Estimation of actuator load during gimballing of a pressurized softgood structure: A numerical simulation

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doi: https://doi.org/10.37285/bsp.SACAD2025.29

Abstract**—***Multi-layer stitched fabric soft good structures (SGS) are generally used in nozzle end closures of launch vehicle structures. They are provided to facilitate nozzle gimballing and protect inner avionic packages from extreme heat generated due to nozzle exhaust plumes during flight operation. It is subjected to differential pressure load as well. During gimballing motion, SGS under this differential pressure acts as pressurized membrane which may offer resistance to the gimballing motion, thus causing an augmentation in the required actuator load. In the present study, an explicit Finite Element (FE) simulation of the pressurized SGS is carried out to estimate the actuator loads required under gimballing motion. The simulated data obtained from this analysis is validated with measured test data as good match is observed in the results.*

Keywords**—***Soft good structures, explicit finite element analysis, membrane, pressure, nozzle, gimballing, actuator load*

Nomenclature

SGS	:	*Soft good structure*
FEA	:	*Finite Element Analysis*
ID	:	*Inner Diameter*
OD	:	*Outer Diameter*
FBD	:	*Free Body Diagram*
dof	:	*Degree of freedom*
FE	:	*Finite Element*
BC	:	*Boundary Condition*

I. INTRODUCTION

Soft good structures (SGS) are constituted of multi-layer stitched fabrics and are generally used in launch vehicle structures near nozzle end closures. They are provided in the annular gap between a movable structure i.e. nozzle and external stationary structure like shroud. They protect the flight critical avionic packages of the inner compartment from extreme heat generated during the nozzle operation [1],[2]. A typical configuration of SGS [3] in nozzle end closure assembly of launch vehicle is shown in Fig. 1.

Layer sequence of SGS is designed in such a way that the inner compartment is restricted to a specific reasonable temperature limit of 120°C, thus protecting the inner avionic packages. SGS is required to be flexible so that it can facilitate nozzle gimballing and accommodate the resulting gap between the interfaced nozzle and the stationary structure. A differential pressure is attributed to difference in the external pressure and ambient pressure inside the compartment during flight operation. This differential pressure is a function of dynamic pressure, coefficient of pressure (Cp) dispersion and the venting pressure.

In the present study, pressurized SGS under gimballing motion of nozzle is carried out to estimate the actuator load required during gimballing using explicit finite element analysis (FEA).

As the pressurized SGS is subjected to transient loading conditions (gimballing motion) within a very short duration, it undergoes large deformation within such short span of time. In such cases, explicit analysis is generally used in aerospace applications [4],[5]. Hence in the present work, explicit finite element analysis (FEA) has been carried out to simulate the behaviour of the pressurized SGS under gimballing motion.

The present study primarily focuses on the estimation of the actuator load required for carrying out the gimballing of SGS under pressure load. This estimation of actuator load is critical for the actuator design, as it should be within its capacity to meet the different gimballing requirements during flight operation.

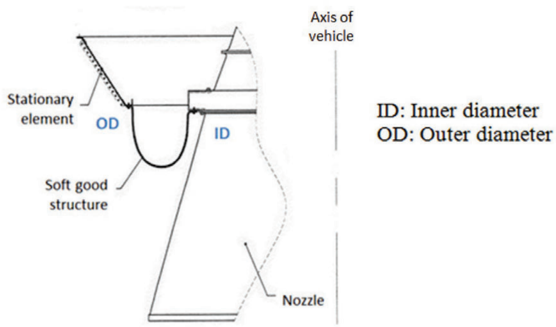


Fig. 1. *A typical soft good structure (SGS) assembly configuration*

II. SOFT GOOD STRUCTURE (SGS) CONFIGURATION

SGS is a multilayer stitched construction consisting of layers like glass fabric, silica fabric, nylon/kevlar reinforced rubber and heat lab etc., stacked over one another and held together by stitching at various locations. It acts as thermal insulation blanket which protects the inner avionic packages from thermal environments due to nozzle exhaust. The inner periphery (ID) of SGS is interfaced with nozzle (movable) and the outer periphery (OD) of SGS is interfaced with external stationary structure like shroud using fasteners. SGS being an annular structure is configured as multiple petals or segments stitched together as shown in Fig. 2. These petal sizes are configured considering the roll length/width available for each of the constituent fabric and length of the fabric needed between the interfaces at either ends [6].

