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Kinematic and dynamic analysis of an automated material handling and transport system for hydraulic system design optimization

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Abstract

The design process of a hydraulic system in industrial equipment must be based on many parameters. Among them, kinematic and dynamic parameters, as well as the relationship between the mechanical structure and these parameters, are the most important input factors. In this paper, the authors use Microsoft Excel as a computational tool to investigate the dynamic model describing the relationships among the equipment structure, motion trajectory, input load, and driving forces. This approach is applied to determine the load distribution domain of the mechanical system under different hydraulic cylinder layout configurations. Based on the analysis of the computational results, several key issues for designing the hydraulic system of an automated material handling and transportation device are identified, including the optimal arrangement of hydraulic cylinders and the maximum required thrust forces of the cylinders.

Keywords: Hydraulic cylinder, required thrust force, cylinder stroke, working domain, kinematics, dynamics, microsoft excel

Introduction

Loading and material-handling equipment is widely used in warehouses, storage yards, ports, and terminals. These devices are capable of automatically lifting and transporting goods along predefined trajectories and placing them accurately at designated positions. When designing such equipment, several requirements must be satisfied, including lifting capacity, motion trajectory, coordinated gripping–lifting–transport operations with correct timing, maintenance of the load orientation during motion, operational safety, compact structural dimensions, and minimum overall cost.

Typically, this type of equipment consists of several main subsystems: a lifting mechanism, a reach-adjustment mechanism, a traveling mechanism, a slewing mechanism, and a gripping mechanism. These subsystems can be driven by mechanical, hydraulic, or electric actuation systems [1], each of which offers distinct advantages depending on the application. For equipment with relatively limited reach and working height, hydraulic transmission is commonly employed due to its favorable power density and controllability [1].

One of the key challenges in designing a hydraulic drive system lies in selecting the appropriate number of hydraulic cylinders, determining their optimal arrangement, and defining the required technical parameters of each cylinder. These parameters must ensure the desired motion trajectory, operating speed, and lifting capacity, while simultaneously satisfying constraints related to overall dimensions and minimizing system cost [2].

Material and Methods

The problem is formulated for an experimental model with a smaller scale than the real system (physical model). Based on this model, the results can be extended and applied to practical mechanisms. The model allows the lifted object to move within a predefined working space. To control the motion trajectory according to specified coordinates, the system must be integrated with a control system to appropriately coordinate the movements of the hydraulic cylinders.

In order to generate diverse motion trajectories and to satisfy the lifting and transfer functions through prescribed coordinates, at least two hydraulic cylinders are required [3]. These cylinders can be arranged in four different configurations, as illustrated in Figure 1.

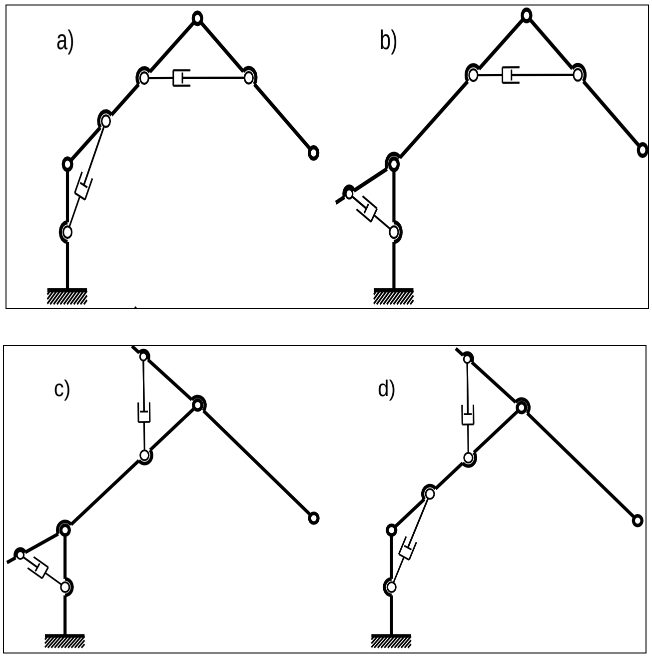

Fig 1: Cylinder arrangement configurations in the mechanism

The angular displacement $\Delta\alpha$ is determined using the following expression:

$$\Delta\alpha = 2\left(\text{arsin}\frac{l_0}{2.a} - \text{arsin}\frac{k_{xl}.l_0}{2.a}\right) \quad (1)$$

Where:

α is the mounting position of the hydraulic cylinder on the link; l 0
l_0 is the initial length of the hydraulic cylinder.

