Characterization of a Pressurized Convoluted Metallic Flexible Hose under Large Bending Angles for Systems Engineering of High Pressure Swiveling Thruster

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Abstract

Metallic flexible hoses with convolutions and wire braiding are used for various of applications in the aerospace systems. One such application is for carrying a high temperature, high pressure gas for a roll control system of a core liquid stage of a launch vehicle. In this application, the flexible hose connects a fixed hot gas inlet rigid line to a swiveling thruster. The flexible hose undergoes bending in a single plane about an axis perpendicular to its length and located in between the two ends. The estimation of torque required to bend the pressurized flexible hose is needed for finalizing the design specifications of the torque motor used for swiveling the thruster. As the flexible hose is fabricated by mechanical/hydroforming process which induces plastic strain and the uncertainties associated with braiding stiffness makes accurate analytical modeling difficult. An experimental approach is adopted in this study for estimating the bending torques required for different bend angles with a specifically engineered unconventional and unique experimental set up. This study presents the results of bending tests performed on a convoluted metallic flexible hose with an internal pressure of 50 bar and assembled under stretched and un-stretched conditions for different offset distances from one of the ends. The roll thruster swivels by an angle of $\pm 60^{o}$*, which subjects the flexible hose to relatively large bending angles. A nonlinear variation of bending torque with bending angle was observed in this study. When the flexible hose is assembled in an un-stretched condition, a snapping behavior is observed during bending, in which the curvature developed in one direction suddenly shifts to the other side. A significant reduction in the snapping behavior was observed upon assembly in a stretched condition. The maximum torque required for bending the flexible hose to the desired swivel angle is estimated for different configurations of the experimental setup. Torque estimated from the testsis used for selecting the torque motor and for detailed systems engineering of the roll control system.*

Keywords: *Convoluted Metallic Flexible Hose, Systems Engineering, Roll Control System*

1. Introduction

Attitude control systems are an essential part of any launch vehicle, which create necessary moments as per vehicle guidance command. Roll control of a launch vehicle can be achieved via different methods depending on the configuration of stage. Here, a hot gas based roll control system is used for liquid stage of a satellite launch vehicle.

The system consists of two roll control thrusters positioned diametrically opposite and each thruster is swiveled upto 60º in vertical plane to generate control force and moments.Figure 1(a) shows the configuration of the system under discussion. Hot gas for the roll control system is tapped from engine. A piping consisting of a metallic flexible hose and rigid lines transports the hot gas from engine to the fixed end of the thruster-side metallic flexible hose. The thruster-side flexible hose carries the hot gas to the swiveling thruster.

The thruster-side metallic flexible hose has a total length of 1.26 m. The swiveling axis is perpendicular to the length of the flexible hose and is located at a distance of L_2 (flexible region length) from the swiveling end. Figure 1(b) shows the swiveled configuration of the flexible hose. This distance L_2 has been referred to as the offset distance from here on. The

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hot gas in the flexible hose is under a pressure of around 50 bar and a temperature above600 K. An estimate of the maximum torque required for bending the flexible hose to the desired swivel angle is needed for the of the torque motor used for swiveling the thruster. Further, the extent of variation of bending torque with bending angle and with offset distance (L_2) is also of interest from the torque motor control perspective. These parameters are necessary to derive the design specification of torque motor.

