10 STUDIES ON A NOVEL COMPLIANT DEPLOYABLE MECHANISM

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This paper investigates the deployment of stacks of three legged single degree of freedom parallel deployable mechanisms. All the revolute joints in the stacks are replaced with single axis flexural hinges. This minimizes the number of components and eliminates friction and backlash in the joints. Constant stiffness springs are used to model the compliant hinges. The novelty of this work is that it brings out a methodology for determining the stiffness of the flexures in each stack such that as they deploy, the individual stacks latch and rigidise progressively from the basal end which is crucial for structural stability of the deploying system. This paper also discusses the deployment controlled by a tether (string) attached at the center of the topmost stack to regulate its motion.

Keywords: Parallel mechanisms, Deployable mechanisms, Compliant hinges.

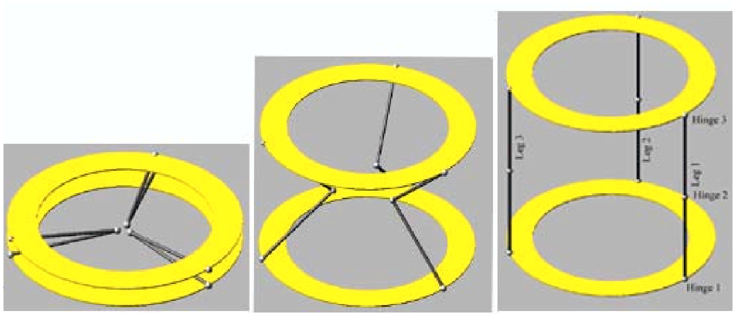
1. INTRODUCTION

Parallel mechanisms are closed loop mechanisms with a very wide range of utility.[3,6,7,10,11] A parallel manipulator with three legs and RRS (revolute, revolute and spherical) joints is known to have 3 degrees of freedom (DOF), the spherical joint situated between the legs and the top platform. If the spherical joint is replaced with a revolute joint, the system becomes an RRR configuration. This system has single DOF. Hence such a system can have only translation along y axis, i.e. the longitudinal axis of the parallel mechanism and can be used as a deployment mechanism along a single direction. If the rotary hinges are replaced by flexural hinges,[1,4,8] then the mechanism becomes self deployable due to inherent strain energy stored in the flexural hinges in the stowed configuration. Figure 1(A), (B) and (C) show the stowed, deploying and locked configuration at the end of deployment. This paper discusses the design of the flexural hinges of a single parallel mechanism and for a stack of mechanisms one above the other such that the mechanisms deploy and latch progressively from the basal end, which is essential for the structural stability of the deploying stack. The modeling and analysis is carried-out using ADAMS [12] software package.

2. MODELLING AND ANALYSIS OF A FLEXURAL PLATFORM MECHANISM

The mechanism is configured such that each link in the legs is 150 mm and the diameter of the platform is 320 mm. Hence the ratio of platform diameter (d) to leg length (l) ie., (d/l) = 1.067 which is greater than 1 as required for unhindered stowing. The deployment is possible because of the compliant hinges that are initially pre-rotated so that they have the requisite energy for the deployment of the same. Each such mechanism has 9 single axis flexure hinges, one at each of the nine joints. The flexure hinges have been modeled using torsion spring and bushing element in ADAMS.

After the deployment is over, the single DOF parallel mechanism becomes a structure as shown in Figure 1 C. Table 1 shows the forces in legs when the different forces and moments are applied at the



(A) **(B)** **(C)**

Figure 1. Shows a parallel manipulator deploying.

Table 1. Leg forces for loads applied one at a time at the center of top platform.

