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SOLID MECHANICS

INFLUENCE OF MOUNTING POSITION OF HYDRAULIC CYLINDER IN SCISSOR LIFT ON ITS WORKING PERFORMANCE

TRINH DONG TINH*
Hanoi University of Science and Technology, Hanoi, Vietnam

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ABSTRACT: This paper presents research on the single scissor lift about two problems: the influence of the mounting position of the hydraulic cylinder on its required actuation force and evaluating the suitability of the selected cylinder length to meet the required lifting height of the load. The results show that when the cylinder is mounted at an inadequate place, the lift cannot reach the require working height. Moreover, the mounting position of the cylinder has a significant effect on the required actuating force of the hydraulic cylinder: this required force varies in a wide range from 4.1 to 11.8 times of the total load acting on the platform, depends on the different mounting positions.

KEY WORDS: scissor lift, cylinder mounting position, cylinder actuating force, cylinder length.

1 INTRODUCTION

The hydraulic lift is a mechanical lifting device, using a hydraulic cylinder as actuating part to raise the load to a height. The single scissor lift (or 1X lift) is shown in Fig. 1. It consists of a base frame 1, top platform 2, legs (outer and inner frames 3,4), and hydraulic cylinder(s) 5. When the hydraulic cylinder extends or retracts, the legs will rotate each other, from which the top platform with the load on it will raise or lower, respectively. To increase the lifting height, X-shaped mechanisms are added to create a multi-stage model of scissor lift (or nX lift). Because of its simple structure, high capacity, safety in work, and low-cost maintenance..., this device is used in many areas for lifting a heavy load vertically, for example, in repair operations, warehouse work, production line...

Studies on nX scissor lifts are diverse. Spackman H. [1] presented a mathematical approach to determine the actuator force of the cylinder for the general case. Lei Bo

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*Corresponding author e-mail: tinh.trinhdong@hust.edu.vn

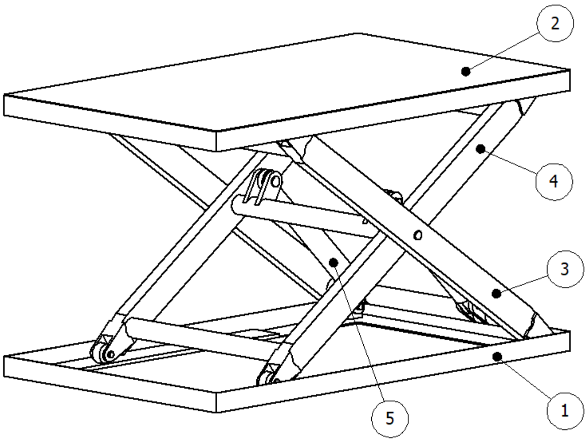

Fig. 1: Typical structure of 1X scissor lift.

Sun *et al.* [2] studied the force acting on the lift members and analysed the stress in the legs and stability of the cylinder piston for a specific structure of the scissor lift.

Sanghong He *et al.* [3] used a mechanical-hydraulic model and design of experiment method (DOE) to evaluate the optimal position of the hydraulic cylinder in the nX scissor lift. Other authors, for example, Stawinsky L. and colleagues [4] focused on the control of the velocity of the hydrostatic system for the scissor lift, while Pan C.S. *et al.* [5] evaluated the risk of workers when they enter or exit scissor lifts, Cupan and colleagues [6] presented the algorithm for designing a lift based on the input data of platform dimensions, lifting height and maximum load.

For the 1X lift configuration, current studies focused on calculating the thrust force of the cylinder [7–9], design review of the lift parts by finite element method (FEM) [10] with one fixed hinged point of the cylinder, evaluating the stability of the lift [7] for some layouts of hydraulic cylinder, or optimization the location of a cylinder by the criterion of stress in scissor legs to be minimum [9]. However, the actuation force of the cylinder with two movable hinged points (both hinged points of the cylinder are linked to the legs) is only calculated for specific cases, for example, in [8, 10] authors only considered a case when the hinged points of the cylinder are in the centreline of the legs. But in practice, to make it easy to mount, the hinged points of the cylinder usually are out of leg's centrelines. For this general case the actuation force of the cylinder is not mentioned yet.