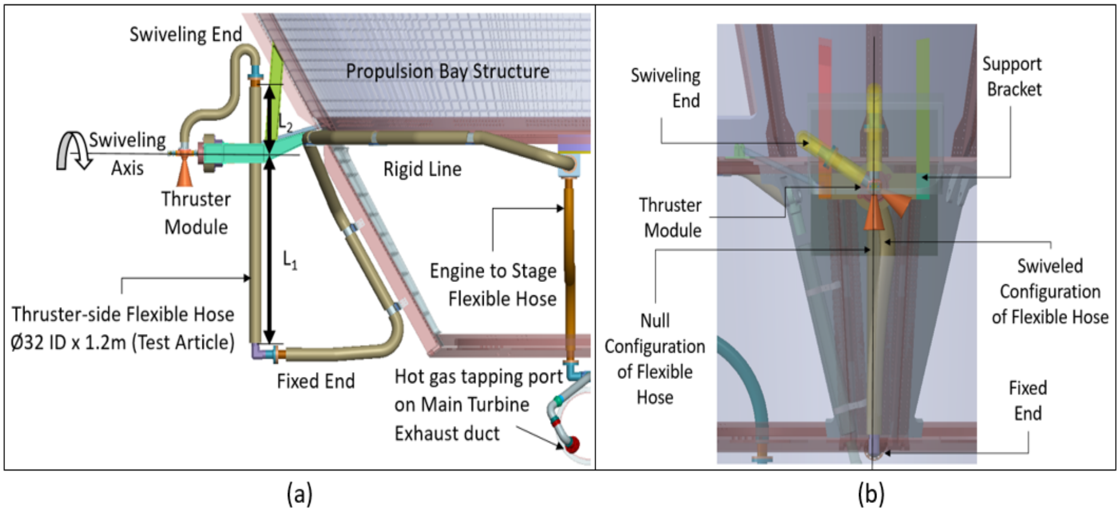

Figure 1: System Configuration

Figure 2 shows the prototype of theconvoluted metallic flexible hose made with SS321 and SS wire branding. The flexiblehose is fabricated by hydro or mechanical forming of SS304L sheets. Multiple braids of SS wiresare wrapped around the convoluted hose to provide axial strength against internal pressure. Deformation of convoluted portion under lateral loads imparts flexing action to the flexible hose assembly. The bending stiffness or in other words the torque required to bend the flexible hose depends on assembly configuration, offset distance L_2, and internal pressure.

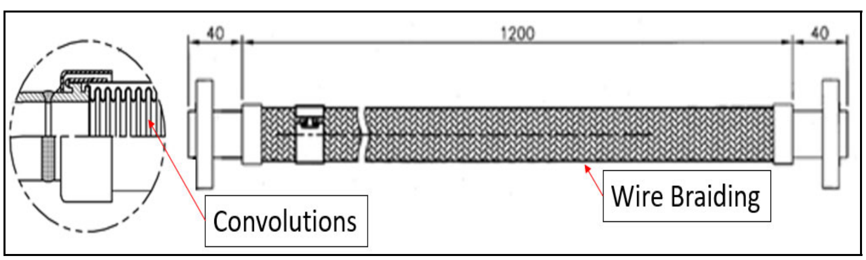

Figure 2: Convoluted Metallic Flexible Hose with Wire Braiding

Analytical estimation of bending torque requires mathematically modeling the kinematic and dynamic behavior of hose using finite element analysis techniques. Tsukimori in [1] presents a simplified theoretical modeling of creep behavior of bellows. Further, Tsukimori in [1] verifiestheoretical results with the analysis results obtained by FEM.Bechtin [2]provides a history of the development of bellows analysis methods and discusses directions requiring further development. Fatigue testing of bellows has been discussed by

Kobatake et al. in [3]. Kobatake et al. in [3] confirmed the applicability of an empirical equation for estimatingthe fatigue life from their analysis. Failure tests and finite element analysis (FEA) of the bellows structure were performed by Ando et al. in [4]. Ando et al.in [4] conclude that it is difficult to calculate final bellow structure shapes obtained in tests by implicit analysis. Sharma &Obaid in [6] present the FEM study on metal expansion bellows under axial and transverse loads. With the help of this analysis,the study confirms the safety of the design under applied loading. Anderson in [7] presents charts for simplified calculations for designing convoluted bellows.

Huang & Zhang in [5] discuss simulations and experimental studies on axial stiffness of the braided corrugated hose. The study finds good agreement between experimental data and simulations. This study can be used as a reference for modeling the braided corrugated hose. Paramasivan in [8] discusses the modeling of steel reinforced rubber flexible hoses. The study mainly focuses on modeling of helically wounded reinforcements. The estimation of bending stiffness through analytical approaches requires defining the material properties. A metallic flexible hose is fabricated by mechanical/hydroforming process, which induces plastic strain.

Hence, it is required to estimate the properties through coupon level testing of convoluted sections. The non-linearity in material property due to plastic behavior poses challenges in modelling the dynamics of flexible hose using FE analysis.

