Modelling, Simulation and Control of a Foldable Stair Mechanism with a Linear Actuation Technique

V.S.Rajashekhar¹*, K.Thiruppathi², R.Senthil³

¹,²School of Mechanical Engineering, SASTRA University, Thanjavur, 613410, India
³Dept. of Mechanical Engineering, Adhiparasakthi Engineering College, Melmaruvathur, 603319, India

Abstract

In places where there is a space restriction, a foldable stair can be used. In accordance with this, we have simulated a mechanism in which the unfolding and folding of the stair is due to the linear motion of the slider at one end. The effect of the change in length of connecting rod that converts linear motion to rotary motion is to be analyzed. Here we consider 10 different lengths of the connecting rod. The force needed to move the slider is measured using MSC ADAMS™ software in each of these cases. Then a linear actuation circuit for the slider using a double acting cylinder is designed and simulated using Festo FluidSIM™ software. Thus in this paper we present the effect of change in length of the connecting rod by considering the force needed for actuation and the linear distance to be moved by it.

Keywords: Foldable stair; crank and slider; four bar mechanism; linear actuating mechanism; Scissor like structure

1. Introduction

Foldable stair mechanism can be used in places where there is not enough space for a fixed stair. A four bar mechanism is used to actuate the scissor like elements (SLE) which form the foldable stair mechanism. Stiffness and strength of the links play an important role in this mechanism [1]. Structural synthesis, analysis of the geometry of the links and statics of the structure were performed and the foldable stair model was manufactured [2]. While the links are actuated, the structure of the mechanism changes and the mobility in the metamorphic mechanism are analyzed [3]. Scissor like platform can be used in vertical lifting of objects in industries [4] which can be modified

© 2014 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license
Selection and peer-review under responsibility of the Organizing Committee of GCMM 2014

* Corresponding author. Tel.: 9600046390
E-mail address: vsrajashekhar@gmail.com
to make the foldable stair mechanism. A planar gate mechanism and a cylindrical deployable structure can be created using scissor like elements [5]. A new kind of scissor-hinge structure, planar in nature called as Modified Scissor-Like Element (M-SLE) is used to produce translational and curvilinear scissor-hinge systems. Linear actuators are used in this case to actuate the mechanism. Circular and non-circular arches can be built using this mechanism [6]. Spatial scissor-hinge structural mechanism (SSM) is used to form arch-like, dome-like and double curved shapes using actuators, which are stable in nature and carry loads [7]. Scissor structures are suitable for making disaster relief shelters due to its light weight and high volume expansion ratio. Their parts can be reused by reconfiguring their structure [8]. A nonlinear vibration isolation system for the scissor like structure was designed using linear springs and damping components [9].

In this paper we use a linear actuator to actuate the crank in the crank and slider mechanism instead of rotary actuator which was used in previous foldable stair mechanism [1]. Here a combination of crank and slider mechanism and four-bar mechanism are used along with the scissor like elements to perform the foldable stair mechanism. By controlling a double acting cylinder using a 5/3 direction control valve, stoppage of the foldable stair mechanism at intermediate levels can be obtained. Moreover by using a 5/3 direction control valve there is no force needed externally to hold the foldable stair mechanism when it is working.

2. Mechanism of the foldable stair

The foldable stair mechanism consists of links arranged in vertical and horizontal manner that make up the stair like arrangement. These links are connected with each other using revolute joints. The crank in the crank and slider mechanism, which pulls the entire set of links up or down makes the stair like arrangement. This crank also acts like an input link for the four-bar mechanism. This folding and unfolding of the stair resemble the scissor like structure. The crank is connected to the connecting rod through a revolute joint, which moves due to the actuation of the slider. The slider moves linearly due to the translatory motion exhibited by the linear actuator. The construction of the mechanism is as shown in Fig 1. Two sets of this planar mechanism are placed parallel to each other at an offset distance. The horizontal links in the two sets are connected together by using a bar over which the foot of the user is placed.

![Fig. 1. Parts of the foldable stair mechanism](image)

2.1 Parts of the foldable stair mechanism

2.1.1 Vertical links

The vertical links are connected to the horizontal links at two or three points. It is used to fold or release the horizontal links when it is actuated by the crank. They decide the height of each step in the stair.

2.1.2 Horizontal links

They are connected to the vertical links at two or three points through a revolute joint. It is used to provide a platform where the foot of the user can be kept. It decides the length of each step in the stair.
2.1.3 Slider
The slider is used to actuate the mechanism due to its linear motion. It moves due to its attachment to the rod of the double acting cylinder at one end. The other end is joined to the connecting rod through a revolute joint.