Load	Leg_1(N)	Leg_2(N)	Leg_3 (N)
Fx = 10N	6.340	6.623	6.623
Fy = 100N	33.33	33.33	33.33
Fz = 10N	6.660	6.396	6.446
Mx = 1000N-mm	0	3.600	3.600
My = 1000N-mm	1.17	1.107	1.107
Mz = 1000N-mm	4.157	2.079	2.079

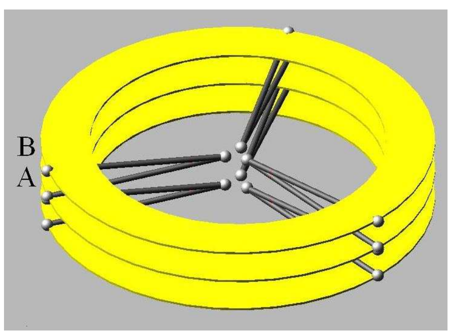


Figure 2. Two identical parallel mechanisms on top of each other.

center of the top platform in Figure 1C which clearly indicates that the configuration does not give rise to uncontrolled motion (class 2 singularity).[2,5,9]

Subsequently, two such mechanisms are put on top of each other as shown in Figure 2. The one at the base is termed as A and the other above it as B.

Both the stacks become a structure once they are allowed to deploy and latch. There may be three different ways in which the mechanisms latch when the two of them are considered together. In the first case, mechanism A latches first and followed by B. In the second case, mechanism B latches first and followed by A and in the third, both A and B latch simultaneously. In the second and the third cases (more in the second case), the system tends to oscillate as the base has not become a structure. The first case where A latches first, followed by B is the most preferable as this results in a stabler deployment and latchup.

3. PROGRESSIVE LATCHING — CONSTANT TORQUE HINGES

Initially single stack deployable system with all hinges acting as constant torque hinges (example: tape springs) were used. The minimum value of torque required so that the system could deploy and latch in $g = 0$ m-sec $^{-2}$ and $g = 9.81$ m-sec^{-2} was found out. The torque value comes out to be 60 N-mm.

Next, two stack system was considered. Here two different approaches are used to find the torque values. In the first approach, the torque requirement using hinge 2 (the hinge between the two links of each leg as shown in Figure 1) as the parameter fixing all other hinges at 60 N-mm was considered. This results in three hinges per stack whose values can be changed and the other six hinges whose values have been fixed. Hinge 2 of each leg in top stack is given a value of 60 N-mm at the center also. Then the value of torque required for hinge 2 of base stack is found out for a few values of spring torque. This is shown in table 2. As can be seen in case 4, for both $g = 0$ m-sec $^{-2}$and $g = 9.81$ m-sec $^{-2}$, the difference in the torque values between A and B for hinge 2 is rather large for the latching to occur in desired sequence, AB. Hence, the second method was used.

In the second approach, all the hinges of each stack have been used as the parameter. Equal amount of torque was given to each of the hinges. The torque at the hinges in top stack is taken as 60 N-mm. The corresponding torques required at the hinges at the base are determined and shown in Table 3. It is seen that for the desired sequence of latching, AB, the value of torque required has decreased because all the hinges are being used. Yet, the change in the torque values is large enough. This means an additional tape spring would be required for each stack from top to base as we increase the no. of stacks.

The analyses is carried-out for three stack system. As in the two stack case, the torque at all the hinges in the topmost stack, ie., C is taken as 60 N-mm. The corresponding torques in the lower stacks are evaluated and are shown in Table 4 along with latching sequences.

For the desired latch sequence of ABC for both $g = 0$ m-sec^{-2} and $g = 9.81$ m-sec^{-2}, the torque required in stacks A and B are reasonably high and are suitable for systems with fewer stacks. For larger number of stacks, we look at the scenario of using constant stiffness springs in place of constant torque spring hinges, which is addressed in the next section.

4. PROGRESSIVE LATCHING - CONSTANT STIFFNESS HINGES

The hinges are now given constant stiffness in the rotational axis and very high stiffness along all other directions to account for the flexural hinges. The bushing elements in ADAMS software are used to give the high stiffness in all other directions and torsional springs are given for rotation about z axis (rotational axis).[14] Initially, for a single stack, all the hinges are given a stiffness of 10 N-mm/deg.