Further, the braiding on the convoluted part controls the axial strength of the hose. The braiding process being sensitive to workmanship and procedure followed, can lead to uncertainties in the initial condition (under equilibrium) of the hose.The FE model must account for the parameters like slackness of braiding and initial profile of convolution, which cannot be quantified and modeled precisely. Hence, the uncertainties associated with manufacturingprocess incur gross approximations in analytical modeling of the convoluted metallic flexible hose.Considering these factors, an experimental approach is adopted in this study for estimating the bending torques required for different bend angles. A specific, unconventional, and unique experimental setup has also been engineered for this purpose. Next, the configuration of experimental setup is briefly explained, followed by assembly of the flexible hose in different conditions, effect of offset distance from swiveling axis, and the effect of internal pressure on maximum bending torque.

2. EXPERIMENTAL SETUP

Figure 3 shows the configuration of test fixture engineered for carrying out the flexible hose bending test. The test fixture is designed such that it replicates the hose mounting configuration in actual flight stage. Fixed end of the flexible hose is attached at the top support plate in the test fixture, and the swiveling end is attached to the bottom support plate. Further, the tests have been conducted at room temperature, since the strength of the material degrades with temperature and hence, the results obtained from the room temperature tests will be conservative. The bottom support plate swivels about an axis which represented the thruster swivel axis. The offset distance (L_2) of the free end of flexible hose from swivel axis is set by an adjustable link.

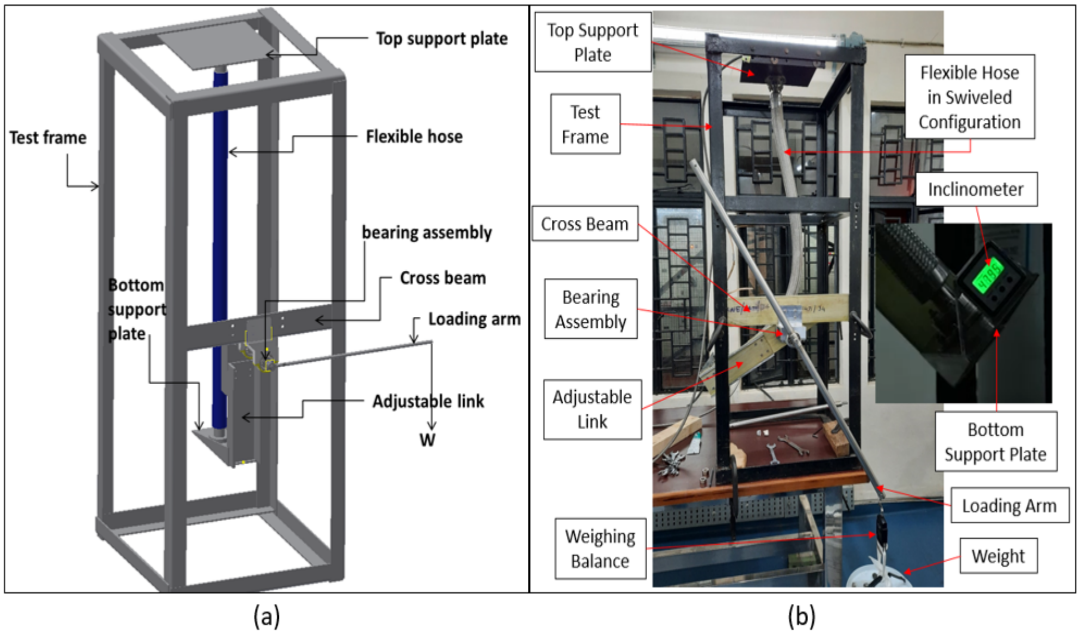

Figure 3: Configuration of Test Fixture

Change in the position of cross beam and length of the adjustable link allow for accommodating different offset distances. Ashaft connects the adjustable link and defines the axis of swiveling. A bearing assembly supports this shaft.The torque is applied by hanging a weight at the end of the loading arm. Figure 3(b) shows the realized experimental setup. A set of known weights at the end of the loading arm. The flexible hose is pressurized with gaseous N_2 at 50 bar.The weight put at the end of the loading arm is weighed using a weighing balance.The bend angle ( ) is measured by an inclinometer mounted on the bottom support plate.

