equilibrium pressure and then changes the flow rate through the nozzle. The principle is based on the controlling the throat area using the pintle valve to change the equilibrium chamber pressure to vary the flow rate achieving the thrust modulation. Moving the pintle outwards increases throat area decreasing the chamber pressure and flow rate. Moving the pintle into the throat region decreases the throat area and increases the chamber pressure increasing the flow rate of the thrusters. Closed control of pintle position using BLDC actuator achieves the thrust modulation in real time.

Geometry:

Solid works 12.0 is an interactive Computer- Aided Design and Computer Aided Manufacturing system. The CAD functions automate the normal engineering, design and drafting capabilities found in today's manufacturing companies. The CAM functions provide NC programming for modern machine tools using the Solid works 12.0 design model to describe the finished part. Solid works 12.0 functions are divided into "applications" of common capabilities. These applications are supported by a prerequisite application called "Solid works 12.0 Gateway"

Solid works 12.0 is fully three dimensional, double precision system that allows to accurately describing almost any geometric shape. By combining these shapes, one can design, analyze, and create drawings of products

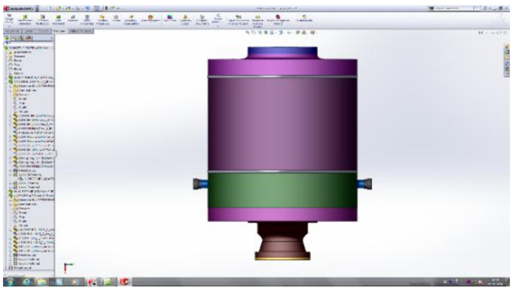

Fig.4.1.Geometric model of Thrust Controlled Solid Motor

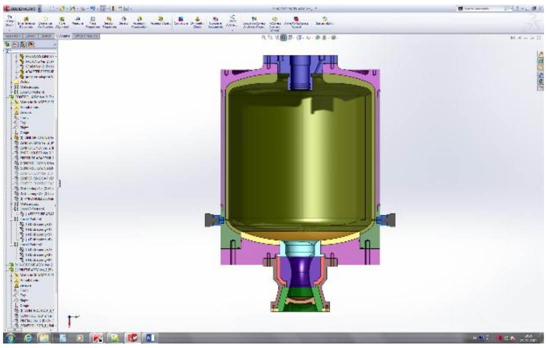

Fig.4.2 3DGeometric model of Thrust Controlled Solid Motor (Cross Section)

Results and Discussion:

Meshing: Finite Element Discretization or Meshing is the process used to "fill" the solid model with nodes and elements, i.e., to create the FEA model. Remember, you need nodes and elements for the finite element solution, not just the solid model. The Solid Model in CAD does NOT participate in the finite element solution

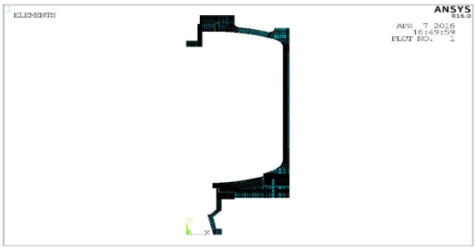

Fig (1): 2d Mesh Model

2D Loads And Boundary Conditions:

- The analysis has been carried out with pre-tension ~61.58°C applied to Bolts.
- Upper area constrained in all D.O.F direction.
- Applied pres on inter area of body

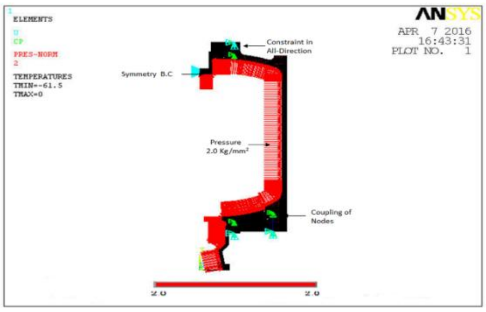

Fig (2): 2d Loads & Boundary Condition Applied To Motor

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Fig (3) : VonMises Stress Plot