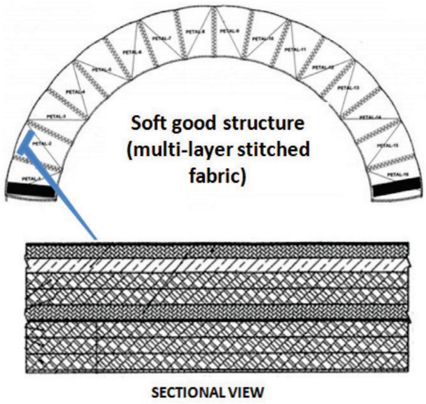


Fig. 2. *Typical construction of soft good structure*

III. REQUIREMENT OF ACTUATOR LOAD ESTIMATION

During the flight operation regime of a launch vehicle, gimballing of nozzle is required to achieve a controlled trajectory path. This results in the movement of the ID interface of SGS interfaced with nozzle being gimballed about a hinge point, while the OD interface of SGS will remain stationary.

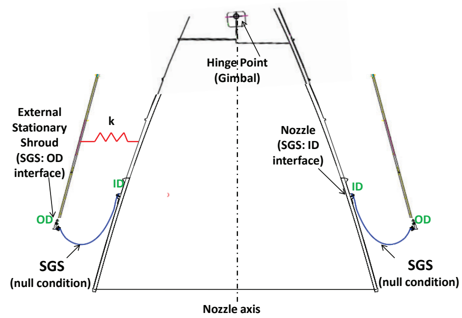
The configuration of SGS in null condition is shown in Fig. 3(a) and the corresponding FBD (Free Body Diagram) is shown in Fig. 3(c). The configuration of SGS in gimballed condition is shown in Fig. 3(b) and the corresponding FBD is shown in Fig. 3(d).

In null condition, all forces are balanced. However, once the nozzle is gimballed, a resistance force offered by the flex seal stiffness which needs to be overcome by the actuator, that can be represented as a spring with a stiffness 'k' being extended by displacement of δ. Hence, the reaction force due to the flex seal stiffness is represented by 'kδ'.

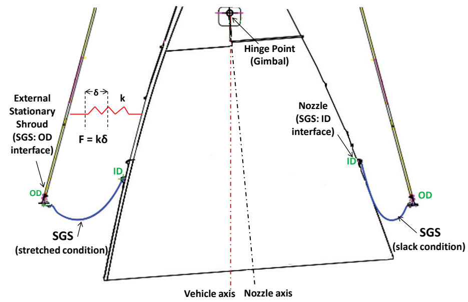
When SGS is subjected to differential internal pressure, it behaves like a *pressurized membrane.* As the SGS is gimballed, it gets under *slack condition* towards the gimballing motion direction and whereas in the opposite end, the SGS gets *stretched*. Owing to the *flexible fabric nature* of SGS which is subjected to gimballing motion under pressure load, the SGS offers resistance to the gimballing motion due to its membrane force which also has to be overcome by the actuator. Suppose the membrane force at stretched condition of SGS is represented by F_{M1} and the force at slack condition of SGS is represented by F_{M2}, then the net force due to membrane effect of SGS is given by (F_{M1}- F_{M2}).

Moreover, depending on the initial gap provided between the SGS in slack condition and nozzle, there could be a possibility that SGS may come in contact with nozzle divergent at some gimbal angle. An attempt was made earlier in the previous work [7] to study such possible scenario of a pressurized SGS coming into contact with nozzle which may further hinder the gimballing motion and additional load ($F_{contact}$) has to be drawn from actuator due to contact to meet the desired gimballing angle as demanded by the control system during the flight operation.