Table 2. Latching sequence when torque values are changed.

Case.	A	B	Latching Sequence	
	N-mm	N-mm	g= 0 m-sec^{-2}	g= 9.81 m-sec^{-2}
1.	**60**	**60**	**BA**	**BA**
2.	120	60	BA	BA
3.	130	60	AB	BA
4.	**140**	**60**	**AB**	**AB**

Table 3. Latching sequence when torque values change in all the hinges of a stack.

Case.	A	B	Latching Sequence	
	N-mm	N-mm	g= 0 m-sec^{-2}	g= 9.81 m-sec^{-2}
1.	60	60	BA	BA
2.	90	60	BA	BA
3.	**100**	**60**	**AB**	**AB**

Table 4. Latching sequence when torque values change in all the hinges of the stacks.

Case.	A N-mm	B N-mm	c N-mm	Latching Sequence $g = 0$ m-sec^{-2}	$g = 9.81$ m-sec^{-2}
1.	**60**	**60**	**60**	**CBA**	**CBA**
2.	**80**	**70**	**60**	**CAB**	**CBA**
3.	100	80	60	CAB	CAB
4.	120	90	60	ACB	CAB
5.	140	100	60	ACB	ACB
6.	**180**	**120**	**60**	**ABC**	**ABC**

Table 5. Latching sequence when torque values change in hinge 2 only.

Case.	A	B	Latching Sequence	
	N-mm /deg	N-mm /deg	$g = 0$ m-sec^{-2}	$g = 9.81$ m-sec^{-2}
1.	10	10	AB	BA
2.	5	10	BA	BA
3.	**10**	**10.25**	**Simultaneous**	**BA**
4.	10	10.4	BA	BA
5.	**10**	**9.35**	**AB**	**Simultaneous**
6.	10	9.25	AB	AB

Also the hinges 1 and 3 are given pre-rotation of 90 deg and hinge 2 is given pre-rotation of 180 deg (refer Figure 1C). This provides the energy for the platform to deploy and latch. It has been checked by energy methods that the stiffness and pre-rotation is enough to cause the deployment and allow the system to latch.

4.1. Two Stack System

For two stacks system as shown in Figure2 earlier, the values of the hinge 1 and 3 in each of the stack is taken to be 10 N-mm/deg. Then taking hinge 2 in each leg as the parameter, various combination of stiffness with stack A and B are checked for the latching sequence. Table 5 shows such sequence.

From Table 2, it is clearly seen that for the hinge stiffness ratio of A/B less than 1, the latching sequence is BA (case 2 and 4) or simultaneous for a certain ratio when g=0 (case 3). For the ratio greater than 1, the latching sequence is always AB (case 6) or simultaneous for certain ratio for g=9.81 m-sec-2 (case 5). For A/B=1, the latching sequence is AB for g=0 and BA for g = 9.81 m-sec-2 (case 1). This shows that gravity has a role in latching sequence.

4.2. Three Stack System

Similar to two stack system, the three stack system was analysed in ADAMS software for various values of hinge 2 stiffnesses keeping the hinge 1 and 3 stiffness in each of the stack as 10 N-mm/deg. Table 6 shows the latching sequence for different gravity conditions.

It is clearly seen from Table 6 that there exists a ratio between the three hinge stiffness values for which these stacks latch simultaneously and this ratio is different for different gravity conditions. This is on similar lines with the results obtained in the two stack system.

An important observation from two stack analysis and three stack analysis is that for progressive latching, for decreasing stiffness values, if the decrement is less than the ratio for simultaneous latching, the three stacks latch in a progressive manner. This gave us a hint of how the hinge stiffness should be maintained for progressive latching from the basal end to occur.

Table 6. Latching sequence when stiffness values in hinge 2 only of each leg.