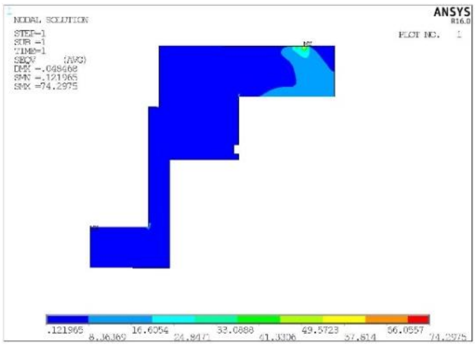


Fig (5.8): Head End Igniter Configuration

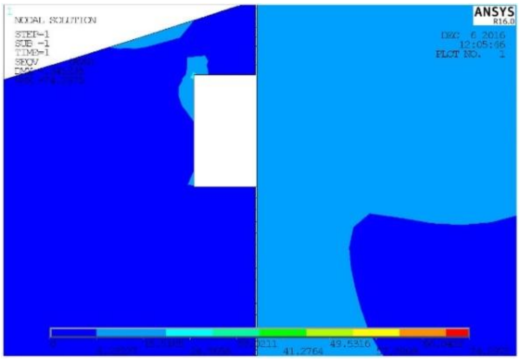


Fig (5.5): contacts mesh

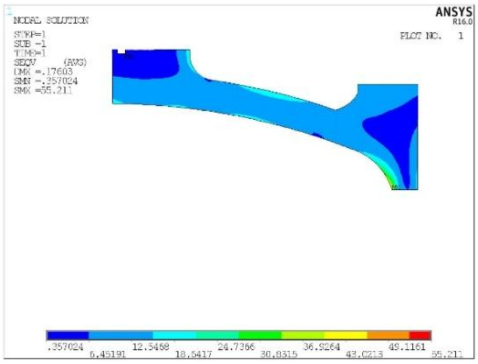


Fig (5.9): Head End Dome Configuration

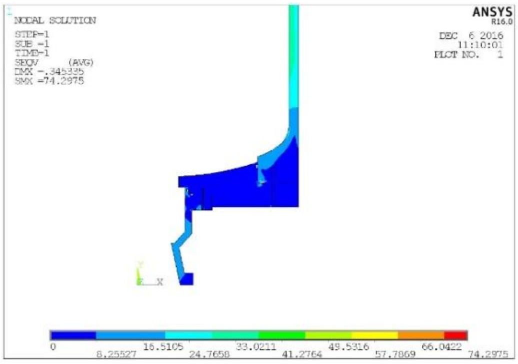


Fig (5.6): VonMises Stress Plot (minimum position)

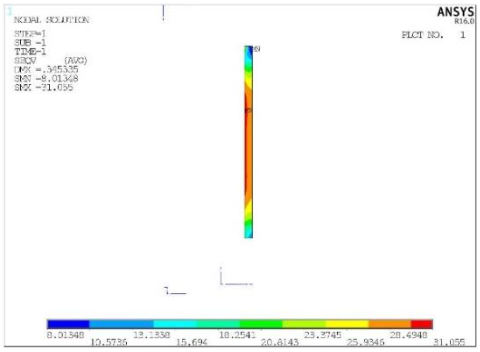


Fig (5.10): Motor shell Configuration

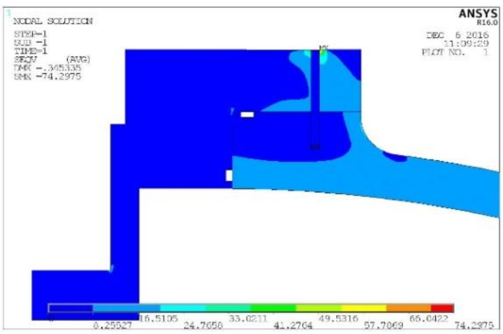


Fig (5.7): VonMises Stress Plot (maximum position)

