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RESEARCH PAPER

Investigation on the Residue Gas Inflation Technique for Space Borne Inflatable Boom with Different Folding Patterns

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Abstract

Background The last two decades have seen a growing trend toward the use of inflatable membranes for spaceborne structures. The spaceborne inflatable membrane structures are the promising solution for the compact and lightweight reflector antenna. The inflation technique is used for pressurizing the inflatable membrane structure once the satellite reaches to its predefined orbit.

Objective The objective of the study is to demonstrate the use of the residue gas inflation technique for the complete deployment of the inflatable thin membrane boom with different folding patterns. The study also aims to find out generalized relation to calculate the safe mass of residue gases to be kept inside spaceborne membrane boom.

Method The novel analytical relation for the safe mass of residue gases that can be carried for any size of the inflatable boom is established. A comparative study is performed to investigate the effect of variation in a folding pattern on the proposed inflation technique. Experimental, numerical, and analytical approaches were employed for the proposed study.

Result The results show that the total inflation time is inversely proportional to the mass of the residue gases. Through the comparative study, it has been observed that the change in the inflation time is negligible for different folding patterns with the same mass of residue gas. The result confirms that the safe mass of residue gas is successfully deploying the inflatable boom in the vacuum environmental condition keeping the stresses in the boom in the tolerance limit.

Conclusions The findings of this research provide insights into a simple and cost-effective design solution for the inflation system along with safe mass of the residue gases which can be used for any size of spaceborne inflatable boom.

Keywords Inflatable · Membrane boom · Inflation technique · Residue gas, spaceborne

Introduction

Recently, there has been renewed interest in developing deployable structures for space and ground station applications worldwide [1–4]. The membrane structures have significant advantages such as higher strength-to-weight ratio, favourable thermal response, and packaging efficiency. Therefore, membrane structures are the best suited for a variety of applications such as inflatable textile beams, spaceborne structures, construction work, and solar sail [5, 6]. The membrane possesses negligible bending stiffness; therefore, wrinkling is the common phenomenon observed in stretched membranes [7]. The inflatable space structures are in stowed form in the launch vehicle and get deployed using pressurize gas once the satellite reaches a predefined orbit. Hence, the design of the inflation mechanism is crucial in the design of spaceborne inflatable structures. The uncontrolled mass of the residue gases can lead to the failure in deployment of the spaceborne structures. The stresses generated due to the inflation of residue gases must be within the tolerance limit of the material being inflated.

Patino-Jimenez et al. [8] developed the inflatable mirror using flexible polymeric membrane materials. The study on the inflated shape and wrinkling instabilities of the inflatable membrane was studied by Roychowdhury et al. [9]. The stable deployment of the payload with exact precision and accuracy is important for the controlled dynamics of satellite systems. Li at al [10]. have developed the generalized

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kinematic model for the stable deployment of the satellite antenna. The use of the inflatable cylindrical boom for the deployment of the sensors of satellites is demonstrated by Szyszkowski et al. [11]. Natori et al. [12] have performed the conceptual model study of the origami-based membrane structures used in space applications. The gain study on the multi-layered sandwich flexible membrane antenna was carried out by Datashvili et al. [13]. The prenecking strategy can be useful in the reduction in wrinkle formation in the planar membrane structures [14]. Liu at al [15]. developed the design methodology for the two-dimensional planar membrane antenna. The tension cable distribution is the key influencing parameter for the surface accuracy of the planar membrane reflector antenna [16]. Chen et al. [17] studied deployment behaviour of the pantographic foldable masts.

The deployable structures can be folded using origami folding techniques. The cylindrical boom can be folded in the axial direction with folding patterns such as the Yoshimura, Miura, and Bellows [18]. The tanked gas system, nitrogen cylinders and chemical reaction-based gas generators are widely used as inflation mechanism for spaceborne inflatable structures [19, 20]. However, such mechanisms introduce an extra mass penalty of tank and gas generators. Therefore, an inflation system for space structures needs to be designed with the objective of a minimum mass penalty and minimum requirement for the on-board power source. Chen et al. [21] have proposed a novel approach for the controlled deployment of the inflatable roll folded boom. Bonin et al. [22] have studied the edge trimming methods for the wrinkle reduction of the rectangular Kapton membrane structure. The analytical model for the shear wrinkle of the rectangular membrane is developed by Li et al. [23]. Vatankhahghadim et al. [24] have investigated the deployment dynamics of the membrane used in the solar sail application.

There has been no detailed investigation on the residue gas inflation technique for the deployment of spaceborne membrane structures. Studies over the past two decades have provided important information on the numerical and experimental methods for the shape adjustment, tensioning, wrinkle reduction technique, and origami folding of inflatable space structures [12, 20, 22, 23, 25]. The previous researchers demonstrated the use of complex and power source-dependent inflation systems for the membrane reflectors [19, 20]. However, to the best of the authors' knowledge, no previous study has investigated the residue gas inflation technique for the complete deployment of the spaceborne inflatable boom.