The torque (T_{se}) applied due to the weight of loading arm, adjustable link, and bottom support plate was estimated by doing a trial without connecting the flexible hose. Hence, the net torque required to bend the flexible hose is given as:

$$T_{total} = (m_{load} . g . L_{arm}) . \cos(\ , \quad \therefore T_{hose} = T_{total} - T_{se}$$

3. Effect of Flexible Hose Assembly Condition

In the first configuration, the swiveling end of the flexible hose was assembled to the bottom support plate without pressurization (referred to as the assembly in free condition). Upon pressurization up to 2 bar, the flexible hose undergoes dilation of about 14 mm. The dilation in length is minimal upon subsequent pressurization up to 50 bar (total dilation 15 mm, refer Figure 4(a)).The axial dilation of hose is mainly due to slackness in braiding. For accommodating this additional length in the assembled configuration, the flexible hose develops a curvature at null position. Figure 4(b) shows this effect. Because of this curvature, a snapping behavior is observed, as shown in Figure 5.

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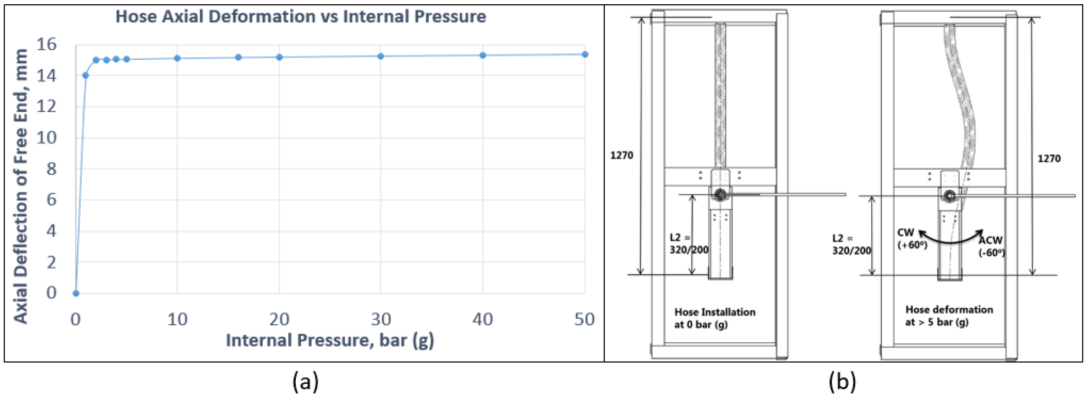

Figure 4: Dilation of Flexible Hose with Internal Pressure

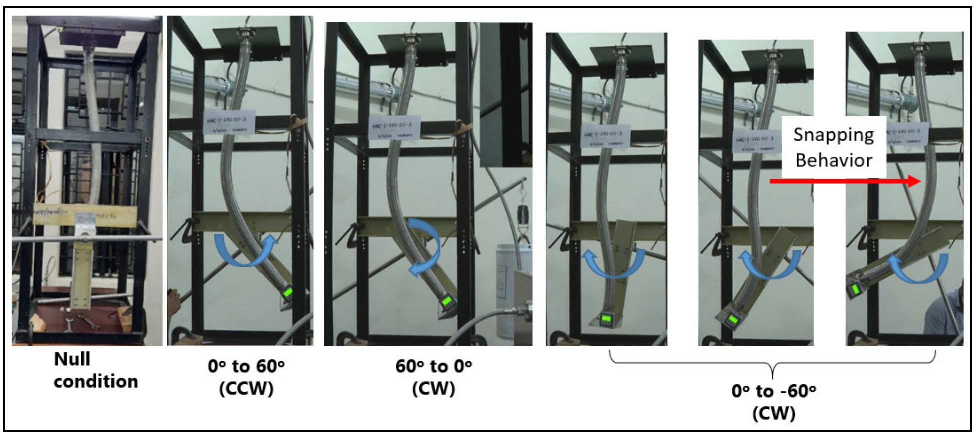

Figure 5: Snapping Behavior of the Flexible Hose

Implications of this effect is increased bending torque and non-uniform & non-linear variation of bending torque with bending angle. The torque and the dynamic characteristics of the hose are different for +60º (CW) bending vs -60º (CCW) bending, refer Figure 6.