Therefore, this study will focus on a model of 1X scissor lift for more general case when hinged points are in or out of the leg's centrelines as shown schematically in Fig. 2 with the goal to evaluate the influence of different positions of these hinged points on working performance of the lift. In this figure, the hinged points P and Q of

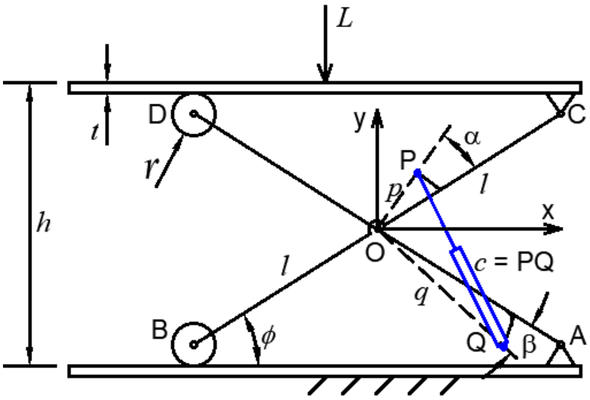

Fig. 2: Diagram of the scissor lift.

the cylinder are determined by four parameters: distance p with angle α for the point P, and distance q with angle β for the point Q.

2 ACTUATION FORCE OF THE CYLINDER

The force generated by the cylinder must ensure that the top platform with the load on it is kept in the intended position. So this load can determine by analyzing the free-body diagram of the legs [8] or by the energy approach [1, 3]. The 1X scissor lift usually is designed with low lifting speed and acceleration, so the inertia effect caused when lifting or lowering the load can be neglected, therefore, the methodology described by Spackman H. [1] can be used.

In Fig. 2 we denote L as the total vertical force acting on the lift. This force comprises the payload and the weight of the top platform. For the 1X lift, the weight of the leg frames is comparatively small to the payload, so it can be omitted. For vertical lift, the horizontal force is only caused by the inertia of the leg frames, so it is also insignificant and can be ignored. Therefore, from [1] the actuation force F of the cylinder can be determined as

$$F = L(dh/dc) = L(dh/d\phi)/(dc/d\phi)\,.$$

Thus, we can express the ratio of F/L as a function of lifting angle ϕ:

$$(F/L)(\phi) = f(\phi) = (dh/d\phi)/(dc/d\phi)\,. \tag{1}$$

In this formula, h is the lifting height, c is the length of the cylinder (distance between the hinged points of the cylinder), $dh/d\phi$ and $dc/d\phi$ denote the derivative of h and c, respectively. From Fig. 2 we have:

$$h = 2r + t + 2l\sin(\phi)\,, \tag{2}$$

$$c = \sqrt{(x_{\mathrm{P}} - x_{\mathrm{Q}})^2 + (y_{\mathrm{P}} - y_{\mathrm{Q}})^2}\,, \tag{3}$$

where r is the radius of the roller, t is the thickness of the platform, l is a haft of the leg's length (l = OA = OB = OC = OD), $(x_{\mathrm{P}}, y_{\mathrm{P}})$, and $(x_{\mathrm{Q}}, y_{\mathrm{Q}})$ are the coordinates of hinged points of the cylinder. These coordinates are determined by the formulas as follows:

$$x_{\mathrm{P}} = p\cos(\phi + \alpha); \qquad y_{\mathrm{P}} = p\sin(\phi + \alpha), \tag{4}$$

$$x_{\mathrm{Q}} = q\cos(\phi + \beta); \qquad y_{\mathrm{Q}} = -q\sin(\phi + \beta). \tag{5}$$

Substituting these last formulas into (3), we have:

$$c = \sqrt{p^2 + q^2 - 2pq\cos(2\phi + \alpha + \beta)}\,. \tag{6}$$

From formulas (2) and (6), after doing some mathematical transformations, the derivatives of h and c are:

$$dh/d\phi = 2l\cos(\phi), \tag{7}$$

$$dc/d\phi = \frac{2pq\sin(2\phi + \alpha + \beta)}{\sqrt{p^2 + q^2 - 2pq\cos(2\phi + \alpha + \beta)}}\,. \tag{8}$$

Substituting formulas (7) and (8) into formula (1) and with some suitable transformations we can derive the ratio F/L as follows:

$$f(\phi) = \frac{\cos(\phi)\sqrt{k_1^2 + k_2^2 - 2k_1k_2\cos(2\phi + \alpha + \beta)}}{\sin(2\phi + \alpha + \beta)}\,, \tag{9}$$

where k_1 and k_2 are the ratios (l/p) and (l/q), respectively.

