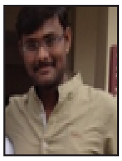
ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
A Peer Reviewed Open Access International Journal

Development and Experimental Characterization of Flexible Joint for Air Borne Propulsion System



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Abstract:

Solid rocket motors are propulsion devices for both satellite launchers and air borne vehicles, which require guidance or steering to fly along a commanded trajectory and to compensate for flight disturbances. Direction is controlled by controlling the thrust vector. To achieve this, the nozzle usually incorporates a flexible joint that allows the nozzle to vector (or rotate) in any direction. The movable nozzle with a flexible joint consists of four main subsystems: the movable nozzle section, the attachment to the rocket motor, the actuation system, and the flexible joint.

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. This paper brings out the development of flexible joint for air borne propulsion system followed by experimental characterization.

Keywords:

Optimization, GUI, MATLAB, thickness, etc .

1. INTRODUCTION:

Propulsion system is the basic driving aid for any air borne vehicle. It is required to control the direction of thrust developed by the propulsion system so as to control vehicles' pitch, yaw and roll motions. Propulsion system of a typical air borne vehicle is shown in Fig. 1.

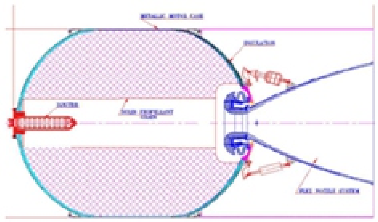

Fig. 1. Propulsion system of a typical air borne vehicle

The thrust control is obtained by steering the nozzle of the propulsion system using actuator-driven ball and socket system also called elastic bearing. The flexible joint may be depicted as a stack of spherical-shaped shims and rubber pads. The rubber sheets are chemically bonded to the rigid inserts, using adhesive agents laid on the inserts, which react during the moulding and vulcanization processes. Typical flexible joint is shown in Fig. 2.

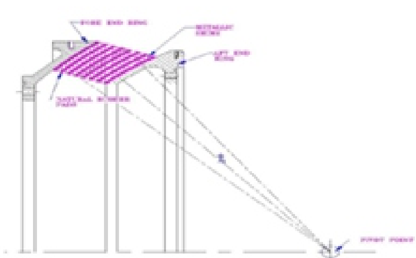

Fig. 2. Typical flexible joint

The flexible joint 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.

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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. For many years, the development and qualification of new flexible joints for several generations of solid rocket motors have been relying on an experimental approach based on numerous tests and full scale manufacturing components. A short implementation using subscale hardware and the corresponding model had been previously developed before the availability of the design and 2D model. This preliminary activity allowed one to identify the relevant design modeling, parameters, and values to address.

Relying on this predictive approach, laboratory tests have started early in the development schedule, with the advantage of reducing the most important risks at a preliminary step where no costly hardware was committed on. Design of complex nozzle systems for solid rocket motors of satellite launchers and air borne vehicles 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 [1] developed empirical relations from the experiments and confirmed by Walker for designing an elastomeric seal for Omni axial movable nozzle. Gajbir Singh and Rao [2] 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 [3] indicate that any modifications to reduce stress may cause increase of torque and weight. Regarding the overall configuration aspects of the nozzle systems. Jeffrey Foote [4] 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. Kirby and Van Vooren [5] 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. Sivaramakrishnan and Bhagwan [6] characterized the natural rubber and determined the material constants of the Mooney-Rivlin model. Press [7] 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. Taine et al. [8] 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. As can be seen, development of flexible joint for air borne propulsion system is not dealt more in fabrication perspective. Furthermore almost no literature is available which speaks about experimental characterization of flexible joint. Based on these limitations development and experimental characterization of flexible joint for air borne propulsion system is taken up in the current research work.

2. DEVELOPMENT OF FLEXIBLE JOINT:

The properties required for flexible joint are low shear modulus, high shear strength and high bulk modulus. These properties are required to design a flexible joint with low spring torque, high shear stress capability and less axial compression. In addition, compatibility with shims for bonding or vulcanizing and good ageing properties are also required. As latex rubber cannot meet these requirements, natural Rubber has been chozen as material for flexible joint. It has been processed to increase the mechanical properties and the properties achieved after processing are given in Table 1.