When the hose is swiveled from 0º position to -60º position in CCW direction. The shape or the curved profile acquired by flexible hose is not in equilibrium for all bend angles. For small bend angles (up to 25º – 30º), a linear variation of torque with angular deformation (swivel angle) is observed. However, for bend angles between 30-40º, non-linear and abrupt change in torque vs swivel angle is observed in the tests. This attributed to change in geometric profile of the hose (i.e. the curvature of hose due to increase in length after pressurization). The curved shape of the hose is kinematically unstable between bend angles 30-40º for CCW bending, as shown in Figure 5. In this behavior, the curvature developed inside the flexible hose in one direction suddenly shifts to the other side during bending. This leads to a sudden drop in bending torque for increasing bend angle. Figure 6(a) shows this effect for the given assembly condition.

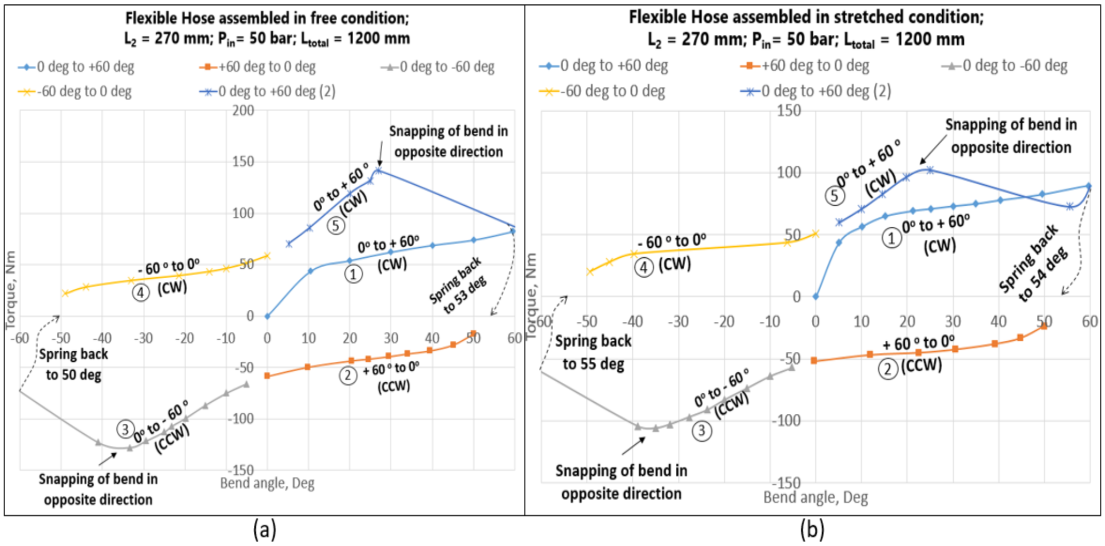

Figure 6: Variation of Bending Torque with Bend Angle for L_2 = 270 mm

In another configuration, the hose was installed after pressurizing it to 5 bar (a) (referred to as the assembly in stretched condition). The increase in hose length is accommodated by adjusting the cross beam, such that the hose is straight and vertical in null position after assembly. The subsequent dilation in the length upon pressurization up to 50 bar was minimal, and hence the curvature developed in the null condition was relatively lower. Figure 6(b) shows the variation of bending torque with bend angle for this configuration with flexible hose assembly in stretched condition. The maximum bending torque in the stretched condition (100 N.m) was considerably lower than the maximum bending torque observed in the free condition (140 N.m). This difference is attributed to the relatively lower development of initial curvature upon pressurizing the flexible hose, and as a result, the reduced snapping behavior.

4. EFFECT OF OFFSET DISTANCE FROM SWIVELING AXIS

The sensitivity of flexible hose bending torque to the offset distance has been studied by conducting further tests with a reduced offset distance of 150 mm.The flight configuration of support bracket, bottom fixed end, etc. were also revised and the flexible region length was reduced to 960 mm.A clamp was devised to help simulate the flexible hose of reduced length.Further, cyclic tests were also performed to understand the repeatability of the flexible hose behavior. Figure 7 shows the variation of bending torque with bend angle for assembly of the flexible hose in both free conditionand stretched condition for a reduced offset of 150 mm.In this case, the maximum bending torque observed for assembly of the flexible hose in the stretched condition was similar to the one observed for an offset of 270 mm. However, there is a significant reduction in the snapping behavior.