Note that the lifting angle ϕ varies from $\phi_{\min}$ to $\phi_{\max}$, corresponding to the minimum and maximum lifting height of the lift. Due to the structure of the lift and lift stability, the limit values of the lifting angle are usually chosen as follows:

$$\phi_{\min} \geq 5^\circ; \qquad \phi_{\max} \leq 60^\circ\,. \tag{10}$$

In addition, when choosing parameters p, q, α, and β, it is also necessary to consider that during the working process the cylinder heads must not collide with the top platform and the base of the scissor lift. This condition is satisfied when:

$$-l\sin(\phi) < y_{\mathrm{P}} < l\sin(\phi), \tag{11}$$

$$-l\sin(\phi) < y_{\mathrm{Q}} < l\sin(\phi). \tag{12}$$

Substituting y_{P} from formula (4) and y_{Q} from formula (5) into formulas (11) and (12), with k_1 and k_2 are defined as in formula (9) and consider the range of ϕ in inequalities (10), we have:

$$-k_1 < \sin(\phi + \alpha)/\sin(\phi) < k_1 \,, \tag{13}$$

$$-k_2 < \sin(\phi + \beta)/\sin(\phi) < k_2 \,. \tag{14}$$

For any constant k, the function $g(\phi) = \sin(\phi + k)/\sin(\phi)$ is monotonic in the range of ϕ defined by inequalities (10) because the derivative $g'(\phi) = -\sin(k)/\sin^2(\phi)$ is always non-negative or non-positive. Therefore, it is only necessary to check the conditions (13) and (14) for the limit values of ϕ, i.e. $\phi_{\min}$ and $\phi_{\max}$ in formula (10).

3 LENGTH OF THE CYLINDER

By substituting $\phi_{\min}$ and $\phi_{\max}$ into formula (6), we can calculate the required minimum and maximum working length of the cylinder.

Using coefficients k_1 and k_2, we can rewrite formula (6) into the parametric form:

$$c/l = \sqrt{1/k_1^2 + 1/k_2^2 - 2\cos(\phi + \alpha + \beta)/(k_1 k_2)} \,. \tag{15}$$

Denoting $c_{\min}$ and $c_{\max}$ as the working length of the cylinder corresponds to the values of $\phi_{\min}$ and $\phi_{\max}$, so from Fig. 3, we can derive the constraints to the hydraulic cylinder as follows:

$$c_{\min} \geq cc \qquad \text{and} c_{\max} \leq oc \,, \tag{16}$$

where cc is Close Centres (distance between the hinged points at the full retracted position), oc is Open Centres (distance between the hinged points at the full extended position) of the cylinder as shown in Fig. 3.

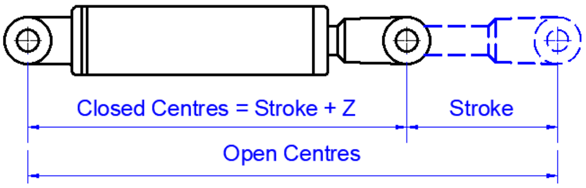

Fig. 3: Scheme of the hydraulic cylinder.

In addition, it should be considered that the dimensions Close Centres (cc), Open Centres (oc), and Stroke (st) are mutual dependent:

$$oc = cc + st = Z + 2st \,, \tag{17}$$

where Z is a portion of the cylinder length used for cylinder mounting heads. The value Z depends on the type, size of the cylinder, as well as the cylinder manufacturer. For the most common purpose cylinders, the ratio $\lambda = co/cc$ is less than 1.8 [8].

4 RESULT AND DISCUSSION

Figure 4 shows some graphs of the F/L-ratio or $f(\phi)$ as defined by formula (9), for k_1, $k_2 = 10$, and three cases of $(\alpha + \beta)$: -25, 0, 25 degrees. These graphs have vertical asymptotes at $\phi = -(\alpha + \beta)/2 + k \times 90^\circ$, where k is an integer. If one of these asymptotes is nearby or in the working range of ϕ, i.e. from $\phi_{\min}$ to $\phi_{\max}$ by formula (10), the cylinder will not able to work, because the required actuation force is extremely large.