The objective of the study is to demonstrate the use of the residue gas inflation technique for the complete deployment of the inflatable thin membrane boom. The residue gas inflation technique will reduce the mass penalty of the inflatable satellite systems. The novel relation for the safe mass of residue gases established which can be used in the design of any size of the spaceborne inflatable boom. A comparative study is also performed to investigate the effect of variation in a folding pattern on the proposed inflation technique. The experimental, numerical, and analytical approaches were employed for the proposed study. This paper has been divided into four sections. The first part gives a brief overview of the recent development in spaceborne membrane structures. The second section deals with the methodology of the proposed approach. The subsequent section deals with the result and discussion. Final section concludes the paper.

Methodology

The procedure of the proposed approach of investigation is described using steps as follows,

Step 1. Geometric modelling of different folding patterns of the inflatable boom. For the comparative study on the residue gas inflation method, the inflatable boom is developed using the Miura, Bellows, and Yoshimura origami folding pattern.

Step 2. Calculation of the safe mass of the residue gases. The analytical expression is developed for the maximum safe mass of the residue gas that can be carried in the boom using the thermal and stress distribution equation.

Step 3. Analytical, Experimental, and numerical study on residue gases with a different folding patterns of the boom. The effect of variation in the mass of residue gases on the internal pressure, stresses generated of the boom, and inflation time are studied.

Step 4. Comparison of result & conclusion. The comparative study is performed in order to investigate the effect of variation in the different folding patterns and mass of residue gases on the deployment characteristics of the inflatable boom with the employed approach.

Geometric Modeling and Development of Spaceborne Inflatable boom

The inflatable boom of diameter 100 mm and height of 200 mm was developed using the Kapton material. The material properties of Kapton material are shown in Table 1.

Table 1 Material properties of Kapton material [26]

Material Property	Value
Density (kg/m^3)	1420
Thickness (mm)	0.05
Young's modulus (GPa)	2.5
Poisson's ratio	0.34
Yield point stress (MPa)	69

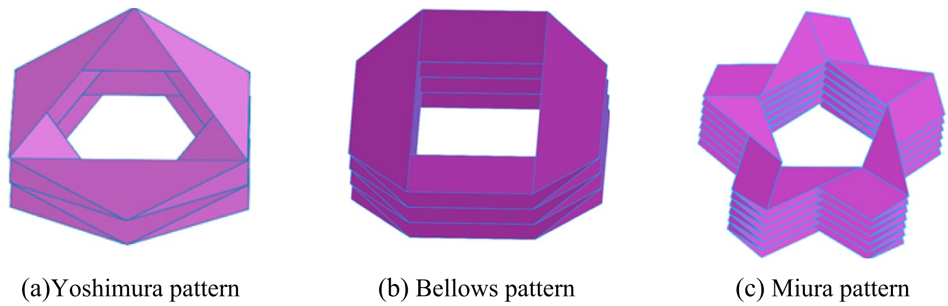


Fig. 1 Geometric model of the folded origami patterns

The guidelines for the development of the folding patterns of cylindrical boom such as Miura, Bellows, and Yoshimura were taken from the literature available [18]. The cylindrical boom was folded with three different basic types of folding patterns, such as Miura, Bellows, and Yoshimura. Initially, the fold lines were drawn on the flat Kapton sheet. After that, the boom is folded according to the origami fold lines. Figure 1 shows the geometric model of origami folded boom is developed using SolidWorks software. Figure 2 shows the fold lines and folded configuration of the booms with Miura, Bellows, and Yoshimura folding pattern with Kapton material.

Residue Gases Inside the Stowed Boom

Nitrogen gas is widely used for pressurizing the inflatable space borne structures. Due to its inherent properties such as non-flammability, inertness, low density, and stability, makes the nitrogen best suit for inflatable space structures. The nitrogen gas is also compatible with most of the space qualified materials. Therefore, nitrogen gas is used as an inflation gas in the present investigation. The residue gasses are the gases present in the voids or gaps of the folded boom. The voids inside the folded boom are governed by a folding pattern. The present study uses a Yoshimura, Bellows, and Miura origami pattern for the folding of the boom. Due to the negligible bending stiffness of the membrane, folded boom tends to bend out of shape. Therefore, it is very difficult to get the exact volume of the residue gases. The mass and initial pressure of residue gases are crucial parameters for the deployment of the spaceborne inflatable membrane structures. If the mass of the residue gases exceeds beyond the safe limit, then these gases can rapidly expand under orbital vacuum condition and there are high chances of the busting of the space borne boom. Therefore, the safe mass of residue gases must be kept inside the folded boom so that the stresses will be within a safe limit on expansion. This will safeguard the boom from busting and ensuring secure deployment. The safe mass of the residue gases is calculated as follows,

Considering the ideal gas equation,

$$PV = mRT \tag{1}$$

where, P=Pressure (MPa), V=Volume (mm^3), m= mass (kg), R = Universal gas constant and T= Absolute temperature (K).