Case.	A	B	c	Latching Sequence	
	N-mm/ Deg	N-mm/ Deg	N-mm/ deg	g=0 m-sec^{-2}	g=9.81 m-sec^{-2}
1.	10	10	10	ABC	BA
2.	10	5	10	ACB	CAB
3.	5	10	10	BCA	CBA
4.	5	5	10	CAB	CBA
5.	**10**	**10.3**	**10.629**	**Simultaneous**	**CBA**
6.	10	10.4	10.816	CBA	CBA
7.	10	9.5	9.025	ABC	CBA
8.	10	9	8.1	ABC	ABC
9.	**10**	**9.35**	**8.74225**	**ABC**	**Simultaneous**

Similarly, analysis was carried-out for four and five stacks on the above approach and the results were as desired. Finally the analysis showed an anomaly when 10 stack system was used. With the values of stiffness for stacks as 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 N-mm/deg for stacks from top to base, the latching sequence was not progressive from the basal end. This was due to the energy needed by the top stack was lesser to deploy and latch than what was being given and hence it had to be reduced. Further, stack B required more energy than being given for latching.

In order to overcome the above anomaly, all the hinges were used as parameters this time. With all the nine hinges of a stack having same values, the analysis was done with 1 stack, 2 stacks, 3 stacks, 4 stacks, 5 stacks and 10 stacks system. It was found that the deployment and latching sequence was from the basal end as desired. The value of the hinge stiffness used in each stack and in each hinge of the stack for a 10 stack system is as follows:

[J I H G F E D C B A] = [1 2 3 4 5 6 7 8 9 10] in N-mm/deg, J being the stiffness of the top stack and downward in the same order to the basal stack being A.

Having obtained a progressive latching sequence upto ten stacks in series with the stiffnesses of all nine flexure hinges in each stack being equal, further analysis is carried-out to find an optimized ratio between the stiffnesses such that this result could be generalized to a deployable system with a number of stacks in series.

5. OPTIMIZATION FOR GENERALIZATION

The minimum value of stiffness required for a single stack to deploy and latch is found out first. All the nine hinges in a stack is assumed to have the same spring stiffness. A preload of 1.1 kg is given to each of the stack acting at the center of the top platform to simulate a payload.

5.1. Optimization of Single Stack System

The first step was to determine the minimum value of stiffness of a single stacked system. The value of the stiffness of all the flexural hinges was taken to be the same. The results are found with both g=0 and g=9.81 m-sec-2. The result of the experiment with the first stack system gave us the required minimum value of the stiffness at the hinges as 3.05 N-mm/deg. By energy method, the energy required for the system to deploy and latch is calculated as follows:

Energy Required = mass of platform * g * displacement along y axis + mass of legs * g * displacement of center of mass (c.m.).

= 665.303 N-mm + 2955.055 N-mm

= 3620.358 N-mm.

The energy given by springs when stiffness value is 3.05 N-mm/deg is = $\frac{1}{2}$ n1 K $(\pi/2)^2$ + $\frac{1}{2}$ n2 K $(\pi)^2$ where K is the stiffness value, n1 is the no. of hinge1 and hinge3 in the stack which have a pre-rotation angle of 90 deg and its value is 6, n2 is the no. of hinge2 in the stack which has a pre-rotation value of 180 deg and its value is 3. The energy comes out to be 3880.652 N-mm which is more than the energy required with a small positive margin.

The gravity acting downwards makes it tougher for the hinges to push the system in upward direction (+ve y axis) as a constant force of 'mg' (mass x gravity) is present with the legs as well as the all the upper platforms which are not fixed as base. Hence the stiffness requirements increase when the gravity is available. Thus the cases run with gravity always hold for cases run without gravity as the stiffness requirements are less without gravity. This has been verified in all the models.

5.2. Optimization of Two Stack System

In case of two stack system, both the stacks have to deploy and hence the sequence of latching comes into play. The sequence of latching, as already explained is always desired to be from base stack to the top stack.

