CHAPTER 1

INTRODUCTION

Solid rocket motors [1-6] are propulsion devices [7-10] for both satellite launchers [11-15] and missiles, which require guidance or steering to fly along a programmed trajectory and to compensate for flight disturbances. Typically, a solid rocket motor as shown in Figure 1-1 consists of the solid propellant grain, the liner whose primary purpose is to provide an adhesive bond between the propellant grain and the insulation, the insulation which provides thermal protection to the case from combustion products, the motor case which structurally supports the propellant grain, the igniter which ignites the grain and the nozzle which helps in providing the desired thrust.

In most solid rocket motors, thrust vector control (TVC) [16-19] is required. By controlling the direction of the thrust vector through one of the mechanisms described later, it is possible to control vehicles’ pitch, yaw and roll motions. The thrust vector control concept can be applied to an engine or motor with single nozzle and, for those that have two or more nozzles [20]. The different mechanisms are classified into

Category-I: Mechanical deflection of the nozzle or thrust chamber.

Category-II: Insertion of heat resistant movable bodies into the exhaust jet which experience aerodynamic forces and cause a deflection of a part of the exit gas flow.
Category-III: Injection of fluid into the side of diverging nozzle section causing an asymmetrical distortion of the supersonic exhaust flow.

Schematic diagrams of eight different thrust vector control mechanisms are shown in Figure 1-2 with working principles. Table 1-1 presents the advantages and disadvantages of the thrust vector control mechanisms with their usage specified for either liquid engines or solid propellant motors.

For large solid rocket motors (above 500 mm in diameter & for more than 10 seconds of operation), secondary injection thrust vector control (SITVC), fin tip control (FTC) [21], Flex nozzle / movable nozzles (hinged by a flexible bearing, a ball and socket, or a hydraulic bearing joint) are mainly being used as TVC mechanisms.
Figure 1-1: Typical Solid Rocket Motor
<table>
<thead>
<tr>
<th>GIMBAL OR HINGE</th>
<th>FLEXIBLE LAMINATED BEARING</th>
<th>FLEXIBLE NOZZLE JOINT</th>
<th>JET VANES</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
</tbody>
</table>

- **Universal Joint Suspension for Thrust Chamber:**
  - Nozzle is held by ring of alternate layers of moulded blastomer and spherically formed sheet metal.

- **Sealed Rotary Seal Joint:**
  - Four rotating heat resistant aerodynamic vanes in jet.

<table>
<thead>
<tr>
<th>JET AERATOR</th>
<th>JET TASS</th>
<th>SIDE INJECTION</th>
<th>SMALL CONTROL THRUST CHAMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
</tr>
</tbody>
</table>

- **Rotating Airfoil Shaped Collar, Gamballed Near Nozzle Exit:**
  - Used with solid propellant motors.

- **Four Paddles that Rotate in and Out of the Hot Gas Flow:**
  - Used with liquid engines.

- **Secondary Fluid Injection on One Side at a Time:**
  - Two or more gimbaled auxiliary thrust chambers.

**Figure 1-2: Schematic Diagrams of TVC Mechanisms**
Table 1-1: Advantages and Disadvantages of Thrust Vector Control Mechanisms

<table>
<thead>
<tr>
<th>Type</th>
<th>L/S</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gimbal or hinge [22,23]</td>
<td>L</td>
<td>Simple, low torques, low power; (\pm 12^\circ) duration limited only by propellant supply, very small thrust loss</td>
<td>Requires flexible piping: high inertia; large actuators for high slew rate.</td>
</tr>
<tr>
<td>Movable nozzle (flexible bearing) [24]</td>
<td>S</td>
<td>No sliding, moving seals; predictable actuation power; up to (\pm 12^\circ) possible</td>
<td>High actuation forces; high torque at low temperatures, variable actuation force</td>
</tr>
<tr>
<td>Movable nozzle (rotary ball with gas seal)</td>
<td>S</td>
<td>No thrust loss if entire nozzle is moved: (\pm 20^\circ) possible</td>
<td>Sliding, moving hot gas spherical seal; highly variable actuation power, limited duration; needs continuous load to maintain seal.</td>
</tr>
<tr>
<td>Jet vanes [25-30]</td>
<td>L/S</td>
<td>Low actuation power; high slew rate; roll control with single nozzle (\pm 9^\circ)</td>
<td>Thrust loss of 0.5 to 3%; erosion of jet vanes; limited duration extends missile length</td>
</tr>
<tr>
<td>Jet tabs</td>
<td>S</td>
<td>High slew rate; low actuation power; compact package</td>
<td>Erosion of tabs; thrust loss, but only when tab is in the jet; limited duration</td>
</tr>
<tr>
<td>Jetavator</td>
<td>S</td>
<td>Proven on Polaris missile; low actuation power; can be light weight</td>
<td>Erosion and thrust loss: induces vehicle base hot gas circulation; limited duration</td>
</tr>
<tr>
<td>Liquid-side injection [31-37]</td>
<td>S/L</td>
<td>Specific impulse of injectant nearly offsets weight penalty; high slew rate; easy to adapt to various motors; can check out before flight; components are reusable; duration limited by liquid supply; (\pm 6^\circ)</td>
<td>Toxic liquids are needed for high performance; often difficult packaging for tanks and feed system; sometimes requires excessive maintenance; potential spills and toxic fumes with some propellants; limited to low vector angle applications.</td>
</tr>
<tr>
<td>Hot-gas-side injection [38,39]</td>
<td>S/L</td>
<td>Light weight; low actuation power; high slew rate; low volume/compact; low performance loss.</td>
<td>Multiple hot sliding contacts and seals in hot gas valve; hot piping expansion; limited duration; requires special hot gas valves; technology is not yet proven</td>
</tr>
</tbody>
</table>