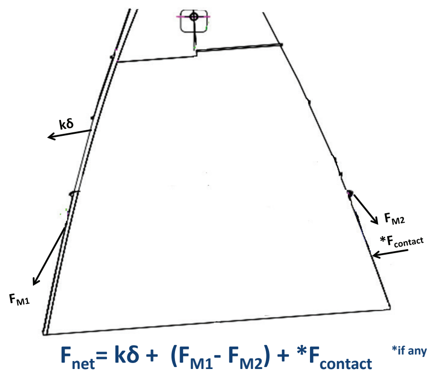
F_{net} = Net force on nozzle
kδ = Reaction force due to stiffness of adjacent hardware
F_M = Reaction force due to membrane effect of SGS
$F_{contact}$ = Force due to contact between SGS and nozzle (if any)



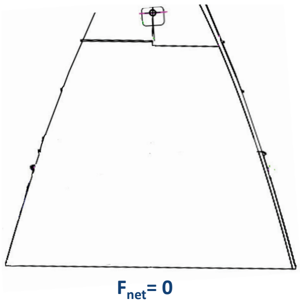
(a) Null condition



(b) Typical Gimballed condition



(c) Free Body Diagram (FBD): Null condition



(d) Free Body Diagram (FBD): Gimballed condition

Fig. 3. *A typical representation of interaction between SGS and nozzle*

The total summation of the load (F_{net}) should be within the capacity of the actuator so that the nozzle can gimbal to the required angle to meet the flight operational requirement. Generally, the actuator load being contributed by membrane effect of SGS is rarely accounted for during the actuator design phase and has not been reported in the literature as well. Hence it is *essential* to estimate the actuator load required during the gimballing motion of pressurized SGS to account for the *membrane effect of SGS*, which the present study aims to highlight.

IV. STRUCTURAL ANALYSIS

Structural analysis of SGS in gimballing motion is carried out using explicit finite element analysis (FEA) to estimate the actuator load requirement. The present assessment focuses on the simulation of *gimballing motion of SGS alone (without modelling nozzle)* to study the sole effect of pressurized SGS on the actuator load.

A. Geometry

The geometric profile of SGS in null condition is generated using a catenary curve. The catenary profile is generated by

i. assuming it to be a string held between two fixed points (fastener locations) and
ii. solving for the two fixity points and length of the string considered.

The generalized equation for a catenary curve as shown in Fig. 4 is described by the following equations [8]:

$$y = c + a\cosh\{(x-b)/a\} \quad \text{------------------ (1)}$$

Arc length from (0 to x) is:

$$L(x) = a\,[\sinh\{(x-b)/a\} + \sinh(b/a)] \quad \text{------------------ (2)}$$

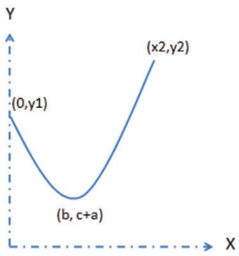


Fig. 4. *Catenary curve: Geometry*

B. FE Model

The finite element model of SGS is generated for 180 degree sector using 4 noded shell elements as shown in Fig. 5. As the objective of the present study is to assess the sole effect of pressurized SGS on the actuator load in gimballing motion, *nozzle divergent is not simulated in the FE model.*

C. Material properties

Equivalent material properties of the SGS obtained through tensile testing of the multilayer stitched specimen (all layers together) is considered for the analysis as follows:

Modulus along warp = E1
Modulus along weft = E2
Shear Modulus = G
Poisson's ratio = 0.3

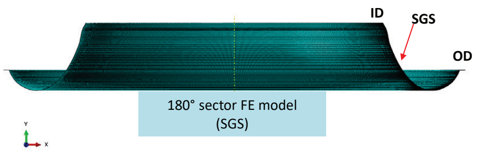
E1/ E2 = 68.29; G/E2 =0.5

D. Loads

SGS is subjected to uniform differential internal pressure load of 0.15 bar (gauge) as shown in Fig. 6.

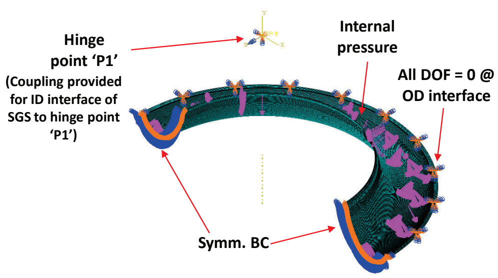
E. Boundary conditions

Fixed displacement constraints (i.e all degrees of freedom, dof=0) are provided at fastener locations at OD interface of SGS and symmetry boundary conditions are applied at the extreme edges of the sector. Coupling (all dof) is provided for the entire ID interface of SGS to the gimballing hinge point (P1) as shown in Fig. 6. The gimballing motion (slow sine) of SGS is simulated by supplying angular rotational movement as input (vectoring angle vs. time as shown in Fig. 7) on the hinge point (P1).