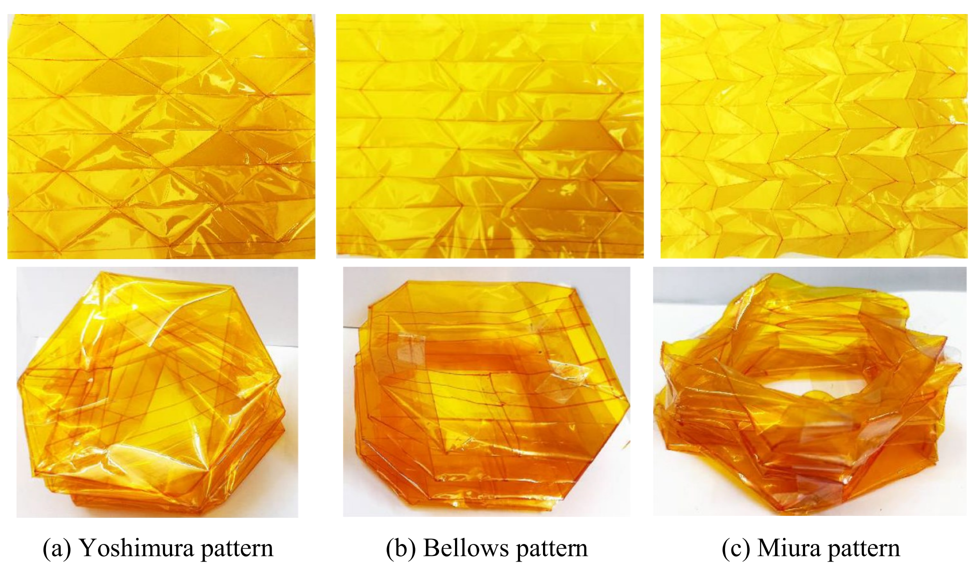


Fig. 2 Fold lines and folded configuration of the cylindrical boom of Kapton material

As the mass of the inflation gas in stowed and deployed condition remains same.

Therefore,

$$m_1 = m_2 \tag{2}$$

where, m_1 & m_2 are the masses of the residue gases before and after inflation respectively.

Comparing the ideal gas equation for stowed and deployed condition,

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2} \tag{3}$$

where, p_1, v_1, and T_1 are the pressure, volume and temperature of the residue gases in stowed condition and p_2, v_2, and T_2 are the pressure, volume and temperature of the residue gases in deployed condition.

The relation between mass and volume is given by,

$$v_1 = \frac{m_1}{\rho_1} \tag{4}$$

where, ρ_1 is the density of the residue gases in the stowed condition.

Substituting in (equation (3))

$$p_1 m_1 = p_2 v_2 \rho_1 T_R \tag{5}$$

The volume of deployed boom is given by,

$$v_2 = \frac{\Pi\, d_2^2 l}{4} \tag{6}$$

where, d_2 and l are the deployed diameter and length of the boom.

$$T_R = \frac{T_1}{T_2} \tag{7}$$

where, T_R is the temperature ratio.

For fully deployed thin cylindrical boom the Hoop's stresses (σ_h) are given by,

$$\sigma_h = \frac{p_2\, d_2}{2t} \tag{8}$$

Therefore,

$$p_2 = \frac{\sigma_h 2t}{d_2} \tag{9}$$

Substituting (equations (6), (7), and (9)) in (equation (5))

$$p_1 m_1 = \frac{\sigma_h 2t \Pi\, d_2^2\, l\, \rho_1 T_R}{4\, d_2} \tag{10}$$

$$p_1 m_1 = 1.57 \sigma_h t\, d_2 l\, \rho_1 T_R \tag{11}$$

Therefore,

$$m_1 = \frac{1.57\, \sigma_h\, t\, d_2 l\, \rho_1 T_R}{p_1} \tag{12}$$

From (equation (12)), it can be seen that the minimum mass of residue gases to keep in the boom depends on the initial pressure, dimension of deployed boom, temperature ratio. Therefore, appropriate temperature ratio needs to be considered while calculating the safe mass of the residue gases. This equation is the combination of the design and the thermal variables. By using this equation, the maximum safe mass of residue gases can be calculated for any size of inflatable spaceborne deployable boom made of any material. From (equation (12)), it can also be seen that the lower mass of the residue gas is required for the higher initial stowed gas pressure. For the present study the test conditions are taken based on the size of the experimental set-up, room temperature and pressure which are shown in Table 2.

After substituting the test data in the (equation (12)), the maximum safe mass of the residue gas is calculated is 1.15 gm. This value of residue gases will expand in vacuum condition keeping the stresses in the boom in the safe limit. If the mass of the residue gases is more than the calculated value, then the boom will bust in the vacuum environment which is not desirable.

Numerical and Experimental Investigation on Residue gas Inflation Technique

The experimental test rig for the comparative study of residue gas inflation is shown in Fig. 3. It consists of a vacuum chamber, pressure sensors, temperature sensors, laser displacement sensor, and gravity compensation mechanism. The laser displacement sensor is used to measure the displacement of the end cap of the inflatable boom. The temperature sensor is attached to the end cap of the inflatable boom. The schematic of the inflation test rig is shown in Fig. 4 for better clarification about the location of the sensor and gauges. The pressure sensor (P1) is attached to the boom, whereas another pressure sensor (P2) is used to

Table 2 Test conditions for the residue gas inflation

Variable	Value
Thickness of Kapton material (t)	0.05 mm
Deployed Diameter of Boom (d_2)	100 mm
Deployed Length of Boom (l)	200 mm
Initial density of residue gas (ρ_1)	1.16 kg/m^3
Initial temperature (T_1)	31 °C
Final temperature (T_2)	29 °C
Initial pressure (p_1)	0.101 MPa