S – used with solid propellant motors, L – used with liquid engines
The flexible bearing [40] is the most widely used device in modern nozzles for ballistic or space applications. The flex nozzle system offers advantages of efficiency, low reduction of thrust and specific impulse. The moulded, multi-layer bearing acts as a seal, load transfer bearing and a visco-elastic flexure. It uses the deformation of stacked set of curved elastomeric (rubbery) layers between spherical metal or composite sheets to carry the loads and permits angular deflections of the nozzle axis. Figure 1-3 and Figure 1-4 show a typical flex nozzle system and a typical flex seal. The convergent portion of the nozzle is made of ablative composites viz. carbon - phenolic either through random fiber compression molding or tape wound-cured and machined. The throat insert is either graphite or carbon-carbon or carbon - phenolic depending upon erosion rates acceptable for the required performance, size and technology available. The divergent portion of the nozzle is usually carbon - phenolic tape wound with metallic or carbon epoxy structural backup or carbon-carbon as in large area ratio or extendable nozzle exit cones. The divergent has a compliance ring (metallic) to transfer the actuator loads through the nozzle to get the required vector angle.

The flexible seal consists of an elastomeric material alternating with rings of metallic or composite material. These rings are usually spherical sections with a common center of radius referred to as the geometric pivot point. Three different sizes of seals wherein the rings were spherically shaped conical sections have been designed moulded
and successfully tested. When an external actuator force acts upon the nozzle, the elastomeric components are strained in shear, each reinforcement ring rotates a proportional part of the total vector angle, and the nozzle rotates about the effective pivot point because of different amounts of distortion in each reinforcement. Omni-axis moment of the nozzle is obtained by using two actuators 90° apart. In addition to providing a means for thrust vectoring the joint also acts as a pressure seal.

An important property of the elastomer in the operation of a joint is that the bulk compressive modulus is thousands of times the shear modulus. Due to this, a joint can transmit high axial compressive loads with low resulting axial deflections, but permits high shear deflections at low applied torques. The reinforcements provide rigidity to the joint against motor pressure and axial loads.

When the nozzle is vectored, the resultant side force acts through the effective pivot point (EPP). Since the EPP is a floating point, for all design purposes, geometric pivot point (GPP) is taken as the reference and wherever required, allowance is given considering effect due to pivot point shift. The pivot point can be either forward or aft with respect to the throat plane. The position is fixed based on the trade off study. Table 1-2 gives the comparison of forward and aft pivot point configurations.

To design a nozzle [41], a certain number of specific parameters are required such as diameter, exit cone expansion ratio and half angle, aft opening diameter of the case and nozzle submergence. A
great number of these parameters are as a result of the overall optimization of the motor based upon the general requirements of the propulsion system. Figure 1-5 gives the nomenclature of flex seal. Some of these parameters are left to the discretion of the designers or imposed by the storage or operating environment.