2.1.4 Connecting rod
It is connected to the slider through a revolute joint at one end and the other end is connected to the crank and coupler of the four-bar mechanism through a revolute joint. The connecting rod is utilized to transfer the linear motion of the slider to the rotary motion of the crank. By varying its length, the linear force needed for actuation and the linear distance to be moved by the slider varies which is studied in detail in this paper.

2.1.5 Crank
The crank is used to transfer the motion from the connecting rod to the coupler. When it rotates, the motion is transferred to the horizontal link (coupler of the four bar mechanism) which further causes the folding or unfolding of the foldable stair mechanism.

3. Orientation and force transfer
The foldable stair mechanism consists of links and joints. The slider moves with a force $F_1$ along the -X axis, which pulls the connecting rod forward. The force $F_2$ exerted by the connecting rod rotates the crank about the revolute joint $R_3$ which is about the global Z axis. Due to this, the horizontal links (coupler) move up in the XY plane which in turn rotates the vertical links and makes the stair in the folded position. While expanding the folded stair mechanism, the force $F_1$ acts in the opposite direction (+X axis) which in turn pushes the connecting rod thereby rotating the crank in the opposite direction. Thus the folding and expansion of the foldable stair mechanism takes place. The force transfer during unfolding of the foldable stair mechanism is represented in Fig 2.

![Fig. 2. Forces acting during folding of the foldable stair mechanism](image)

4. Working of the foldable stair mechanism
The slider moves linearly (-X axis) and pulls the connecting rod backward. The connecting rod in turn rotates the crank and at the same time pulls the coupler of the four bar mechanism forward. The coupler in turn pulls the vertical links which in turn pulls the horizontal links upward. This makes the stair to be in the folded position. When the stair needs to be unfolded, the slider moves along the +X axis which pushes the connecting rod forward. This rotates the crank which in turn pushes the coupler forward. This causes the vertical links to move thereby unfolding the stair. The working is as shown in the Fig 3.
5. Choosing the dimensions of foldable stair mechanism

The volume in which the mechanism is to be implemented is taken to be 1650x750x1000mm (length*breadth*height). This volume is suitable for heavy trucks to manually load and unload and in storage places for human to climb and place the goods. The initial distance between the pivot point of the crank and the slider is taken in the range between 0mm and 800mm for 10 cases. This is due to the space consideration in the volume. The stroke length for ten cases is chosen between 130mm and 300mm due to the availability of the linear actuators in this range [10]. Based on the initial distance between the pivot point of the crank and the slider, and the crank length, the length of the connecting rod is calculated in each of the 10 cases. The length of the connecting rod ranges between 150mm and 820mm. Considering the force needed to actuate and the stroke length, a FESTO PNEUMATIC double acting cylinder is chosen [10].

6. Modelling of the foldable stair mechanism

The foldable stair mechanism was modelled using Solidworks™. The volume of space was decided based on the height to be reached. The links including crank, connecting rod and coupler were modelled. Two sets of scissor like mechanism were made parallel to each other. The horizontal links in the two sets are connected together using a cuboid structure. It serves as a platform to keep the foot while the user is moving on it. The model is as shown in Fig 4.
7. Simulation of the foldable stair mechanism

The model was imported from Solidworks™ to MSC ADAMS™. The joints were given to the links based on the motion required. The extent to which the slider has to move with respect to time was assigned to the translational joint. The simulation was carried out and the mechanism was successfully tested for its performance. It is as shown in the Fig 5. Initially the stair is unfolded (Fig 5(a)). When the force is applied on the slider, the stair starts to fold (Fig 5(b)). When the maximum stroke length is reached, it becomes fully folded (Fig 5(c)).

![Fig. 4. Modelling of the foldable stair mechanism](image)

The force required in the translation joint was measured after simulation. The forces needed to pull the connecting rod in each of the 10 different cases were plotted against time. The minimum length of the connecting rod was taken to be the length of the crank. The maximum length was taken based on the available space to place the mechanism and the maximum length of stroke by the linear actuator. The forces obtained during one stroke of folding and unfolding are as shown in the Fig 6 and the maximum force needed in each of the cases are tabulated.
below in Table 1.

![Diagram of force vs time for connecting rods of varying lengths](image)

Fig. 6. Force vs Time for connecting rod of length (a) 150mm (b) 180mm (c) 250mm (d) 336mm (e) 427mm (f) 475mm (g) 522mm (h) 618mm (i) 716mm (j) 814mm

8. Stress analysis of the connecting rod

The critical part of the foldable stair mechanism was identified as the connecting rod. The connecting rod with the varying linear force acting on it is to be tested. In order to analyze the stresses acting on it, ANSYS™ software was used. The connecting rod was modeled and meshed for each of the ten cases and the forces obtained from MSC ADAMS™ were applied to it. The material was considered to be stainless steel. The results obtained showed that the stress concentration is high at the ends. They are as shown in Fig 7.
Fig. 7. Von-Mises stress for connecting rod of length (a) 150mm (b) 180mm (c) 250mm (d) 336mm (e) 427mm (f) 475mm (g) 522mm (h) 618mm (i) 716mm (j) 814mm
9. Design of the linear actuation circuit