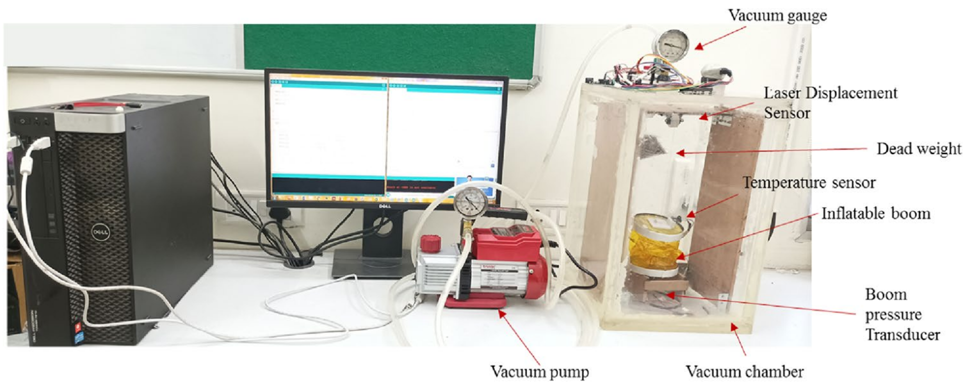


Fig. 3 Inflation test rig

measure the pressure of the vacuum chamber. For compensation of the weight of the end cap of the boom, the counterweight of equal weight was attached with the help of a pulley mechanism, as shown in Fig. 4. With the calculated mass of residue gasses, the boom is folded and kept inside the chamber. After that, the vacuum environment is generated inside the chamber to study deployment characteristics. The experiment was carried out for the different folding patterns of the boom. The uncertainty in the temperature and pressure measurement is less than ± 1 °C and 0.01 MPa respectively. The mass of the air inside the boom is maintained by calculating the weight of the open boom and fully closed boom. The minimum inflation time with minimum mass penalty and stresses generated in the boom are the investigating point of the present study.

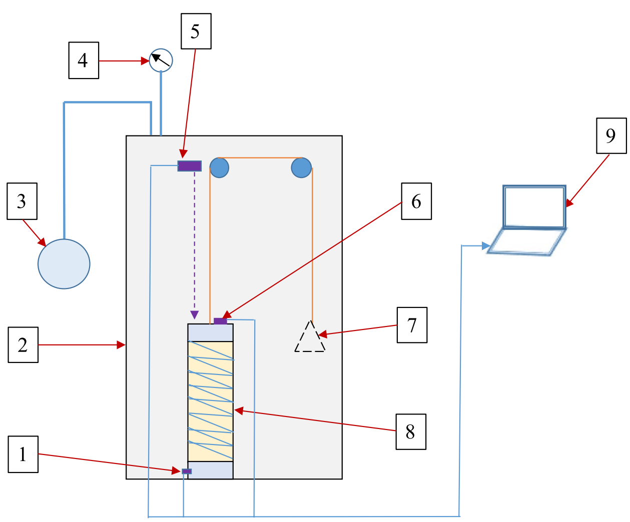


Fig. 4 Schematic of the experimental set-up (1) Pressure sensor (P1) (2) Vacuum chamber (3) Vacuum pump (4) Pressure sensor (P2) (5) Laser displacement sensor (6) temperature sensor (7) Counter weight (8) Inflatable boom (9) Data acquisition and processing Workstation

The minimum height of the packed boom is governed by the mass of the residue gases, Therefore, selecting the sufficient mass of residue gases is the key design parameter of the inflatable boom. The complete inflation of the boom is achieved with the volumetric expansion of the residue gases. The comparison is made for the different analysis parameters such as the inflation time, stresses induced, and internal pressure of the boom. The numerical simulation of the employed approach was carried out using the Abaqus software. The boom was modelled using the M3D4R four-node quadrilateral membrane element with the total number of elements being 104442 with the element size of 2 mm. The explicit dynamic load step was used in the numerical simulation with the overall time step of 1 second with increment of 10^{-6} seconds. The fluid cavity pressure was given to the folded boom. The initial boundary condition of fluid cavity pressure of 0.101 MPa is given to both residue gases and the outside environment. In the subsequent load step, the fluid cavity pressure of the environment is reduced to vacuum pressure and stresses in the boom are observed. The numerical outcome of the stresses generated in the boom is compared with the developed analytical relation. The encastre boundary conditions was given to the one end of the boom, whereas another end is free to translate in the axial direction of the boom. The end caps of the booms were attached using the tie constraints. The tie constraints enable equal degree of freedom for mating surfaces.

Result and Discussion

Effect of mass of Residue Gases on Stresses Generated in the Boom

The fully deployed boom which was inflated due to the pressure difference between the residue gases and the vacuum environment is shown in Fig. 5. The safe mass of the residue gases is kept inside boom as 1.15 gm, as calculated from previous section. It can be seen that the residue gases are