Table 1-2: Comparison of Forward and Aft Pivot Point Configurations

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Description</th>
<th>Forward Pivot point</th>
<th>Aft pivot point</th>
<th>Booster</th>
<th>Upper stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Envelope requirement at nose entry</td>
<td>Less</td>
<td>More</td>
<td>Aft</td>
<td>Fwd</td>
</tr>
<tr>
<td>2.</td>
<td>Envelope requirement at nozzle exit</td>
<td>More</td>
<td>Less</td>
<td>Aft</td>
<td>Fwd</td>
</tr>
<tr>
<td>3.</td>
<td>Actuator stroke requirement</td>
<td>More</td>
<td>Less</td>
<td>Aft</td>
<td>Aft</td>
</tr>
<tr>
<td>4.</td>
<td>Actuator force requirement</td>
<td>Less</td>
<td>More</td>
<td>Fwd</td>
<td>Fwd</td>
</tr>
<tr>
<td>5.</td>
<td>Vector angle requirement for the same control moment</td>
<td>More</td>
<td>Less</td>
<td>Aft</td>
<td>Aft</td>
</tr>
</tbody>
</table>

The flexible joint is a non-rigid pressure-tight connection between the rocket motor and a movable nozzle that allows the nozzle to be deflected in a specified direction. The deflection of the nozzle deflects the motor thrust vector and generates a moment about the vehicle center of gravity, thereby altering the course of the vehicle. Flexible joint design consists of the determination of the joint configuration, the number of reinforcement rings, the material for the reinforcement rings and elastomeric layers and the materials for environmental protection. These elements must be selected and combined to provide the required spring torque, performance and
reliability at minimum weight and within cost and envelope limitations. Joint design is also affected by the attachment to the rocket motor and the movable nozzle.

The joint design is dependent on many geometric variables. Analysis of a flexible joint is complicated by non-linearity of material properties, large deflections and strains, non-symmetric loading systems and non-symmetric geometries during vectoring. This thesis presents the details of the design of a typical flex-bearing joint of a rocket motor nozzle followed by finite element modeling and experimental validation.
Figure 1-3: Typical Flex Nozzle System
Figure 1-4: Typical Flex Seal
Figure 1-5: Nomenclature of Flex Seal

Middle of Flex Seal

ID - INNER DIA
OD - OUTER DIA
H - OVERALL HEIGHT
Rp - PIVOT RADIUS
β1 - INNER JOINT ANGLE
β2 - OUTER JOINT ANGLE
β - MEAN JOINT ANGLE
Φ - CONE ANGLE

PIVOT POINT
(GEOMETRIC)
1.1 LITERATURE SURVEY

Design of complex nozzle systems for solid rocket motors of satellite launchers and missiles and its validation through finite element modeling and testing are challenging tasks for designers in aerospace industries. Empirical relations for the design of nozzle systems developed by researchers based on extensive tests have limitations. Wood Berry [40, 42] developed empirical relations from the experiments and confirmed by Walker [43] for designing an elastomeric seal for Omni axial movable nozzle. Gajbir Singh and Rao [44] proposed empirical relations for reinforcement stresses for both pressure loads and vectoring loads for joint diameters between 19.3 cm to 56 cm. Their FEA results are compared with the empirical relations only for pressure loads. However, these relations are applicable for conical shims only.

Preliminary theoretical flex seal design sensitivity studies of James Donat [45] indicate that any modifications to reduce stress may cause increase of torque and weight. Prins, Mayer and Cox [46] carried out a 2D non-linear axisymmetric analysis for pressure loads specifying the hyper-elastic rubber properties. Shimon Shani, Putter and Aric Peretz [47] carried out a 2D axisymmetric fourier analysis using harmonic element of ANSYS code for vectoring loads. The elastomeric strains and joint stiffness are found to match well with those obtained from the empirical relations of Wood Berry [40,42].

Regarding the overall configuration aspects of the nozzle systems, Michel Berdeyes [48] presented the history of flex nozzle
development in Ariane program, choice of C/C composites for nozzles, configuration of P80 nozzle and performed cold tests to examine the flex seal torque variation with chamber pressure. The investigators [48-50] briefed the use of advanced materials in solid rocket motor. These include the use of new energetic propellants that allowed more sophisticated grain drawings, the emergence of new fibres for solid rocket motor cases exhibiting higher and higher mechanical properties, tremendous break throughs in the nozzles by introduction of new concepts and the elaboration of advanced composite materials. The author emphasised on the use of 3D and 4D carbon–carbon composite material for the nozzle liners to reduce weight.

Michel Berdeyes, Bernard Broquere and Sylvie Loison [51] briefly brought out the advanced materials and technology used in solid rocket motor nozzles. The technologies are all composite extendible nozzle exit cone, supersonic split line nozzle, hot ball and socket nozzles and hot gas injection thrust vector control system. The author gives the details of 4D carbon-carbon composite materials in the throat, extendible exit cone. Use of composite polar bosses in place of metallic ones in composite casing is briefed.