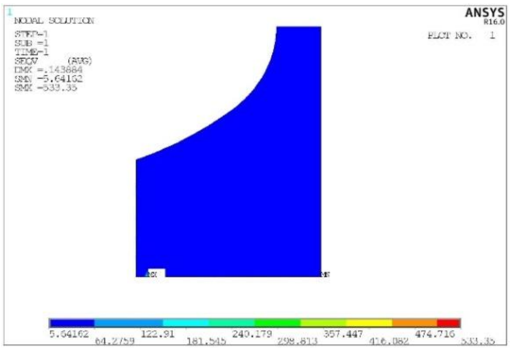


Fig (5.11): Nozzle End Dome Configuration

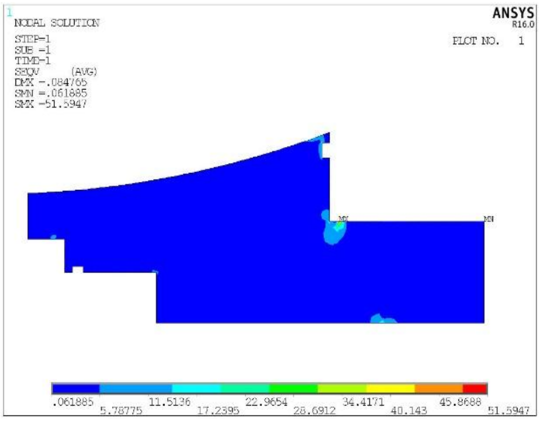


Fig (5.12): Nozzle End Flange Configuration

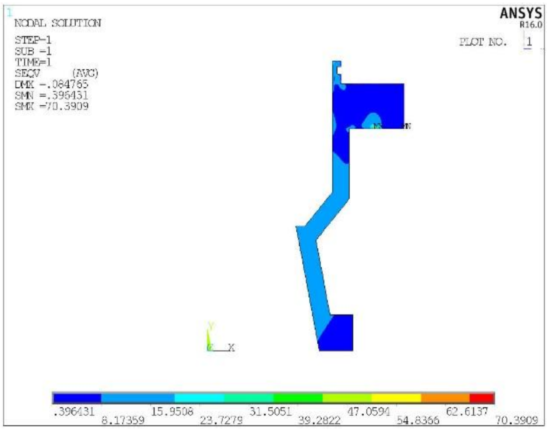


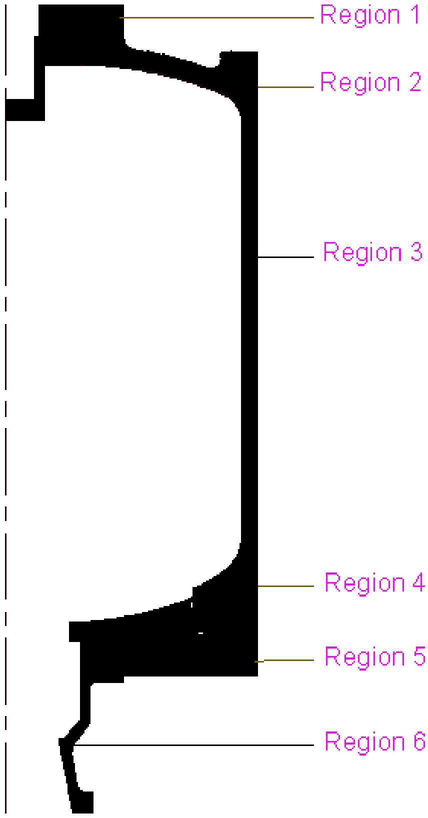
Fig (5): Nozzle Exit End Flange Configuration

REGION	Von-Mises	FOS on
Region-I	16.605 (74.29)*	2.76
Region-II	30.831 (55.211)*	1.48
Region-III	31.055	1.47
Region-IV	16.668	2.75
Region-V	13.21(39.72)*	3.47
Region-VI	17.23(55.59)*	2.66

Allowable stress on weld = 45.9 Kg/mm2

Table 1.0. FOS and stresses at various locations of Motor (Excluding localized stresses).