$$Actuator\ load\ (FEA) = \frac{\text{Reaction moment at hinge point from FEA}}{\text{Actuator lever arm length}}$$

Fig. 5. *FE model (180^0 sector) of SGS for structural analysis*



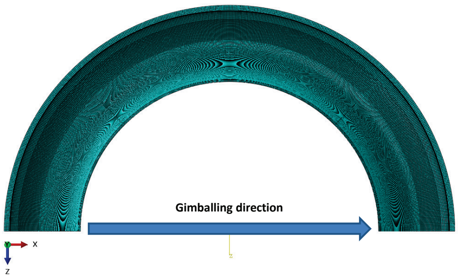


Fig. 6. *Loads and Boundary conditions for structural analysis*

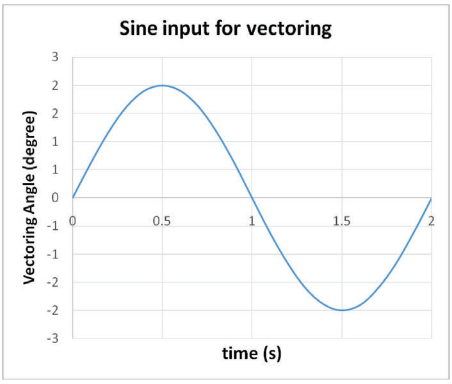


Fig. 7. *Gimballing motion simualtion in SGS: Variation of vectoring angle (slow sine)*

V. Results and Discussion

A. FEA results

From the structural FE Analysis carried out, the actuator load required for gimballing is estimated using the reaction moment generated at the gimballing hinge point (P1) and dividing it with the lever arm length of the actuator.

B. Test results

A gimbal test was performed with SGS simulating gimbaling motion as referred in Fig. 7. The configuration of the test setup used for simulating gimballing of SGS is shown in Fig. 8.

The test was carried out initially by simulating gimballing motion without any application of pressure on SGS i.e. free gimballing. Gimbal test was repeated subsequently with internal pressure on SGS.

As the objective of this test is to assess the sole effect of pressurized SGS on the actuator load in gimballing motion, *nozzle divergent extending below the SGS-to-nozzle attachment point was not simulated in the test.*

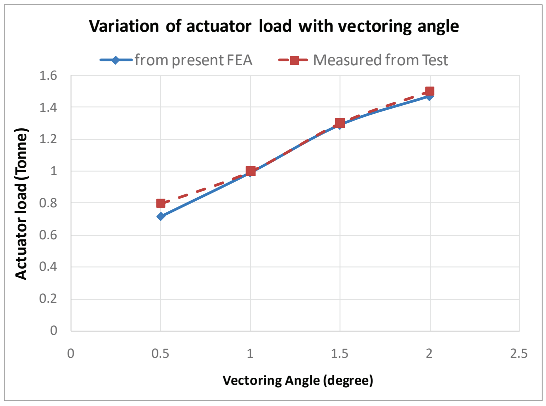


Fig. 8. *Test setup for gimballing motion of pressurized SGS (Courtesy: VSSC Project)*

The actuator load during gimbal test is estimated by converting the measured actuator current drawn into load. Hence, from the gimbal test, actuator load was measured in both the cases, i.e. for gimballing without pressure of SGS (A) as well as gimballing with pressurized SGS (B) as shown in Table 1.

Hence, the sole contribution of pressurized SGS on the actuator load is computed as follows:

'A' stands for Actuator load due to gimballing of SGS system without pressure

'B' stands for Actuator load due to gimballing of pressurized SGS system

Therefore, the sole contribution of pressurized SGS on the actuator load is calculated by subtracting the actuator load due to the flex seal contribution *(A)* from total actuator load in pressurized condition *(B).*

The sole contribution of pressurized SGS on the actuator load during gimballing is given by *(B –A).*

The actuator load measured from the test during gimballing of SGS (without pressurization and with pressurization) at different vectoring angles is summarized in Table I.