Steven Peake, Russell Ellis and Bernard Broquere [52] briefed about the Ariane 5 booster nozzle development status with C2 rayon based carbon cloth phenolic parts. The use of carbon cloth has reduced the number of parts and in turn reduction in production cycle and cost. The exit cone area ratio has also increased from 9.58 to 11.0.
Henke, McGrath, Rade and Weldin [53-55] presented the details of star motor 48D with movable nozzles and characterized the flex seal in terms of torque versus pressure to show the systems behavior. The author also presented the details about STAR series of solid rocket motors being designed and tested by Thiokol Corporation. The motors designed have been demonstrated in more than 2150 missions with a success rate of nearly 99.86% across a motor range of 5 inch diameter and 10 lb weight to 75 in diameter to 18,000 lb weight. The STAR 48 motor was the first to be tested with flex nozzle. The researchers briefed the details of TVC mechanisms used in all STAR motor missions. Most of them uses flex nozzle for thrust vector control. The author also presented the bench test results of the motor STAR 63 DV and STAR 48. The actuation torque versus angle of star 48 and star 37V motor were brought out. The flex seal of star 48/27V consists of four steel shims and five polyisoprene pads. The flex seal is capable of vectoring 40. The maximum slew rate for actuation is 800/s with the help of hydraulic actuators. However design methodology was not presented.

Thomas Redman [56, 57] indicate that 165 kg weight reduction in the motor case and flex nozzle of Titan IV SRMU was due to changes in materials. The author also briefed the light weight design of the SRMU of TITAN IVB, which is made up of 3 segment graphite composite case and having a flexible gimballed nozzle. The author claimed that this is one of the largest solid rocket motor. The SRMU burns for about 123 s at a chamber pressure of 1200 PSIa. The nozzle
is designed for $6^0$ omni directional actuation. The actuation system consists of two electro hydraulic actuators with nozzle position transducers for position feedback of the nozzle.

Jeffrey Foote [58] presented the details of TITAN IV solid rocket motor upgrade program. There was a need for increased lift capability and improved booster reliability. The increased lift is obtained by three ways. The diameter of the rocket motor has been increased. The propellant density and specific impulse were increased. The inert weight of the rocket motor was reduced.

Chang [59-61] presented the details of propellant grain structural and internal gas flow analysis of the solid rocket motor. A methodology was developed and applied to reconstruct the failure of the TITAN-IVB, prequalification motor.

Boury, Roy and Cronier [62] discussed the rubber materials for solid rocket propulsion systems and presented generic details on the characterization of rubber-metal combination in sample level in terms of stiffness in shear and axial compression. Larrieu [63] presented a preliminary design procedure of SRM with little information about conical flex seal and developed a software program for designing rocket motors.

Calbra and Max [64, 65] discussed large SRBs with conventional architecture using a downstream metallic flex seal protected by carbon reinforced rubber thermal insulator. The author along with Jean Paret presented a brief introduction of solid rocket motors at Aerospatiale. The authors also briefed about the
development of advanced technologies like low density EPDM insulation, finocyl or axi-symmetric propellant geometry, composite flex seal, carbon-carbon integral throat entrance and extendible nozzle exit cone.

Didier Boury et al. [66] presented the details on the development of Nozzle B and manufacturing process to reduce its number of parts and cost in addition to the general comments on low torque flex seal. Richard Fawcett [67] discussed the interfaces and fabrication details of advanced third stage (A3S) carbon-carbon exit cone with fixed nozzle. Wilson and Johnson [68, 69] discussed dual flex, a low horse power flexible seal nozzle with a combination of aft and forward pivot point seal. Kearney and Moss [70] discussed about the advanced solid rocket motor (ASRM) nozzle with self ablative flex seal configuration.

Kirby and VanVooren [71] discussed selection of thrust vector control systems for solid rocket motor and liquid engines. The usability and suitability of various thrust vector methods are discussed.

Gaffin [72,73] discussed the pivot point dynamics of flex seal, actuator stroke evaluation with vector angle and pressure, and testing without providing the details on the prediction of seal compression with pressure. E. Gautronneau [74, 75] worked on P80 FW SRM nozzle of VEGA program and brought out the variation of spring torque with respect to chamber pressure and ageing of the elastomer tends to increase the spring torque.
Olivier Merrier [76] gave a brief introduction of Ariane 5 nozzle named MPS [77,78]. The motor is operating for 125s with a maximum nominal motor pressure of 6.0 MPa. The nozzle throat diameter is 895 mm and expansion ratio of 9.7. The nozzle divergent is bell shaped with an average exit cone angle of 18° and a flow turn back angle of 11°. The nozzle is designed for 6° omni directional actuation. The paper dealt with the design of flex seal assembly, aft dome, cowl assembly, nose throat assembly, forward exit cone and aft exit cone in a very generic manner. However no detailed calculations or design methodology is given.