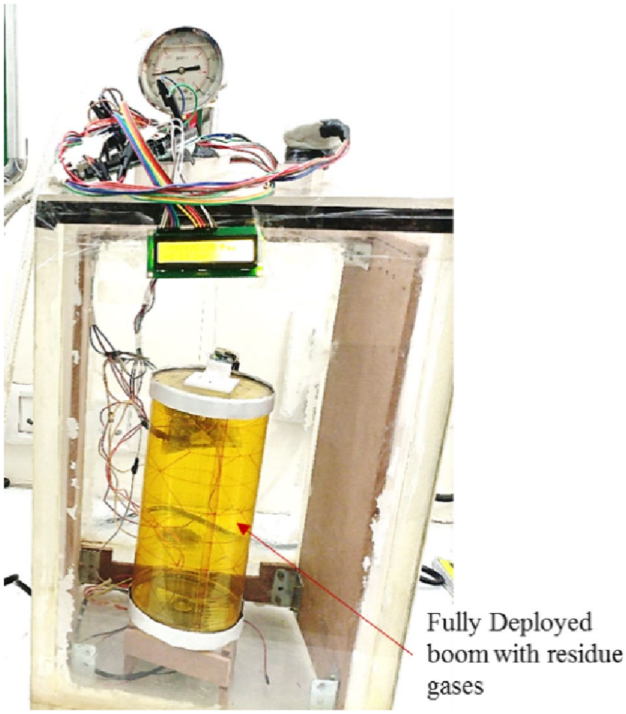


Fig. 5 Experimental results of residue gas inflation

successfully deploying the boom without busting because the mass of the residue gases is less than the safe limit.

The hoop's stresses generated in the boom was compared with the developed analytical relation and numerical simulation. The comparative study of hoop's stresses developed for a different mass of the residue gases is shown in Fig. 6. It can be seen that the stresses generated after the completed deployment of the boom are less than the yield point stress of the boom material. Therefore, the boom is deployed safely for different masses of residue gases.

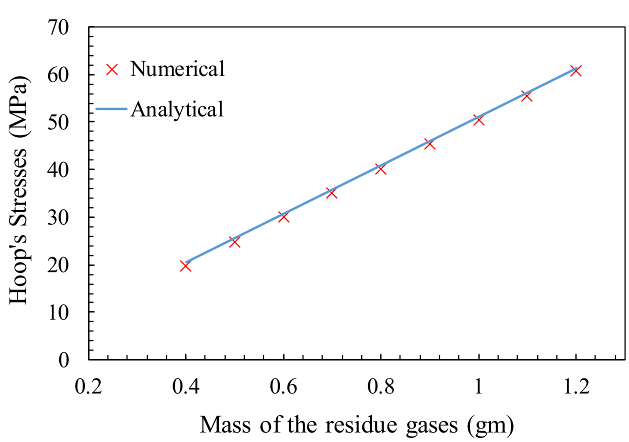


Fig. 6 Relation between the mass of residue gases and Hoops stresses generated after boom deployment

The numerical simulation results for the boom deflection along with different folding patterns is shown in Fig. 7. It can be seen that the stress values calculated from developed analytical relations are found consistent with the numerical outcomes. The mass of the residue gases must be less than the safe limit, which was calculated in the previous section. The effect of variation in the mass of the residue gases is made in order to investigate the deployment characteristics such as deployment time and end plate displacement. From (equation (11)) the relation between Hoop's stresses and the mass of the residue gases can be written as,

$$\sigma_h = \frac{p_1 m_1}{1.57\, t\, d_2 l\, \rho_1 T_R} \tag{13}$$

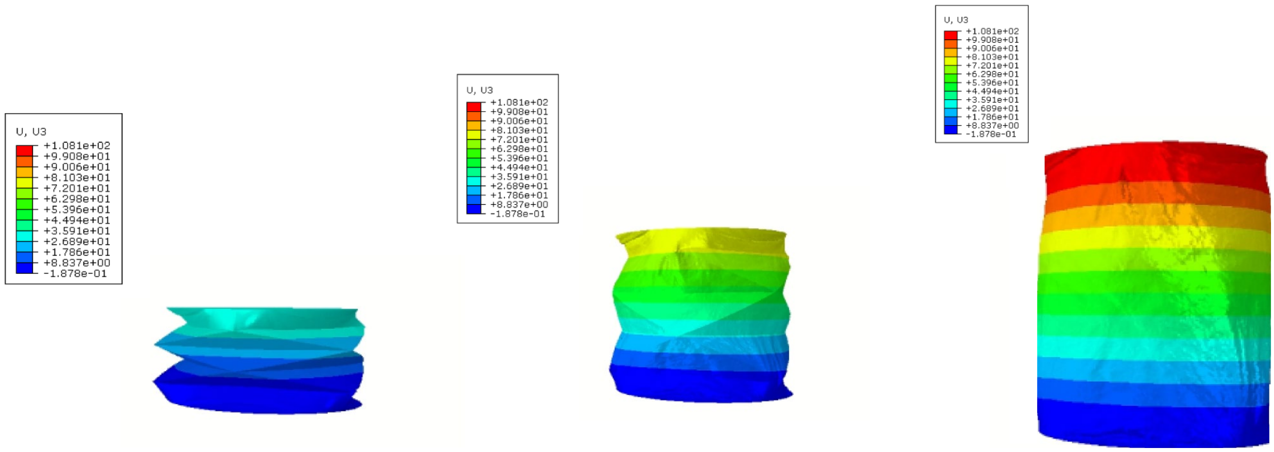
Effect of Mass of Residue Gases on the End Displacement and Inflation Time of Boom

The inflation time of the spaceborne boom is dependent on the mass of the residue gases. Therefore, the four cases of residue gases are studied to study the effect of residue gases on deployment behavior. The mass of the residue gases is taken as 0.8 gm, 0.9 gm, 1.0 gm, and 1.15 gm for Case I, Case II, Case III, and Case IV, respectively. As per the calculations from the previous section the maximum mass of the reissue gases that can be carried is 1.15 gm, which is taken for Case IV. For Case I, Case II and Case III, the values are selected based on the arbitrary interval of 0.1 gm. The comparative study of end displacement with different fold patterns of the boom is shown in Figs. 8, 9, 10 and 11. It has been observed that the inflation time is inversely proportional to the mass of the residue gases.