TABLE I. Actuator Load Measured in Gimbal Test of SGS

Vectoring angle	**Actuator load (Tonne) measured during gimbal test of SGS**		***Actuator load (Tonne) contribution due to pressurized SGS alone (B-A)***
	Without Pressure on SGS (A)	***With internal pressure on SGS (B)***	
0.5^0	0.6	1.4	**0.8**
1^0	1.5	2.5	**1**
1.5^0	2.4	3.7	**1.3**
2^0	3.2	4.7	**1.5**

C. Comparison of results

The actuator load during gimballing of pressurized SGS obtained from the present FEA and the measured test data at different vectoring angles are compared as shown in Table II.

TABLE II. COMPARISON OF ACTUATOR LOAD DURING GIMBALLING OF PRESSURIZED SGS: TEST VS. PREDICTION

Vectoring angle	Actuator load (Tonne) due to gimballing of pressurized SGS		*Ratio of actuator load:* $\frac{Measured\ from\ test}{Predicted\ from\ FEA} = \frac{T}{P}$
	Measured from gimbal test (T)	*Predicted from FE analysis (P)*	
0.5^0	0.8	*0.72*	**0.90**
1^0	1	*0.99*	**0.99**
1.5^0	1.3	*1.29*	**0.99**
2^0	1.5	*1.47*	**0.98**

Fig. 9 shows the variation of the actuator load with vectoring angle during gimballing of pressurized SGS compared between the results from FEA and the measured test data.

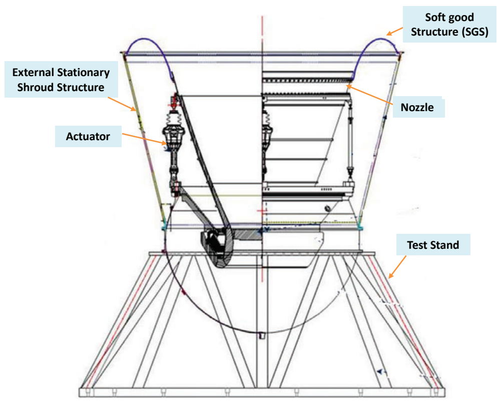


Fig. 9. *Comparison of actuator load in pressurized SGS varying with vectoring angle during gimballing motion simualtion*

It can be observed from Table II and Fig. 9 that there is an excellent match between the actuator load obtained from FEA results and the gimbal test measured data. Hence, the present FE assessment is validated with the test results.

It can be inferred from Fig. 9 that as the vectoring angle increases, the actuator load required during gimballing increases. This is due to the membrane effect of SGS under pressurized condition owing to its fabric nature.

This results in higher load required to be overcome by the actuator for a higher gimballing angle requirement of nozzle.

Hence the present assessment is essential to design the actuator of a nozzle as it is needed to account for the additional effect of membrane nature of SGS on the actuator load during nozzle gimballing of pressurized SGS such that the total actuator load is within its capacity.

VI. CONCLUSIONS

Soft good structures (SGS) are constituted of multi-layer stitched fabrics and are generally used in launch vehicle structures near nozzle end closures. In the present study, structural analysis of pressurized SGS under gimballing motion of nozzle is carried out to estimate the actuator load required during gimballing using explicit finite element analysis (FEA).

The present study focuses on the assessment of sole contribution of pressurized SGS on the actuator load required during the gimballing motion to account for the *membrane effect of SGS.*

The actuator load during gimballing of pressurized SGS obtained from the present FEA and the measured test data at different vectoring angles are compared and an excellent match is found. The present FEA results are validated with the test results. *As the vectoring angle increases, the actuator load required during gimballing increases.*

Hence it is essential to estimate the actuator load required during the gimballing motion of pressurized SGS so that the total load should be within the load capacity of the actuator so that the nozzle can gimbal to the required angle to meet the desired gimballing angle as demanded by the control system during the flight operation.

Thus, the present study plays a crucial role in emphasizing the need to account for the membrane effect of a pressurized SGS on the actuator load during its gimballing motion.

VII. ACKNOWLEDGEMENT

The support and guidance provided by Shri. Yezhil Arasu A (VSSC Project) and his team towards carrying out this study is gratefully acknowledged. We also extend our sincere gratitude to Shri. Adarsh Kumar Sahu, former engineer, VSSC/ISRO for his invaluable contribution towards carrying out the present assessment study.

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