Ellis et al [79] gave the advantage of using a supersonic split line flex seal (SSSL) nozzle. The SSSL flex seal nozzle concept offers movable nozzle thrust vector control system incorporating the proven reliability of flex seal thrust vector control element in an unsubmerged nozzle. A static test has been conducted. The weight of the submerged nozzle is 36.2 lb with 12 major components and the weight of the unsubmerged nozzle is 20lb with only 9 major components.

Gigou [80] commented about the status of design, qualification and static testing of P230 booster motor of Ariane 5 launch vehicle which is a successor of Ariane 4. The need for upgrade was to increase performance, lower the launch cost, high reliability and safety levels.

Wilbur and Felix [81] gave a brief description of the development of solid rocket motors at United States. The development of Solid rocket motors for space shuttle like, SRM, ASRM and RSRM, the tests carried out and the configuration parameters are only summarized.
Marco Biagioni [82] presented about the P80 FW solid rocket motor which is the first stage of Vega launch vehicle and the new technologies associated with it. The throat housing is made from aluminium castings, the low torque self ablative flex seal is made up of composite shims, carbon-carbon throat and nose assembly.

Most of the published work does not contain enough information on the design/analysis, dimensions of configurations, materials and their properties and tests.

Valanis and Landez [83] expressed the strain energy as a function of extension ratio, which is used to obtain material constants from the stress-strain data of hyper elastic material like elastomers. Ghosh et al. [84] presented four most commonly used hyper elastic models of Mooney-Rivlin, Ogden, neo-Hookean and Yeoh to use in the design/analysis of tyres for manufacturing. Yeoh [85] examined the adequacy of the ansys & flexpac packages through comparison of the theoretical solution provided by Rivlin. Sivaramakrishnan and Bhagwan [86] characterized the natural rubber and determined the material constants of the Mooney-Rivlin model.
1.2 OBJECTIVES OF THE RESEARCH

Motivated by the importance of the design / analysis of the complex nozzle systems for solid rocket motors of satellite launchers and missiles, the main objectives of the present research are:

- To Design a typical flex bearing joint of a rocket motor nozzle.
- To establish a three dimensional finite element analysis methodology with pressure and asymmetric loads on the combined metal-elastomer combination.
- To Design, realize the flex bearing joints and test set ups including instrumentation for testing.
- To characterize the flex bearing joint with experiments including study of flex bearing spring torque variation with pressure and contribution of torque due to attached masses.
- To validate the empirical relations for design of flex bearing joints.

1.3 OVERVIEW OF THESIS

Chapter 1, enumerates the various thrust vector mechanisms (TVC) in vogue, advantages & disadvantages of each type of TVC & applications. It also introduces the principle of operation of flex nozzle system. Comprehensive literature study is reported pertaining to various thrust vector control systems including flex bearing joint, materials and models used for validation. The objectives of research are brought out.
In this thesis, chapter 2 discusses the development of large solid rocket motor configuration, propellant systems used, structural loads for design, safety factor guidelines and critical issues to be addressed during flex nozzle development.

In chapter 3, the detailed design of flex seal, configuration of nozzle, dynamic envelop clearances & actuator requirements are brought out. Ejection load calculations, summary of design details of three each of cylindrical & conical flex seal configurations are presented. The processing & development plan of flex seals is discussed.

In Chapter 4, the characterization of 15CDV6 steel & natural rubber based elastomer is investigated by testing specimens & studying different material models for elastomer modeling. The validation of material models is done through analysis & testing.

In chapter 5, detailed investigation is done by finite element modeling & analysis of the flex seal using validated material models. 3D non linear material & geometry with asymmetric loading combined with large deformation problem is solved to estimate the shim stresses and characteristics are mapped. Comparison of FEA results with empirical relations are brought out.

In chapter 6, the evolution of developmental test plan is discussed with various tests with loading conditions. The detailed instrumentation plan for testing is presented along with design approach adopted for test setups for all the tests. The test setups realized for testing all the configuration are presented.
In chapter 7, Details of experimental studies carried out and comparison of results obtained by empirical & FEA predictions are brought out. Investigation on thermal boot contribution to the total torque which influences the actuator sizing is also detailed. Characterization of flex seal in terms of variation of shim stresses with pressure & vectoring loads, stress distribution within the shim has been brought out. Summary of stresses in mid shim for pressure & vectoring loads of total 6 configurations tested are compared.

In chapter 8, overall conclusions drawn & future scope of work is highlighted for future investigations.