The problem is to determine the ratio l_0/a such that $\Delta\alpha$ reaches its maximum value. Figure 3 present the variation of $\Delta\alpha$ according to ratio l_0/a. Since the ratio l_0/a is constrained by the stroke coefficient k_{xl} and the allowable limit value of the angle α [2], the calculation results indicate that l_0/a <1.25. Therefore, the function $\Delta\alpha$ is only analyzed within this domain.

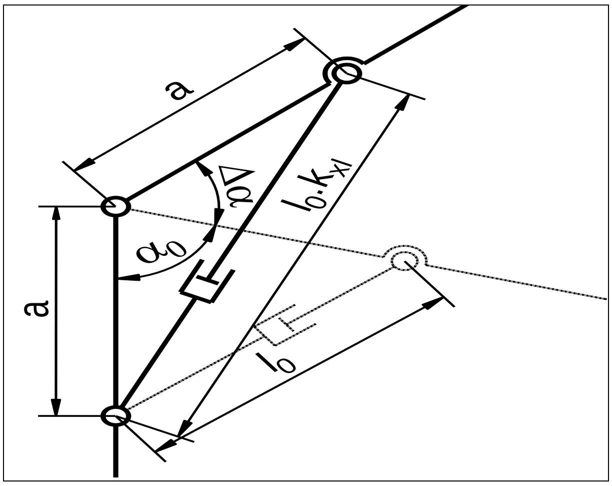

Fig 2: Schematic diagram for determining the angular displacement $\Delta\alpha$

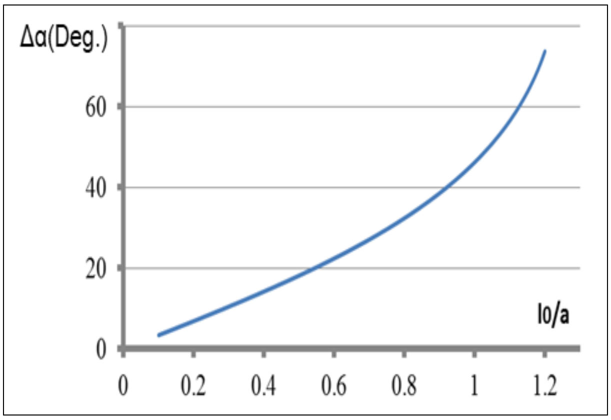

Fig 3: Relationship diagram of boom angular and the cylinder mounting position

From the above graph, it can be observed that $\Delta\alpha$ reaches its maximum value and simultaneously satisfies the working conditions of the mechanism when $l_0/a=1.2$. Based on this ratio, for each selected hydraulic cylinder (corresponding to a given value of l_0), the appropriate mounting position of the cylinder (a) can be determined.

During the lifting and transferring process, the loads acting on the members of the lifting mechanism assembly (including the cylinder driving force and joint reaction forces) vary continuously depending on the displacement coordinates. Therefore, it is necessary to evaluate these quantities at all operating positions.

The external force diagram acting on the mechanism for configuration 1 is illustrated in Figure 4.