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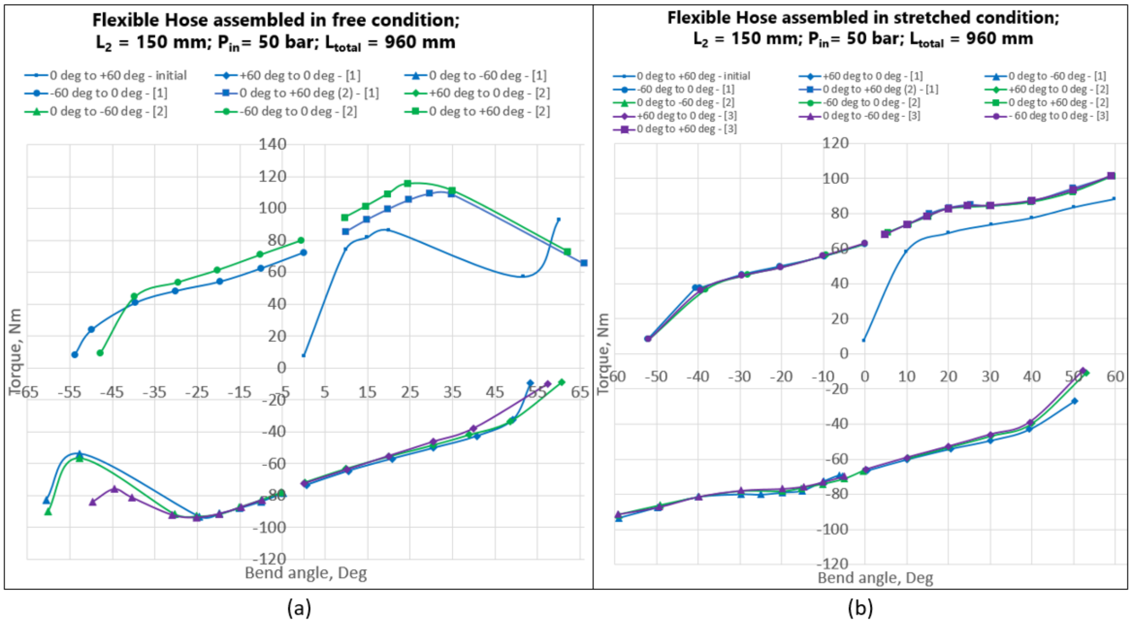