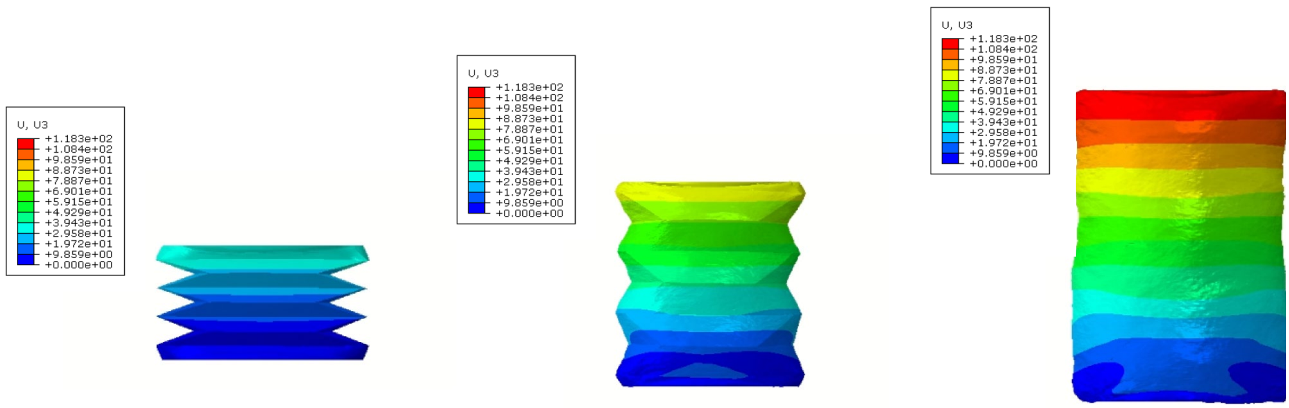
As the mass of the residue gases increases, the total deployment time, and total displacement of the end cap of boom decreases. The end displacement of the boom is more in Case I which signifies that the initial stowed height of boom is less in Case I. Therefore, the limitation of the proposed method is that more mass of the residue gases will reduce the packaging efficiency of the spaceborne inflatable boom. For all the three folding patterns, the displacement pattern remains approximately the same for a respective mass of the residue gases.

Internal Pressure of the Boom

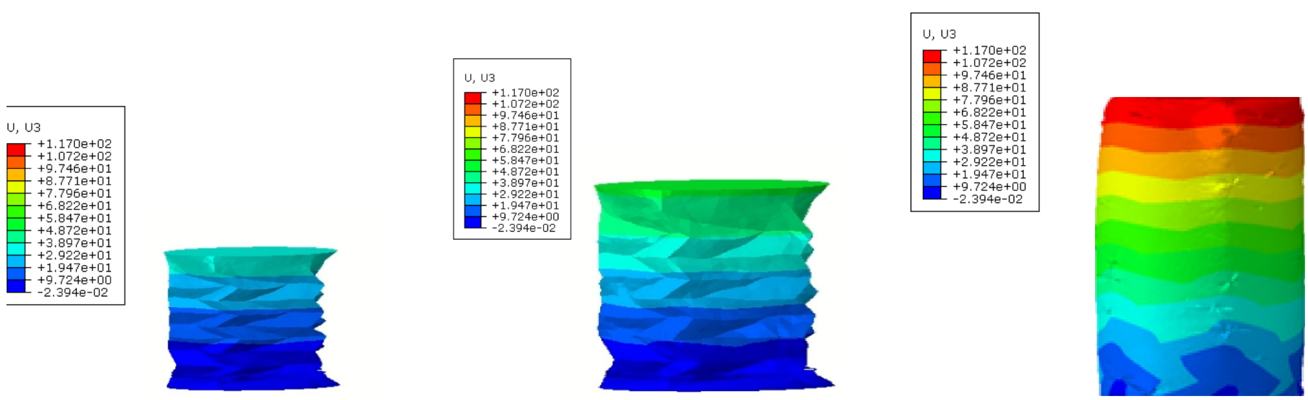
The residue gas inflation technique uses an expansion of the calculated mass of residue gases in order to achieve the total inflation of the boom. The pressure difference between the residue gases and the vacuum environment is responsible for the total inflation of the boom. The residue gases which are stowed in the boom are at a higher pressure than the



(a) For Yoshimura pattern deflection of boom (mm)



(b) For Bellows pattern deflection of boom (mm)



(c) Miura pattern deflection of boom (mm)

Fig. 7 Numerical simulation results for the boom deployment stages

vacuum pressure. Therefore, the volume of the residue gases expands, subsequently reducing the pressure inside the boom and inflating the boom. A comparative study was performed in order to investigate the effect of the mass of the residue gases on the internal pressure of the boom along with three folding patterns. This internal pressure is responsible for the