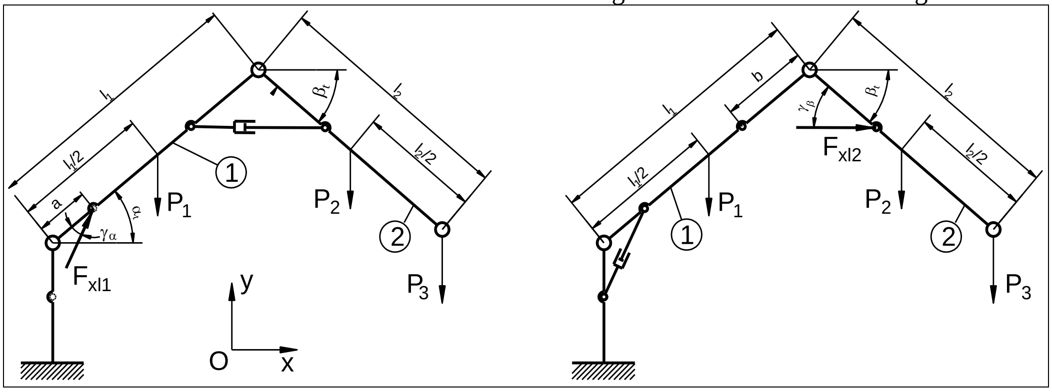

Fig 4: Force acting on the cylinder: (a) Free-body diagram with constraints released at cylinder 1; and (b) at hydraulic cylinder 2

From the force diagram, the equations describing the relationship between the cylinder pushing force and the displacement coordinates of the lifted load are established for each configuration.

According to Figure 4, the forces acting on cylinders 1 and 2, when both are arranged on the inner side, are determined by the following expressions:

$$F_{xl1} = \frac{P_1.\frac{l_1}{2}\cos\alpha + P_2\left(l_1.\cos\alpha + \frac{l_2}{2}.\cos\beta\right) + P_3\left(l_1.\cos\alpha + l_2.\cos\beta\right)}{a.\sin\gamma_\alpha} \qquad (2)$$

$$F_{xl2} = \frac{P_2.\frac{l_2}{2}.\cos\beta + P_3.l_2.\cos\beta}{b.\sin\gamma_\beta} \qquad (3)$$

Where:

P_1, P_2, P_3 are the external forces acting on the mechanism (P_1 and P_2 are the weights of the links, and P_3 is the weight of the lifted load).

α, β are the inclination angles between the boom and the positive x-axis, representing the coordinates of the load during motion.

Similarly, the force equilibrium equations for cylinders 1 and 2 can be established for the configuration in which the cylinders are arranged on the outer side.

It can be readily observed that the equation determining the required pushing force of each cylinder depends only on the mounting position of that cylinder itself (inner or outer arrangement), and does not depend on the position of the other cylinder. Therefore, when investigating the cylinder forces for the four structural configurations shown in Figure 1, the problem is reduced to solving four individual cases corresponding to the two possible positions of cylinder 1 and the two possible positions of cylinder 2.

Results and discussion

Based on the derived equations for determining the cylinder pushing forces, load distribution diagrams over the working workspace of the mechanism for each cylinder arrangement were generated using Microsoft Excel, as shown in Figure 5. The cylinder ranger from 74-144 cm