Figure 7: Variation of Bending Torque with Bend Angle for L_2 = 150 mm

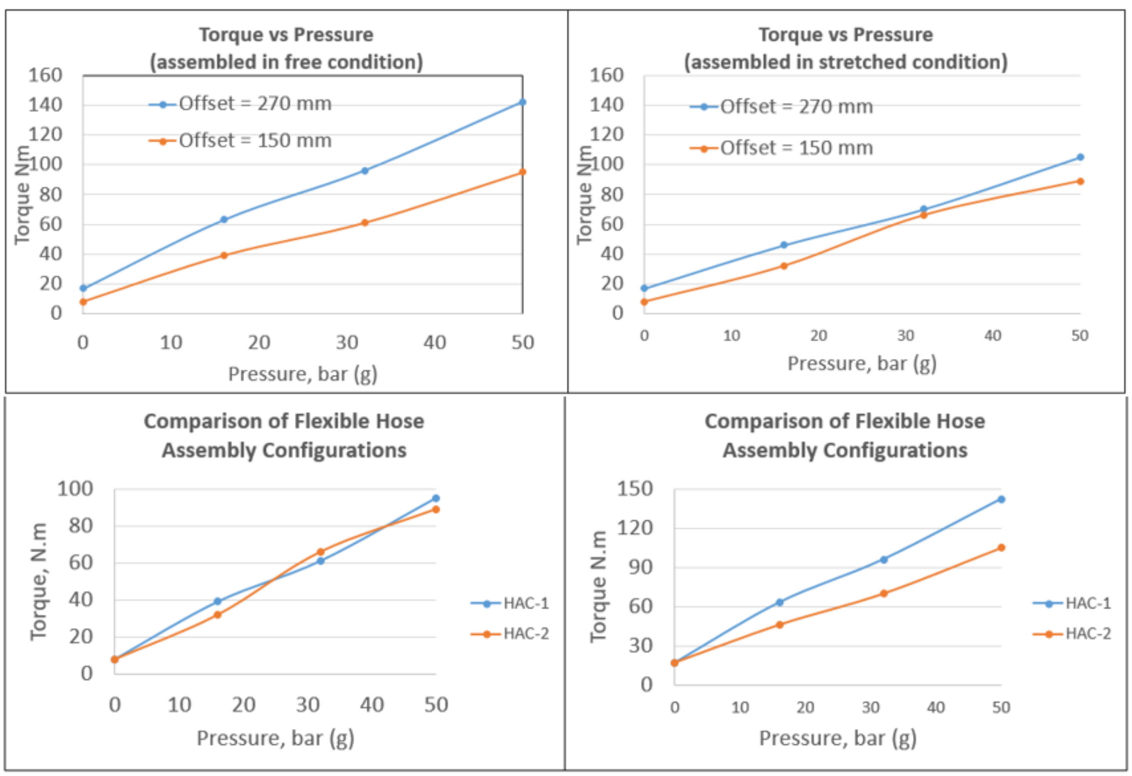

Figure 8: Variation of Maximum Bending Torque with Internal Pressure

5. EFFECT OF INTERNAL PRESSURE

Further tests were conducted with hose pressurized to internal pressure of 16, 32, 50 bar. Figure 8 shows the variation of maximum bending torque with internal pressure for both the offset distances (L2 = 270 mm and 150 mm). [NOTE: HAC: Hose Assembly Configuration, HAC-1: Assembly in free condition, HAC-2: assembly in stretched condition]

A significant increase in maximum bending torque is observed with increase in internal pressure. The difference in magnitudes of maximum bending torques is higher for assembly of the flexible hose in free condition. Further, the magnitudes of maximum bending torques are lower for the assembly of flexible hose in stretched condition.

6. OBSERVATIONS AND DISCUSSIONS

The peak torque (140 N.m) observed for assembly of the flexible hose in free condition for an offset of 270 mm and total flexible region length of 1200 mm was maximum among all the test cases. The peak torque for this offset distance reduced significantly upon assembly in the stretched condition. Some improvement in the snapping behavior was also observed because of this modification. Changing the offset distance to 150 mm with reduction in total flexible region length to 960 mm offered a slight increase in the peak torque. However, assembly in the stretched condition in this case, led to reduction in peak torque and a significant improvement in the snapping behavior. Table 1 summarizes the major observations made in all the different tests.

Table 1: Results for Flexible Hose Bending Tests for the Internal Pressure of 50 bar

Sr. No.	Total Flexible Length [mm]	Offset Distance (L_2) [mm]	Assembly Condition of the Flexible Hose	Peak Torque [N.m]	Snapping Behavior
1	1200	270	Free Condition	≈ 140	Significant
2	1200	270	Stretched Condition	≈ 100	Reduced
3	960	150	Free Condition	≈ 120	Considerable
4	960	150	Stretched Condition	≈ 100	Significantly Reduced

7. CONCLUSIONS

A specific, unconventional, and unique experimental setup was engineered and realized to experimentally verify the maximum bending torque requirement. This result was important for finalizing the design specifications of the torque motor used for swiveling the thruster. Number of experiments were carried outfor studying the effect of assembling the flexible hose in different conditions, effect of offset distance from swiveling axis, and the effect of internal pressure on maximum bending torque.

Based on the observations made from the test data, the offset distance of 150 mm with a total flexible region length of 960 mm, and a flexible hose assembly in the stretched condition was chosen as the desired configuration. This configuration requires considerably lower bending torque and offers almost linear variation of bending torque with bend angle. The major conclusions derived from the tests are summarized below:

(a) A significant increase in maximum bending torque is observed with increase in internal pressure. The difference in magnitudes of maximum bending torques is higher for assembly of the flexible hose in free condition.

(b) The maximum bending torques observed for an offset of 150 mm were lower than values for an offset of 270 mm, if we negate the change in total length. Further, a significant reduction in the snapping behavior was observed for an offset of 150 mm.

(c) The magnitudes of maximum bending torques are lower for the assembly of flexible hose in stretched condition as compared to the assembly in free condition.

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