Table 1 Properties of rubber for flexible joint

Sl. No.	Property	Value
1.	Type of Polymer	Natural Rubber
2.	Shear Modulus	1.8 ± 1.2 Ksc
3.	Ultimate Shear Strength	25 ± 5 Ksc
4.	Ultimate Shear Strain	800 ± 100%
5.	Ultimate Tensile Strength, (min.)	100 Ksc
6.	Hardness, Shore 'A' (max.)	40
7.	Ageing coefficient	0.8 mm
8.	Compression set	20 %

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Chemlok has been used as an adhesive between rubber and metal. To begin with silicon Oil has been applied to all the mould components. All the mould components were assembled as per tool drawing. Rubber Slab has been cut as per requirement to place between shim. Quantity 8 number slab was placed between shim. Spacer has been provided between shim to achieve exact thickness of Rubber sleeves. Fore End Ring, Shims -7 nos & Aft End Ring have been placed in the mould cavity as per drawing. Rubber slabs were placed between the shims with the help of spacers. Finally top plate of mould was closed and hydraulic press was loaded. In the later stage the stack of shims and rubber pads were obtained by means of a compression molding process. In both cases, the shims were maintained in the heating mold by combs.

These combs determine the final thickness of the rubber pads. Bonding agents were applied on both faces of the shims, and then a layer of elastomer is applied above by means of an air-slip process. The mold was equipped with several resistive heating zones. The heating cycles usually involve several stages. The first ones aim to heat the remaining elastomer and to decrease its viscosity so that it may be easily transferred from the transfer pot to the injection channels. The second ones are effective curing stages. Natural Rubber compound has been cured in hydraulic press. The following curing cycle and loading has been followed

•140 ± 5°C for 13 minutes
•Hydraulic load of 30 – 40 tones was applied on mould

Flexible joint thus developed has been shown in Fig. 3.

Fig. 3. Flexible joint after Extraction

3.EXPERIMENTAL CHARACTERIZATION:

The following are the test objectives of the various tests that were performed on the flexible joint.

•To test pressure sealing capability of flexible joint.
•To evaluate the axial compression and strains due to pressure.
•To evaluate the pivot point shift at null positions at maximum ejection load simulated pressure.
•To test pressure sealing capability of flexible joint during vectoring.
•To evaluate the strains due to pressure and vectoring (up to $\pm 5^0$).
•To evaluate rotational stiffness of the flexible joint.
•To test the structural integrity of flexible joint.

The following tests were carried out to meet above mentioned objectives.

•Pull Test
•Proof Pressure Test
•Null Position Test
•Vectoring Test

3.1 Pull test:

This test was done to access the bonding between shims and elastomers immediately after seal moulding and after acceptance tests as shown in Fig. 4.

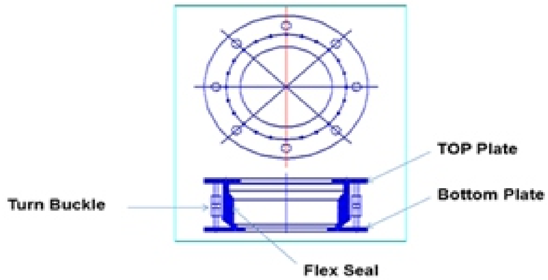

Fig. 4. Pull test setup

The flexible joint was subjected to a maximum pull of 2 mm in steps of 0.5 mm by using four turn buckles at 90^0 apart operated simultaneously. The pull was measured by 4 dial indicators. Typical acceptable value of minimum bond area between shims and elastomer is 95% with 2 mm axial pull. The flexible joint sub assembly after moulding and spacer removal was assembled in pull test fixture and an axial pull of 2mm has been applied. Minor debonds, if any, were recorded with reference to R2T and noted the depth of debond using feeler gauges.

3.2.Proof Pressure Test:

This test is done to simulate motor maximum expected operating pressure up to proof pressure levels and check the pressure sealing capability.

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The chamber will be pressurized to the proof pressure in steps of 1.0 MPa with a hold time of 3 minutes at proof pressure and return back to zero pressure in same steps. At each pressure step, strains on shims, seal compression and pressure will be recorded in the data acquisition system. The flexible joint along with throat housing is tested up to proof pressure level of 63 Ksc. Test setup is show in Fig. 5.