* The values shown in brackets are highly localized. These are not considered for calculation of FOS.



Regions of 2D Motor for stress reporting

3D Loads And Boundary Conditions:

- The analysis has been carried out with pre-tension ~61.58°C applied to Bolts.
- Upper area constrained in all D.O.F direction.
- Applied pres on inter area of body

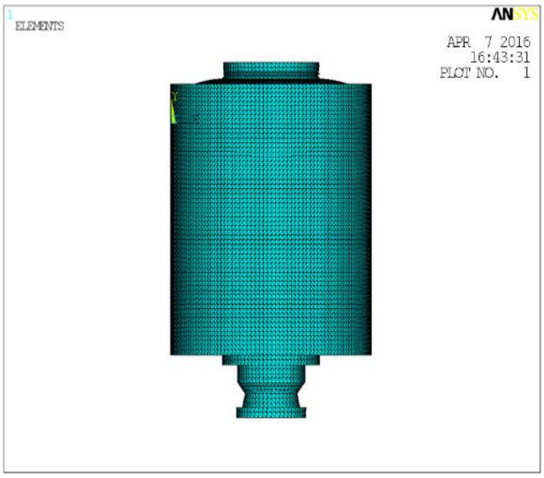


Fig (5.15): 3D: FE Mesh Model of Motor

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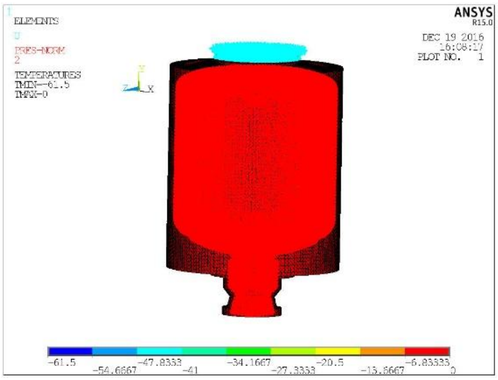


Fig. 5.16: Loads & Boundary Condition Applied to Motor

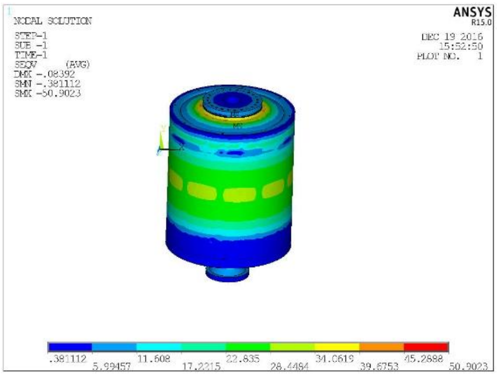


Fig. 5.17: VonMises Stress Plot

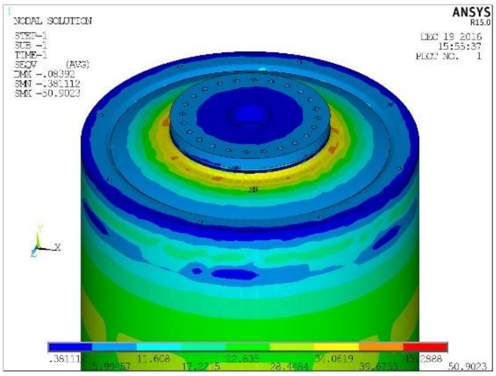


Fig. 5.20: VonMises Stress Plot (maximum Position)