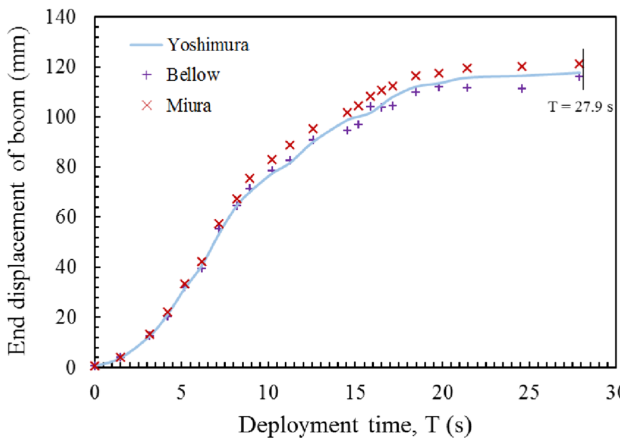


Fig. 8 End displacement of profile of boom for Case I with the mass of residue gases as 0.8 gm

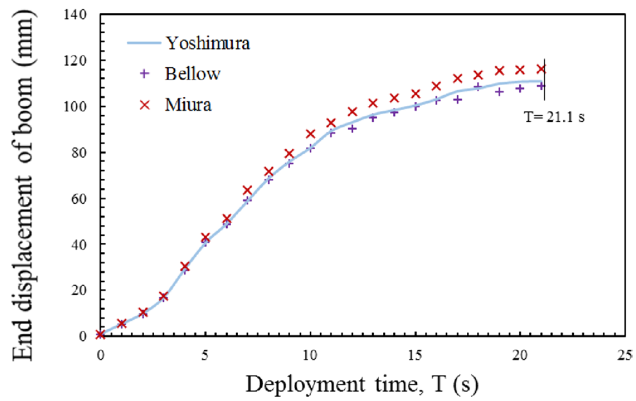


Fig. 10 End displacement of profile of boom for Case III with the mass of residue gases as 1.0 gm

stresses generated in the boom. Therefore, the stresses generated inside the boom should not exceed the yield limit of the material for the safe deployment of the boom. The effect of residue gases on the internal pressure on the boom for Case I to Case IV is shown in Figs. 12, 13, 14 and 15.

From Figures 12, 13, 14 and 15, It has been observed that as the mass of the residue gases is reduced, the internal pressure to deploy the boom is also reduced. The internal pressure is responsible for the tightness in the boom after deployment. The pressure range shown in Figs. 12, 13, 14 and 15 is the gauge pressure in which the initial pressure in the boom is assumed as zero bar. The expansion in the volume is ultimately deploying the boom under the vacuum environmental condition. The pressure difference and the mass of residue gases plays the vital role for the inflation of the boom with the residue gases. The mass of residue gases significantly contributing to the stresses induced in the

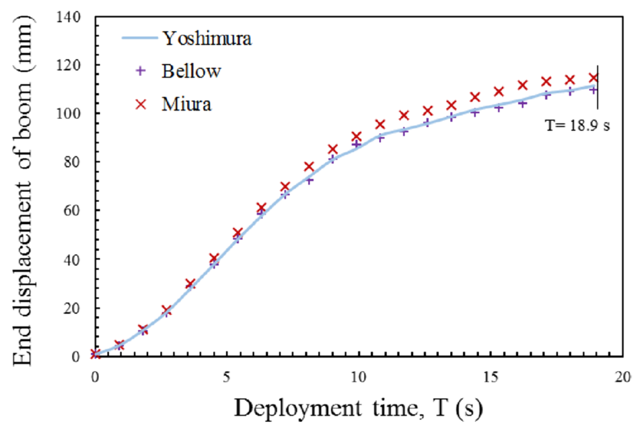


Fig. 11 End displacement of profile of boom for Case IV with the mass of residue gases as 1.15 gm

boom. From Figs. 12, 13, 14 and 15, it can be seen that as the mass of the residue gases decreases, the final boom pressure is also reduced. The expansion of the gas is responsible for

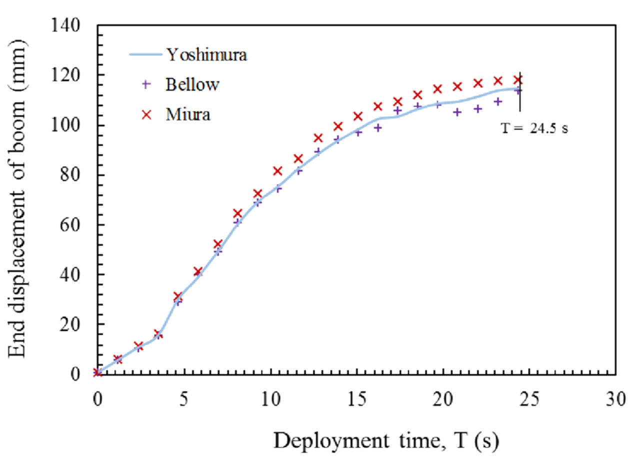


Fig. 9 End displacement of profile of boom for Case II with the mass of residue gases as 0.9 gm