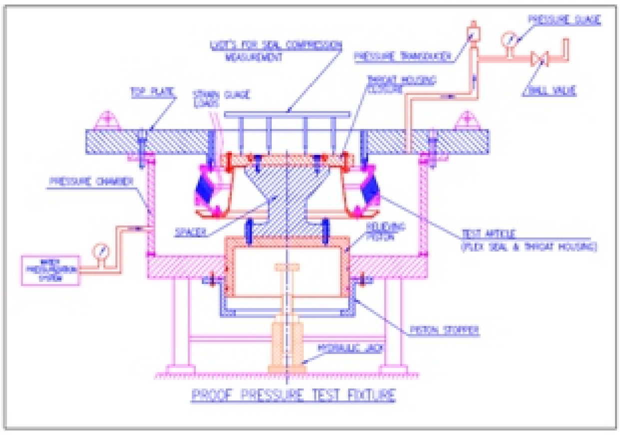

Fig. 5. Proof pressure test setup

The test set up comprises the B2 seal test fixture fabricated with interfaces to assemble the test article. It consists of a pressure chamber and closure plate and a relieving piston supported on a jack. The pressurization system is capable of maintaining the chamber pressure for the entire test duration and is independent of the actuator / control system. The relieving piston is provided to prevent overloading of the seal during the proof pressure test. The relieving piston with jack is kept engaged to the closure plate during the proof pressure test and will be disengaged for the actuation tests. The test set up has got provisions for mounting the actuators and, LVDT s for measurement of the displacement/deflection.

The first phase of testing comprises leak testing, cyclic testing and proof pressure testing. For these tests the piston is jacked up and engaged to the top plate. No data is recorded during the leak and cyclic tests and chamber pressure alone is monitored. The seal shall be pressurized up to 94.5 KSC in steps of 10, 20, 30,40,50,60,70,80,90, 94.5 KSC and depressurized to zero in the same steps. The axial deflection and strain gauge readings were monitored at the different steps both during pressurization as well as depressurization.

3.3.Null Position Test :

This test has been done to simulate ejection load and measure the behavior of flexible joint due to asymmetry in geometry. In this test, the pressure is increased from zero to a pressure, which creates equivalent ejection load in steps of 1.0 MPa with a hold time of 3 minutes at maximum pressure. Apart from this, the readings at 0.5 MPa and motor average pressure will also be recorded. Seal compression, the force required to correct the deflection due to asymmetry, pressure and strains on the shims are measured during each load step. The pivot point shift is measured by placing four LVDT's radially on the simulated divergent nearest to the pivot point. At every pressure step the shift is recorded after null correction and the maximum is reported. Test setup is shown in Fig. 6.

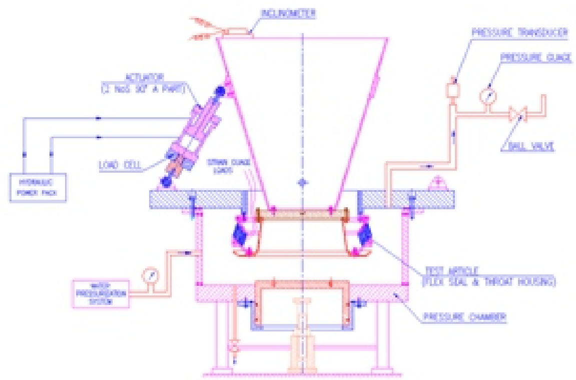

Fig. 6. Null position test setup

The flexible joint and throat housing assembly is tested up to a pressure of 48 Ksc, simulating proof ejection load of 23.1 tons corresponding to 63 Ksc. The actuators are in assembled condition at R2T and R1L locations during the null test. For assuring null position, 2 inclinometers are used. In the second phase of testing involves characterization of the seal.The actuators are connected at R2B and R1L locations and the relieving piston is disengaged during this phase of testing. Tensile loading of the seal is avoided by pressurizing the chamber to 0.5 KSC prior to mounting the actuator frame. The actuators, load cells and LVDT s are kept in position and connected. The position of the seal prior to pressurization is taken as null position for the actuator. The assembly shall be pressurized in steps of 5, 10, 20, 30, 40, 50, 60, 69 and then depressurized in the same steps. The null position of the seal will be maintained by monitoring the LVDT readings and giving commands to one of the actuators.

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The axial deflection, strain, LVDT and load cell readings will be monitored and recorded at each pressure level. The test is repeated keeping the second actuator in the null position and commanding the first actuator alone for retaining the seal in null position.

3.4.Vectoring Test:

The thrust vectoring requires the nozzle to be vectored in perpendicular planes resulting in shear loads in the elastomer of the flexible joint. The seal stiffness in shear has to be minimum to reduce the actuator load and its associated design. The requirement of actuator force is inversely proportional to the pressure. Test setup is shown in Fig. 6 is also applicable for this test. These tests are done to simulate angular deflection of flexible joint with ejection load to characterize seal torque / Actuator force requirement and Actuator stroke requirements. The flexible joint is vectored from 0^0 – maximum angle – 0^0 – negative maximum angle – 0^oin steps in one degree. Separate tests are done in individual pitch, yaw and in simultaneous planes. Vectoring tests are done at three pressures for configuration-D namely 0.5 MPa, 4.02 and 5.3 MPa to map the characteristics at lower, average and upper bound of rocket motor operations. Similar test have been done for other configurations with vectoring angles given in Table 6-1. The actuator force, stroke, deflection angle, pressure and strains on shims are measured at every load step. The seal throat housing assembly is tested at 5 Ksc, 38 and 48 Ksc under actuation conditions of ± 4.5 degrees in two planes individually and also in simultaneous actuation condition.