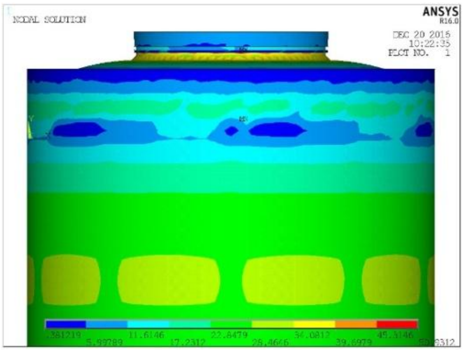
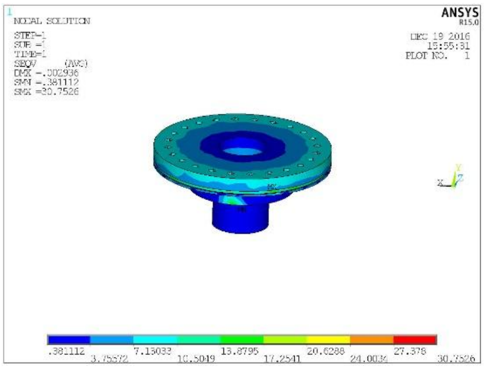
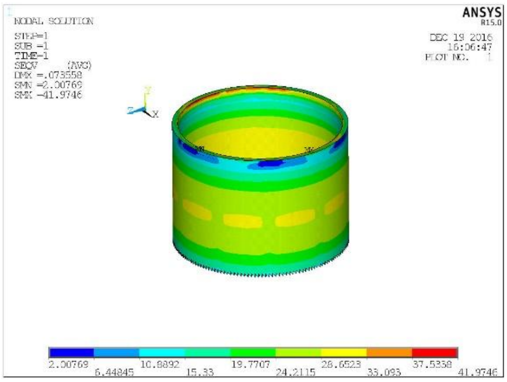


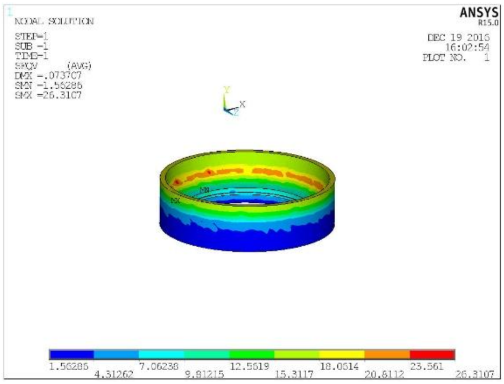
Fig. 5.21: VonMises Stress Plot (minimum Position)