The slider needs to be actuated linearly in order to perform the folding and unfolding operation of the foldable stair mechanism. In order to make this possible, a pneumatically actuated double acting cylinder is used. It is controlled by a 5/3 push button operated valve. Values for force, maximum stroke, piston position, piston area and ring area are given as input to the double acting cylinder. The force and maximum stroke are taken based on the values obtained in MSC ADAMS™ during the simulation. The velocities of the plunger during the forward and return stroke are measured in each of the ten cases using FluidSIM-P™ software by giving force and stroke length as input. The value of the velocities is presented in the Table 1. The pneumatic circuit designed and simulated using FluidSIM-P™ software is as shown in the Fig 8.

![Linear actuation circuit with double acting cylinder in (a) retracted position (b) holding position (c) extended position](image)

**Fig. 8. Linear actuation circuit with double acting cylinder in (a) retracted position (b) holding position (c) extended position**

10. Effect of the change in length of connecting rod on various parameters

The change in length of connecting rod causes the force needed for actuation to change. It also influences the length of stroke. The velocity of the plunger during the forward and return stroke is also influenced due to the change in length of the connecting rod. These are as shown in the Table 1.

<table>
<thead>
<tr>
<th>Length of the connecting rod (mm)</th>
<th>Force needed in the linear actuator (N)</th>
<th>Linear distance to be moved/Stroke length (mm)</th>
<th>Initial Linear distance between crank and slider (mm)</th>
<th>Velocity of the plunger during forward stroke (mm/s)</th>
<th>Velocity of the plunger during return stroke (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>4.5x10^7</td>
<td>285</td>
<td>0</td>
<td>110</td>
<td>340</td>
</tr>
<tr>
<td>180</td>
<td>170</td>
<td>220</td>
<td>100</td>
<td>110</td>
<td>320</td>
</tr>
<tr>
<td>250</td>
<td>150</td>
<td>190</td>
<td>200</td>
<td>110</td>
<td>290</td>
</tr>
<tr>
<td>336</td>
<td>125</td>
<td>180</td>
<td>300</td>
<td>110</td>
<td>280</td>
</tr>
<tr>
<td>427</td>
<td>114</td>
<td>170</td>
<td>400</td>
<td>110</td>
<td>260</td>
</tr>
<tr>
<td>475</td>
<td>95</td>
<td>165</td>
<td>450</td>
<td>110</td>
<td>250</td>
</tr>
<tr>
<td>522</td>
<td>92.5</td>
<td>160</td>
<td>500</td>
<td>110</td>
<td>250</td>
</tr>
<tr>
<td>618</td>
<td>90</td>
<td>150</td>
<td>600</td>
<td>110</td>
<td>250</td>
</tr>
<tr>
<td>716</td>
<td>81</td>
<td>140</td>
<td>700</td>
<td>110</td>
<td>240</td>
</tr>
<tr>
<td>814</td>
<td>73</td>
<td>130</td>
<td>800</td>
<td>110</td>
<td>230</td>
</tr>
</tbody>
</table>

It is observed that the force needed to actuate the slider decreases as the length of the connecting rod increases. This variation is as shown in the graph in Fig 9(a). When the length of the connecting rod is equal to the crank length in the crank and slider mechanism, the force required to actuate the slider is extremely high. As the length of the connecting rod increases, the stroke length decreases. It is as shown in the graph in Fig 9(b). When the length of the connecting rod increases, the initial distance between the crank and slider also increases. The velocity of the plunger during the forward stroke is constant as the length of the connecting rod increases. It is also inferred that the
velocities of the plunger during the return stroke decreases with increase in the length of the connecting rod. These are as plotted in the graph as shown in Fig 9(d).

Fig. 9. Graphical relationship between the length of the connecting rod and other parameters

11. Conclusion

Thus in this paper, a foldable stair mechanism actuated linearly is designed and discussed in detail. There are two such sets of mechanism placed at an offset distance from each other. The horizontal links in the two sets are connected together using a bar over which the foot of the user can be kept. The length of the connecting rod in the crank and slider mechanism places an important role in deciding the force needed for actuation and stroke length required. Thus ten different lengths of connecting rod are taken into account and the force needed and stroke lengths required for actuation were analyzed. The mechanism was modelled and simulated to verify its working. Then stress analysis for the connecting rod for ten different lengths (by giving the forces as input) was carried out and their results are presented. The effect of force needed for slider actuation, stroke length of the slider, initial linear distance between the crank and slider, velocity of the plunger during the forward and return strokes were analyzed by changing the length of the connecting rod in the crank and slider mechanism.

References