The steps followed for finding the minimum values of hinge stiffness required for two stack system are:

1. Take the hinge stiffness of stack B as the stiffness of first stack system i.e. 3.05 N-mm/deg.
2. Find the hinge stiffness of A required for deploying in requisite sequence.
3. Find the minimum value of hinge stiffness of B required for latching such that the latching sequence is AB.

There are two conditions that have to be met in each of the above mentioned steps when finding the stiffnesses.

1. The base stack has to latch first. i.e. stack A latches first in all the cases.
2. The angle between the links of the legs of stack A should be greater than that of stack B. Figure 3 shows such criteria diagrammatically. $\theta 2 > \theta 1$ is the required criteria.

Figure 4 shows the value $\theta 2 - \theta 1$ is always greated than. The value of the stiffness of the hinges comes out to be [A B] = [3.77 3.00] N-mm/deg.

5.3. Optimization of Three Stack System

Similar to the way the two stack system was optimized to the minimum values of the hinge stiffness required, the three stack system was also optimized. All the considerations required in the two stack systems were put up with the systems in three stack system.

The initial stiffness taken was as follows: [B C] = [3.77 3.00] in N-mm/deg

First the minimum value of required hinge stiffness of stack A was found out. Then the minimum stiffness requirements of all the three stacks were found out as described in section 5.2. The final stiffnesses are:

[A B C] = [4.54 3.75 2.95] in N-mm/deg. Figures 5, 6 and 7 show that the criteria of $\theta 3 > \theta 2$ and $\theta 2 > \theta 1$ is always positive throughout the deployment and at the time of latchup.

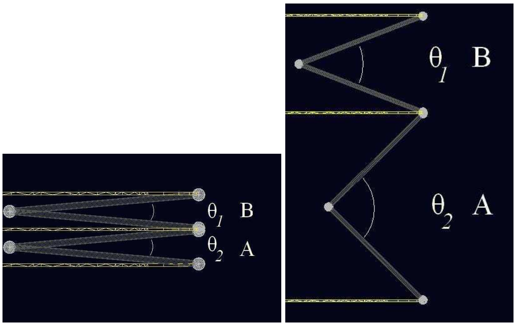


Figure 3. Criteria of optimization for two stack system.

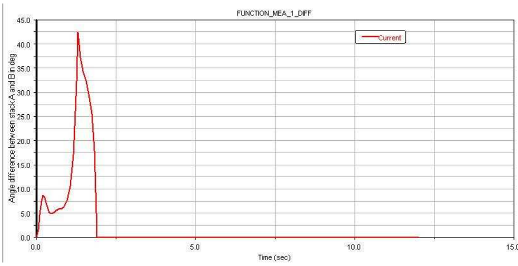


Figure 4. Graphical representation of $\theta 2$ - $\theta 1$.

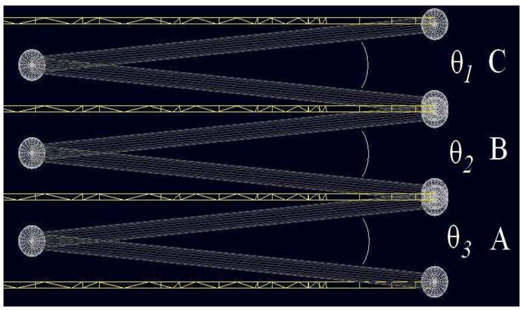


Figure 5. Wire-frame model of one portion of the three stack system.

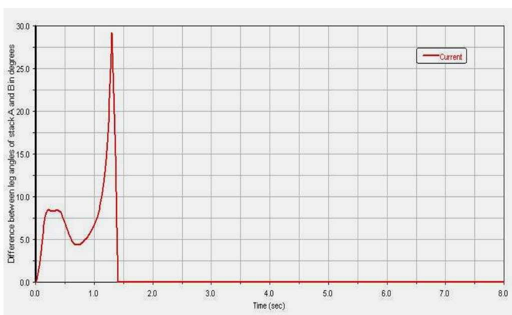


Figure 6. Difference of leg angles between stack A and stack B.