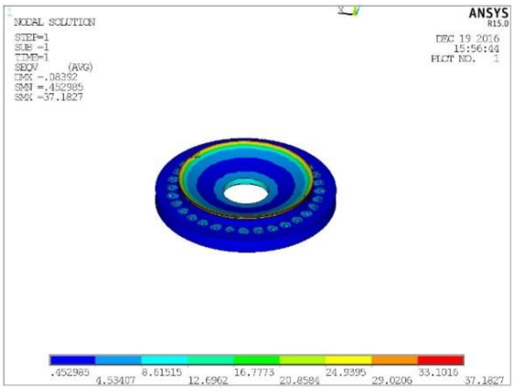
3D Head End Igniter Configuration



3D Motor shell Configuration



3D Nozzle End Dome Configuration



3D Nozzle End Flange Configuration

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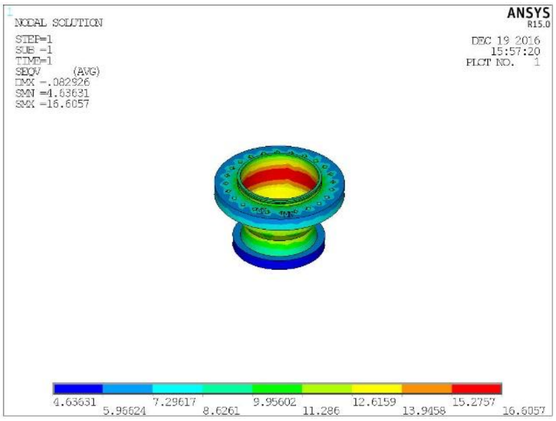
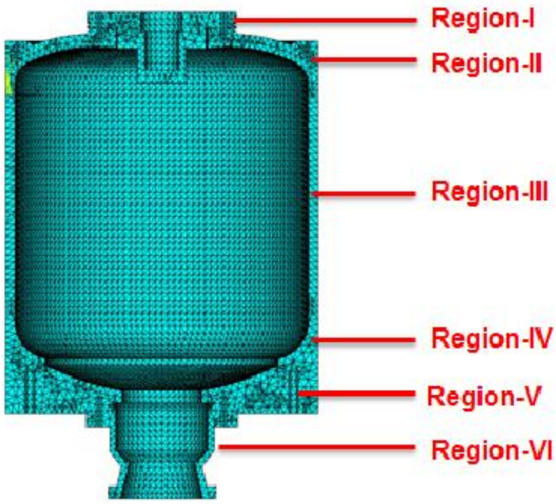


3D Nozzle Exit End Flange Configuration

REGION	Von-Mises stress in (Kg/mm^2)	FOS on Yield
Region-I	27.4338	1.67
Region-II	24.669 (55.316)*	1.86
Region-III	33.093	1.38
Region-IV	20.8112	2.20
Region-V	16.77(37.1827)*	2.73
Region-VI	16.6057	2.76

Allowable stress on weld = 45.9 Kg/mm2
Table 2.0. FOS and stresses at various locations of Motor (Excluding localized stresses).
*The values shown in brackets are highly localized. These are not considered for calculation of FOS.



Regions of 3D Motor for stress reporting

Conclusions and Future Scope of Work

The straight nozzle motor design is carried out as per ASME pressure vessel code for MEOP of 200.0 bar.

The flange design is carried out following the Schneider's approach. To meet the functional requirements, igniter, nozzle end dome and nozzle casing has been configured with grooves and 'O'-Ring dimensions are finalized keeping its dilation more than 16% of 'O'-Ring Diameter. Finite element analysis is carried out for the above design to verify the stress levels are within allowable limits and also dilation expected due to internal pressure. The flange joint modeled using contact element method to verify opening of 'O'-Ring due to internal pressure and applying prestress through thermal stress values to verify stress level in bolt. The result indicates that the maximum stresses and dilation are within allowable limits. Hence the motor design is meeting the ground test requirements.

Bibliography

1. ASME Boiler & Pressure Vessel Code Vol. VIII, Div. 2.

2. Simpson Earland, David Nash & Bill Garden, "Guide to European Pressure Equipment – The Complete Reference Source," Professional Engineering Publishing 1st Edition, 2003.

REFERENCES

[1] V.R. Sanal Kumar, B.N. Raghunandan, T. Kawakami, H.D. Kim, T.Setoguchi, and S. Raghunathan, " Boundary-Layer Effects on Internal Flow Choking in Dual-Thrust Solid Rocket Motors," AIAA Journal of Propulsion and Power, Vol.24, No.2, March-April 2008.

[2] V.R. Sanal Kumar, and B.N. Raghunandan, "Ignition Transient of DualthrustMotors – A Review," 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Atlanta, Georgia, USA, 28 July – 1August 2012, Paper No. AIAA 2012-4043.

[3] V.R. Sanal Kumar, "Thermoviscoelastic Characterization of a Composite Solid Propellant Using Tubular Test," Journal of Propulsionand Power, Vol. 19, No. 3, pp. 397–404, 2003.

[4] H. Ikawa, and F.S. Laspesa, "Ignition/Duct Overpressure Induced by Space Shuttle Solid Rocket Motor Ignition," Journal of Spacecraft and Rockets, Vol. 22, No. 4, pp. 481, 1985.

[5] G.D. Luke, M.A. Eager, and H.A. Dwyer, "Ignition Transient Model for Large Aspect Ratio Solid Rocket Motors," AIAA Paper 96-3273, 1996.