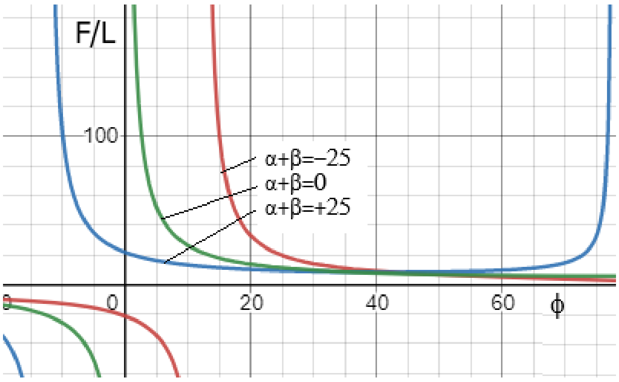

Fig. 4: The ratio F/L as a function of angle ϕ.

Furthermore, from Fig. 4 we can note that when $(\alpha + \beta)$ increases, the value of F/L at $\phi_{\min}$ decreases, but conversely, it increases again at $\phi_{\max}$ when $(\alpha + \beta)$ is a large value. Therefore, the smallest value of the required actuation force will be achieved when $f(\phi_{\min}) = f(\phi_{\max})$. By solving this equation for the cases when k_1 and k_2 vary from 1 to 10, with a step of 1, and $\phi_{\min} = 5^\circ$, $\phi_{\max} = 60^\circ$, we can find the appropriate values of $(\alpha + \beta)$.

The hinged locations of the cylinder are also constrained by the conditions (13) and (14). Therefore, to find the suitable values of $(\alpha + \beta)$ we must consider these constraints.

The appropriate values of $(\alpha + \beta)$ for $\phi_{\min} = 5^\circ$ and $\phi_{\max} = 60^\circ$ are shown in Table 1. The values in italic are the cases where the condition $f(\phi_{\min}) = f(\phi_{\max})$ is not fulfilled due to constraints (13) and (14). Because of the symmetry of the scissor mechanism, it is only necessary to consider the cases when $k_1 \geq k_2$.

With the values of $(\alpha + \beta)$ in Table 1, the maximum F/L-ratio for each case can be calculated by formula (9). The results are shown as a graph in Fig. 5.

Table 1: Value of $(\alpha + \beta)$ for optimizing actuation force

					$k_2 = l/q$					
$k_1 = l/p$	1	2	3	4	5	6	7	8	9	10
1	0.0	1								
2	5.0	0.0								
3	10.2	15.2	0.0							
4	15.4	20.4	12.7	0.0						
5	20.8	25.8	19.0	10.3	0.0					
6	26.5	28.3	22.7	16.3	8.6	0.0				
7	34.1	29.8	25.2	20.0	14.3	7.4	0.0			
8	34.6	30.9	27.0	22.7	18.0	12.7	6.4	0.0		
9	35.0	31.7	28.3	24.6	20.6	16.3	11.4	5.6	0.0	
10	35.3	32.4	29.4	26.1	22.7	19.0	14.9	10.3	5.0	0.0

When both k_1 and k_2 decrease, the ratio of F/L decreases too, i.e. the required actuation of the cylinder decreases. Thus, the farther the cylinder mounting points

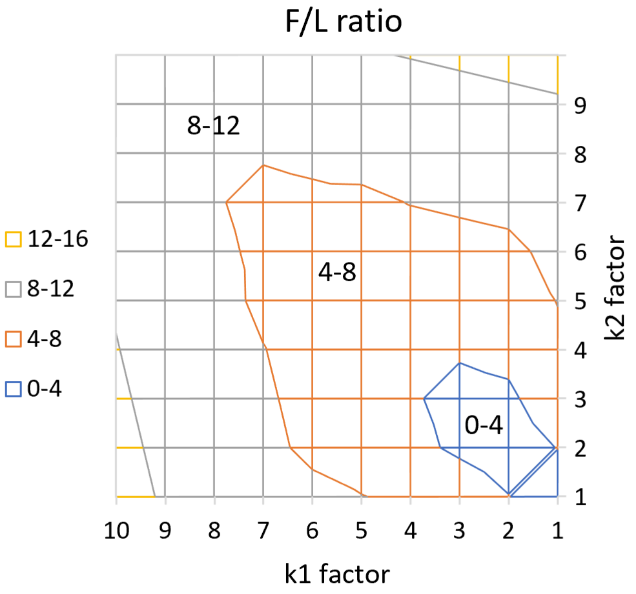

Fig. 5: Influence of k_1 and k_2 on F/L-ratio.

from the pivot center O of the scissor legs, the lower the required actuation force, but the length of the cylinder will also increase.