5.4. Optimization of Four, Five, and Six Stack System

Similarly, stiffness requirement of four, five and six stack system was found out. The stiffness requirements for four stack system are: [A B C D] = [5.31 4.51 3.70 2.92] in N-mm/deg.

The stiffness requirements for five stack system are: [A B C D E] = [6.09 5.29 4.43 3.65 2.88] in N-mm/deg. The stiffness requirements for six stack system are: [A B C D E F] = [6.88 6.08 5.21 4.40 3.60 2.84] in N-mm/deg.

5.5. Generalization of Stiffness Values for 'n' Number of Stacks

Ratios of the hinge stiffness of the abutting stacks were taken next. This is shown in Table 7. Here rows show the ratio between the hinge stiffness requirements in two abutting stacks. Column represents single system with no. of stacks. As we can see, in any of the systems, the ratio between the two

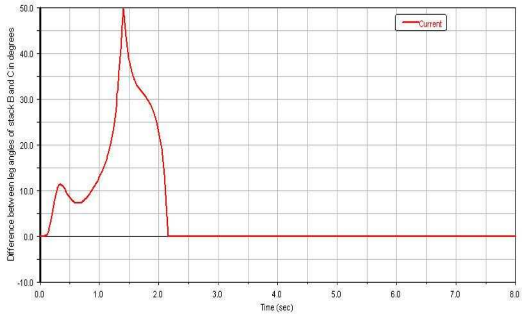


Figure 7. Leg angle between stack B and stack C.

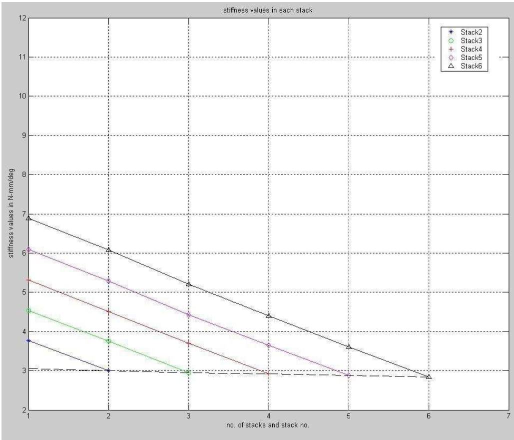


Figure 8. Leg angle between stack B and stack C.

topmost stacks is the highest. Figure 8 shows the stiffness values of hinges in different stacks for two, three, four, five and six stack system. The variation in stiffness values in the different stack systems is found to be linear.

From section 5.3 and 5.4, it is seen that the hinge stiffness required for the top stack keeps on decreasing as the number of stacks in the system increases. These graphs are shown for system till 6 no. of stacks as the results have been found till 6 stacks system only. Also from Figure 8 and table 7 that if the hinge stiffness of the top stack in any system with ‘n’ stacks, the highest stiffness ratio between the two abutting stacks, the hinge stiffness value of the top stack and same stiffness ratio for finding the hinge stiffness requirements for all the stacks can be found out for ‘n’ no. of stacks deploying in the desired sequence.

6. REGULATION OF DEPLOYMENT: TETHER SYSTEM

It is desirable to minimize velocity at the end of deployment up as it reduces the shock at latch-up. This is achieved by regulating the deployment using a string (tether[9]). One end of the tether is connected to the center of the top platform of the topmost stack and the other is connected and controlled by a motor mounted at the fixed base platform at the basal end. We use the varying tension in the tether to control the motion of the deployment. Since this is equivalent to a force acting downwards, it does not alter the sequence of latching. The analyses was done for the system under zero gravity conditions.

Table 7. Ratios between the stiffness values of each stack in a system.