4. RESULTS AND DISCUSSION:

Results obtained in all the tests are discussed below.

4.1 Pull test:

The flexible joint sub assembly, after moulding and spacers removal, an axial pull of 2mm has been applied. No de-bonds were observed.

4.2.Proof pressure and null position test:

Seal compression noticed during proof pressure test is shown in Fig. 7.

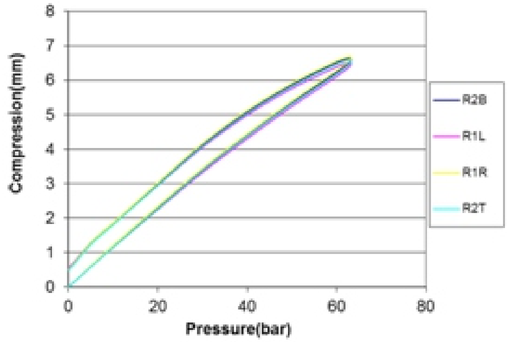

Fig. 7. Seal Compression during Proof Pressure Test

Seal compression noticed during null position test is shown in Fig. 8.

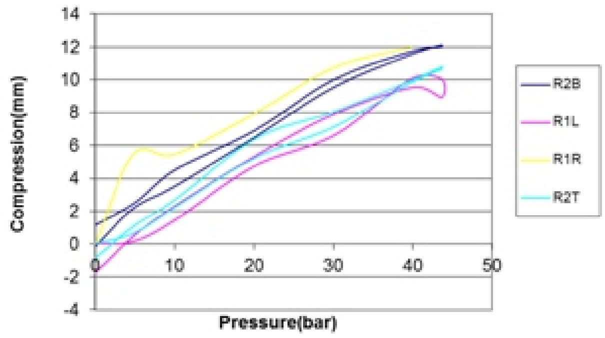

Fig. 8. Seal Compression during null position Test

•Seal compression was measured with 4 LVDTs mounted 90^0 apart and average is reported which match very well with the predictions for seal tested for each configuration.
•Average seal compression measurements show a maximum variation of 0.22 mm from FEA predictions
•This is attributed to the variation in rubber properties. Pivot point shift and null correction force vary from seal to seal depending on asymmetry and is mapped for every seal tested.
•Simulation of ejection load is as per requirement during PPT and NPT with a pressure controller of ± 0.01 MPa accuracy used to control the load.

4.3.Vectoring test:

Actuators loads on seal for Pitch actuation test is shown in Fig. 9.

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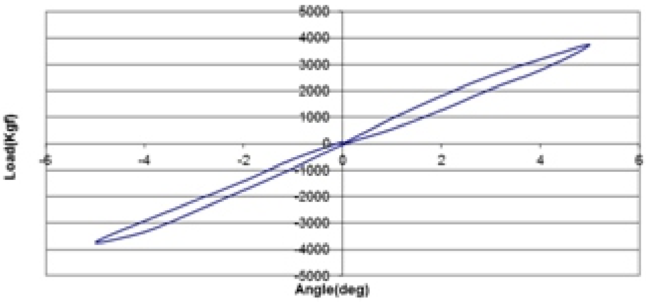

Fig. 9. Actuators loads on seal for Pitch actuation test

•During testing, the nozzle is vectored from 0^0 to -5^0 to 0^0 to 5^0 in steps of one degree in individual planes of pitch and yaw and repeated in both planes simultaneously. The test is repeated at three pressures.
•The actuator force / seal torque is maximum at minimum pressure.
•The stresses on the shims are maximum during maximum chamber pressure and vectoring angle.
•Plot of stress versus angle during simultaneous actuation shows that increase/decrease in stress only in the resultant plane of actuation whereas in planes 90° to resultant plane of actuation the stress remains almost unchanged.
•This is as per predicted behavior of seal. the hoop stress in mid shim with vectoring angle shows a good match with FEA prediction. The vectoring pattern from -5^0 to $+5^0$ is examined in detail for the middle shim. The actuator force is directly proportional to the vectoring angle.

5. CONCLUSIONS:

Development of flexible joint has been taken up with new methodology to avoid time and cost-consuming experimental iterative steps. Acceptance and qualification tests have been done as per the test procedure of flexible joints.

6. ACKNOWLEDGEMENT:

This research is supported by Department of mechanical Engineering, Malla Reddy Engineering College (Autonomus), Hyderabad.

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