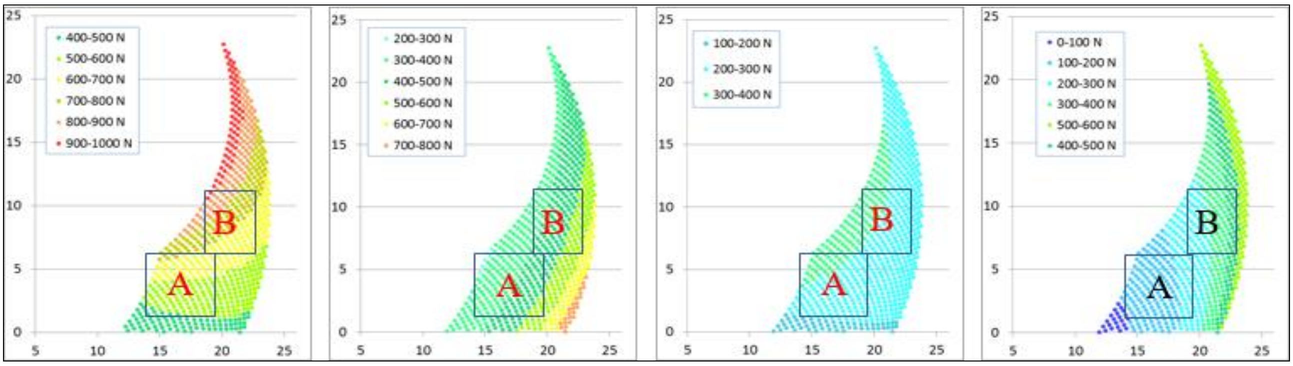

Fig 5: Load distribution diagrams acting on each cylinder within the working: a) cylinder 1 arranged inside; b) cylinder 1 arranged outside; c) cylinder 2 arranged outside d) cylinder 2 arranged inside

Based on the four diagrams above, during the design process, the designer can determine the required pushing force for each cylinder according to the specified working space of the mechanism. For example, consider the working space of the mechanism as region A with configuration 2 (Figure 1b). From Figure 5b (case where cylinder 1 is arranged outside), cylinder 1 must generate a maximum pushing force of $F_{xl1} = 600$ N. From Figure 5c (case where cylinder 2 is arranged inside), cylinder 2 must generate a maximum pushing force of $F_{xl2} = 300$ N. Moreover, the diagrams in Figure 5 allow the designer to analyze and select the cylinder arrangement that minimizes the required pushing force, thereby enabling a more compact cylinder design. For instance, for working space A, when cylinder 1 is arranged inside (Figure 5a), the maximum required pushing force is $F_{xl1} = 700$ N; when cylinder 1 is arranged outside (Figure 5b), the maximum required pushing force is reduced to $F_{xl1} = 600$ N. For working space B, when cylinder 1 is arranged inside (Figure 5a), the maximum required pushing force is $F_{xl1} =900$ N; whereas when cylinder 1 is arranged outside (Figure 5b), the maximum required pushing force decreases to $F_{xl1} = 700$ N. A similar analysis can be carried out for cylinder 2. The calculated results are summarized in Table 1, which presents the maximum required pushing forces of the cylinders within the working space for each arrangement configuration.

Table 1: Maximum required cylinder thrust force within the working region for each arrangement configuration

Figure Operation range	Figure 1a	Figure 1b	Figure 1c	Figure 1d
A	700 N	600N	300N	400N
B	900N	700N	400N	300N

Thus, in the design stage, if the mechanism is required to operate within working region A and a compact cylinder configuration is desired, cylinder 1 should be arranged outside while cylinder 2 should be arranged inside (Configuration 2 – Figure 1b). If the mechanism is required to operate within working region B, both cylinder 1 and cylinder 2 should be arranged outside (Configuration 3 – Figure 1c).

Results and Discussion

Through dynamic analysis of the physical model simulating the lifting–transport mechanism using two hydraulic cylinders in an automatic material-handling machine, the optimal mounting positions of the cylinders that maximize the working region of the mechanism have been determined. The load distribution diagrams of the required cylinder pushing forces over the working region were established for each cylinder arrangement configuration.

These diagrams enable designers to select an appropriate cylinder arrangement with the objective of minimizing the required cylinder force, thereby allowing the use of more compact cylinder designs. At the same time, the maximum required pushing force of each cylinder within the working region can be clearly identified from the diagrams.

The parameters determined in this study are essential inputs for the mechanical and hydraulic design of the mechanism. Although the analysis was conducted on a physical-scale model, the proposed methodology and the obtained results can be readily extended and applied to the design and analysis of full-scale practical mechanisms.

Specifically, for a required working region A, if the design objective is to achieve the most compact hydraulic cylinder configuration, the optimal arrangement is to place cylinder 1 outside and cylinder 2 inside (configuration 2, Figure 1b). In contrast, if the mechanism is required to operate within working region B, the preferred configuration is to position both cylinder 1 and cylinder 2 outside (configuration 3, Figure 1c).

Acknowledgments

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