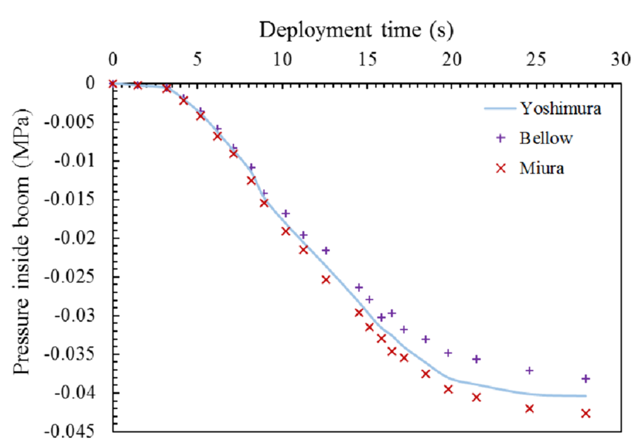


Fig. 12 Relation between boom pressure and deployment time for Case- I

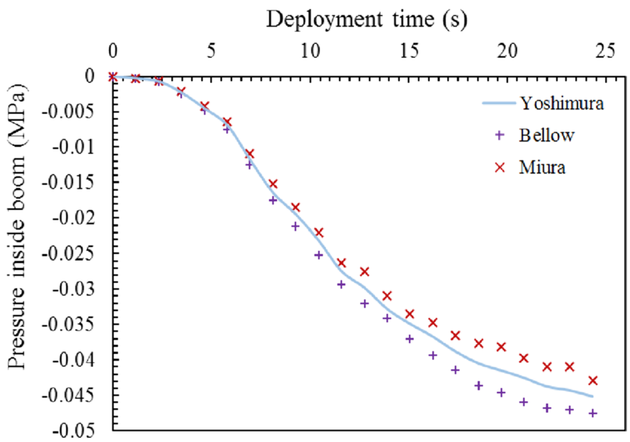


Fig. 13 Relation between boom pressure and deployment time for Case- II

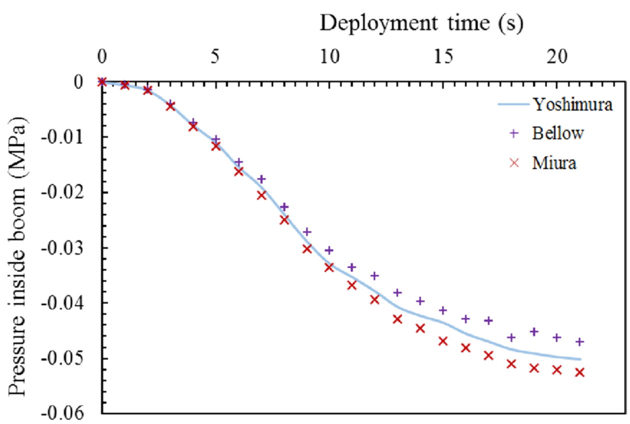


Fig. 14 Relation between boom pressure and deployment time for Case- III

the development of the pressure in the deployed boom. For the all three-fold pattern, the profile of the pressure drop approximately remains the same for the respective mass

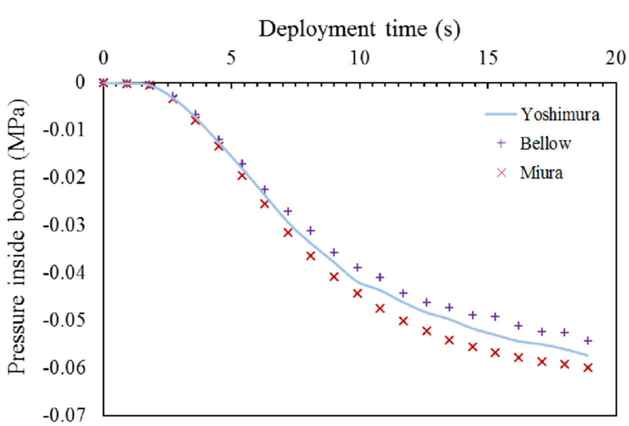


Fig. 15 Relation between boom pressure and deployment time for Case- IV

of the residue gases. Therefore, the total inflation time is minimum with Case IV. However, the mass penalty of the residue gases is more in Case IV. The total deployed height of the boom is more in Case I which subsequently signifies the initial stowed height is less in Case I.

Conclusion

This paper studies the residue gas inflation method for the complete deployment of the spaceborne inflatable boom through analytical, numerical, and experimental approaches. The effect of different mass of the residue gases along with three folding patterns on the deployment behavior is investigated. The novel relation was developed for the calculation of the safe mass of residue gases, which can be carried for the complete deployment of the inflatable boom. The developed analytical relation calculates the safe mass of residue gases inside the boom. Therefore, this study can be implemented to design and development of any size of the inflatable spaceborne boom. The results show that the total inflation time is inversely proportional to the mass of the residue gases. Through the comparative study, it has been observed that the change in the inflation time is negligible for different folding patterns with the same mass of residue gas. The result shows that the safe mass of residue gases successfully deploys the inflatable boom in vacuum environment condition, keeping the stresses in the boom within the tolerance limit. The residue gas inflation method is a simple and cost-effective solution for the inflation of spaceborne membrane structures. These findings provide insights for future research to investigate deployment characteristics of different shapes of inflatable spaceborne structures with different temperature and pressure conditions.

Declarations

Conflict of interest The authors have no conflict of interest to declare.

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