[6] S. Alestra, I. Terrasse, and B. Troclet, "Identification of Acoustic Sources at Launch Vehicle Lift-Off Using an Inverse Method," AIAAPaper 2002-926, 2002.

[7] M. Salita, M., "Modern SRM Ignition Transient Modeling (Part 1): Introduction and Physical Models," AIAA Paper 2001-3443, 2001.

[8] V.R. Sanal Kumar, B.N. Raghunandan, H.D. Kim, A. Sameen, T.Setoguchi, and S. Raghunathan, "Starting Transient Flow Phenomena in Inert Simulators of SRM swith Divergent Ports," Journal of Propulsionand Power, Vol. 22, No. 5, pp. 1138–1141, 2006.

[9] V.R. Sanal Kumar, B.N. Raghunandan, H.D. Kim, A. Sameen, T.Setoguchi, and S. Raghunath "Studies on Internal Flow Choking in Dual-Thrust Motors," Journal of Spacecraft and Rockets, Vol. 43, No. 5,pp. 1140–1143, Sept.-Oct. 2006.

[10] B.N. Raghunandan, V.R. Sanal Kumar, C. Unnikrishnan, and C. Sanjeev, "Flame Spread with Sudden Expansions of Ports of Solid Rockets," Journal of Propulsion and Power, Vol. 17, No. 1, pp. 73–78, 2001.

[11] B.N. Raghunandan, N.S. Madhavan, C. Sanjeev, and V.R. Sanal Kumar, "Studies on Flame Spread with Sudden Expansions of Ports of Solid Propellant Rockets Under Elevated Pressure," Defence Science Journal, Vol. 46, No. 5, pp. 417–423, Nov. 1996.

[12] A. Peretz, K.K. Kuo, L.H. Caveny, and M. Summerfield, "Starting Transient of Solid Propellant Rocket Motors with High Internal Gas Velocities," AIAA Journal, Vol. 11, No. 12, 1973, pp. 1719–1729.

13] D.L. Baker, "Method of predicting chamber pressure transient's during the ignition of solid propellant rocket motors," United Technology Centre, Sunnyvale, California, UTC TM – 14 – 62 – UZ, March 1962.

[14] L.H.Caveny, and K.K.Kuo, and B.W. Shackelford, "Thrust and ignition transient of the space shuttle solid rocket motor," Journal of Spacecraft and Rockets, Vol.17. Nov-Dec. 1980, pp. 489-494.

[15] D.R. Manson, S.K. Folkman, and M.A. Behring, "Thrust Oscillations of the Space Shuttle Solid Rocket Booster Motor During Static Tests," AIAA Paper 79-1138, 1979.

[16] Lemic, Dragan_" Flame spreading over solid rocket propellants during ignition transient", Sci. -Tech. Rev., 52 (3), 33-39, 2002.

[17] N. Lukin, Alexander,"Numerical modeling and method of prevention of the anomalous combustion regimes development in the high-loading density solid propellant rocket motor", Proc. Int. Pyrotech. Semin 28th, 513-528, 2001.

[18] Cho, In Hyun; Baek, Seung Wook "Numerical analysis of ignition transient in an axisymmetric solid rocket motor equipped with rear ignition system", Combust. Sci. Technol, 152, 81-98, 2000.

[19] C. Aswin, S. Srichand Vishnu, D. Aravind Kumar, S. Deepthi, S.K. Kumaresh, M. Arun, and V.R. Sanal Kumar, "Studies on Ignition Delay and Flame Spread in High-performance Solid Rocket Motors, "Applied Mechanics and Materials, vol. 232, pp 316-321, 2012.

[20] Report of the Presidential Commission on the Space Shuttle Challenger Accident, June 1986. http://science.ksc.nasa.gov/shuttle/missions/51-l/docs/rogers-commission/table-of-contents.html

[21] T.F. Zien, "Integral Solution of Ablation Problems with Time-Dependent Heat Flux," AIAA Journal, vol. 16, No. 12, 1978, pp. 1287–1295.