Another problem to consider is whether it is possible to choose or design a cylinder to fit the above-mentioned positions. Therefore, using formula (15) with the values of k_1, k_2, and $(\alpha + \beta)$ in Table 1 we calculated the length of the cylinder at the lowest and highest position of the top platform, corresponding to lifting angles $\phi_{\text{min}} = 5°$ and $\phi_{\text{max}} = 60°$, for example, with $l = 1000$ mm. The feasibility of the cylinder design is evaluated through the coefficient $\lambda = co/cc$ as described in Section 3 above.

Table 2 presents the calculated values of the ratio $c_{\text{max}}/c_{\text{min}}$. In some cases the cylinder cannot be designed, because the ratio λ is very large. Furthermore, in some cases, although it is easy to choose the cylinder, the ratio λ is so small, which will result in not using the full stroke of the cylinder. These unsuitable cases are shown in Table 2 as the cells with text in italic.

Table 2: Ratio of $c_{\text{max}}/c_{\text{min}}$ for $(\alpha + \beta)$ in Table 1

	$k_2 = l/q$									
$k_1 = l/p$	1	2	3	4	5	6	7	8	9	10
1	11.5									
2	1.8	11.5								
3	1.4	2.9	11.5							
4	1.3	1.8	2.9	11.5						
5	1.2	1.5	2.1	3.4	11.5					
6	1.2	1.4	1.8	2.4	3.8	11.5				
7	1.2	1.3	1.6	2.0	2.6	4.2	11.5			
8	1.1	1.3	1.5	1.8	2.2	2.9	4.6	11.5		
9	1.1	1.2	1.4	1.6	1.9	2.4	3.1	5.0	11.6	
10	1.1	1.2	1.3	1.5	1.8	2.1	2.5	3.4	5.3	11.5

Table 3 shows the required values of ratio F/L for the combinations of coefficients k_1 and k_2 that are applicable as mentioned in Table 2. We can see that some combinations of k_1, k_2 require a large actuation force of more than ten times the lifting load, and may not be effective.

Another aspect to consider when choosing a cylinder is its length and stroke. These parameters must meet requirements in constraints (16), (17) and can express as the ratios cc/l and oc/l. In Table 4 are calculated results for the applicable combinations of k_1, k_2 mentioned in Table 2. With a given length of the leg $(2l)$ we can calculate the maximal cc_{max}, the minimal oc_{min}, then select a cylinder with the length in closed state $cc_{\text{sel}} \leq cc_{\text{max}}$, and with the stroke $st \geq oc_{\text{min}} - cc_{\text{sel}}$.

Table 3: The required value of F/L

	$k_2 = l/q$									
$k_1 = l/p$	1	2	3	4	5	6	7	8	9	10
1	—									
2	4.1	—								
3	6.0	—	—							
4	7.3	4.9	—	—						
5	—	6.1	—	—	—					
6	—	7.4	7.1	—	—	—				
7	—	8.7	8.4	—	—	—	—			
8	—	10.1	9.8	9.4	—	—	—	—		
9	—	—	11.1	10.8	—	—	—	—	—	
10	—	—	12.4	12.1	11.8	—	—	—	—	—

Table 4: Maximum of cc/l and minimum of oc/l

	$k_2 = 1$		$k_2 = 2$		$k_2 = 3$		$k_2 = 4$		$k_2 = 5$	
k_1	cc/l	oc/l	cc/l	oc/l	cc/l	oc/l	cc/l	oc/l	cc/l	oc/l
1										
2	0.51	0.91								
3	0.68	0.94								
4	0.77	0.97	0.29	0.52						
5			0.34	0.52						
6			0.37	0.52	0.20	0.35				
7			0.39	0.52	0.22	0.35				
8			0.41	0.52	0.24	0.35	0.15	0.21		
9					0.25	0.35	0.16	0.21		
10					0.26	0.35	0.17	0.21	0.12	0.18

5 CONCLUSIONS

From the calculation results and discussions above the following conclusions can be made:

The mounting location of the hydraulic cylinder in a single scissor lift has a great influence on the actuation force, length, and stroke of the cylinder. Inappropriate choosing the position of cylinder hinged points can result in a higher actuation force, a collision between the cylinder heads and other parts of the scissor lift, or insufficiency of the stroke of the scissor lift than intended.

The established formulae are in a general form, so they can be used for other purposes, for example, as a basis for analysing the forces acting on the parts of a scissor lift during the working process, which is important for the detailed design of the structure.

Table 4, together with Table 2 and Table 1 can use as a guideline for the preliminary selection of the suitable cylinder and its mounting location by the criterion of minimal actuation force for the single scissor lift.

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