Stacks	Two	Three	Four	Five	Six
E/F					**1.268**
D/E				**1.267**	1.222
C/D			**1.267**	1.214	1.184
B/C		**1.27**	1.219	1.194	1.167
A/B	**1.257**	1.211	1.178	1.151	1.131

6.1. Single Stack System with Tether

Firstly, a tether is used with the single stack system. The minimum tension in the tether, F1, the equilibrium tension in static condition is found out. At F1, there can be no motion in the stacks. Now the maximum tension, F2, which when applied by the tether on the platform can deploy the stack is found out. The stiffness of the hinges used is 3.05 N-mm/deg. The tensions F1 = 17N and F2 = 12 N are evaluated. The tether was given a linearly varying tension from F1 to F2 to occur ina time of 10 secs. Also, the more the time taken for the deployment, i.e. the more the time it takes for the tension to decrease from F1 to F2, the lesser the shocks and better the deployment.

6.2. Two Stack System with Tether

The two stack system was controlled similarly as the single stack system. F1 and F2 is found as for single stack system. Next, the difference of F1-F2 is given in the tether with the motor it is attached to. The time required for each stack being 10 sec. The total time for the force to vary is given as 20 sec. The stiffness of the hinges in the stacks used is as follows:

[A B]=[3.77 3.00] in N-mm/deg.

Tension F1=21N and Tension F2=14 N. There exist two values of tensions in the tether between 21N and 14N for which each of the stacks deploy. Let them be F3 and F4 where F3>F4. When the tension in tether falls from F1 to F3, the stack A starts deploying. It keeps deploying as the tension in the tether keeps decreasing with time. When the tension in the tether reaches F4, stack B also starts deploying. Hence this way both the stacks deploy.

Hence the same way tension values for 3, 4 and 5 stacks were found out. Till the five stack system, there is a very good relation that can be seen among the tensions F1 in all the systems. Also, a relation exists between the tensions F2, in these stacks. It can be seen that except in the two stack system, F2 is equal for all other systems. Figure 9 shows the graph between the no. of stacks in the system to the

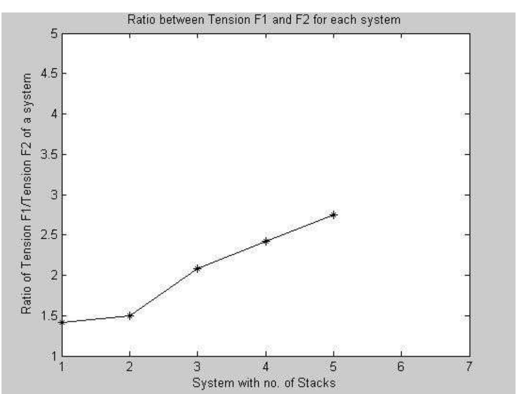


Figure 9. F1/F2 with no. of stacks in system.

ratio of tensions F1/F2. The results have been found upto 5 stack systems. Hence it can be seen that the tether system can also be designed in such a way that a general solution is possible for the same.

This deployable mechanism thus discussed has potential application in spacecraft where a payload or a manipulator is required to be mounted at certain distance from it in orbit.. The tether is used to control the acceleration with which it deploys. The tether is attached to the manipulator top platform. After the deployment is over, the tether is unhooked from the manipulator top platform to enable manipulation.

7. CONCLUSION

This paper presents the detailed studies carried-out for a novel compliant deployable mechanism with several three legged parallel mechanisms in series with an aim to deploy from the basal end progressively and latchup at the end to become a structure. The analysis of deployable stack system with constant torque hinges up-to three stack system with $g = 0$ m/sec^2 and 9.81 m/sec^2 is carriedout. Further, the analysis of deployable stack system with constant stiffness hinges up-to 10 stack system with $g = 0$ m/sec^2 and 9.81 m/sec^2 is reported. This is followed by optimization of hinge stiffness for zero 'g' and '1g' gravity conditions up-to 6 stack system for progressive latching from the basal end. Further, controlled deployment of the stacks with a tether upto to 5 stacks are reported. A novel methodology for determining the stiffness of the compliant hinges in the different stacks for a progressive deployment and latchup from the basal end is effectively broughtout. This work has got significant applications in the domain of aerospace.

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