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Research paper

Optimal design of toggle-linkage mechanism for clamping applications

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ABSTRACT

Finger clamp units (FCU) are widely used in industries to clamp flat-shape materials such as steel plates by using a toggle-linkage mechanism. Generally, in toggle-linkage mechanisms, a near singular configuration is used to obtain a high clamping force. Because the high force characteristics in a singular configuration change dramatically for a near singular workspace, the thickness of the plate is limited for a specific toggle-linkage mechanism. In this study, the design of a FCU is optimized such that a single FCU is used for plates with different thicknesses. First, various linkage alternatives are investigated to determine the mechanism that is more useful for a toggle linkage. Second, the design is optimized to ensure a high clamping force in a pre-defined range of plate thickness. Verification experiments are performed based on the simulation results. We expect that the proposed toggle-linkage mechanism can be used for various clamping applications.

1. Introduction

Toggle-linkage mechanisms are widely used in everyday life. Based on their singular characteristic, toggle-linkage mechanisms can be used to generate a large output force from a small input force. Hence, the mechanism is particularly used for tasks that demand large forces. Yossifon and Shivpuri [1] applied a toggle-linkage mechanism to a mechanical press and analyzed the load-stroke characteristics. Tso and Liang [2] proposed a novel nine-bar toggle-linkage mechanism for a forming press machine. Jencks et al. developed an electric circuit breaker with a high contact pressure using a toggle mechanism [3]. Francart [4] improved the over-center toggle-linkage valve mechanism by preloading with an adjustable tension spring. Bakermans invented a plier-type hand tool that discloses and claims a multi-contact electrical connectors [5]. Toggle mechanisms are used to fix objects wherein large forces are produced.

A FCU is widely used in industrial parts. A FCU can clamp sheet metallic parts by applying toggle mechanism. Boyd [6] proposed a concept of a FCU using a pneumatic cylinder. A pneumatic cylinder is commonly used as an actuator in current FCUs. However, pneumatic actuators have some disadvantages such as large size, high weight, and complex wiring of hydraulic lines. To overcome these problems, attempts have been made to use an electrical actuator in FCUs. Nagai et al. [7] patented an electrically actuated FCU wherein a ball-screw mechanism is employed. Tünkers [8] proposed an electric-

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powered FCU using a worm gear as a motor reducer. Fukui [9] patented an electric FCU by employing a worm gear directly on the output joint. Unlike a pneumatic actuator, an electrical actuator can exhibit rotational motion; hence, a different type of FCU is needed.

However, typical FCU can be used to generate a large force in limited positions, because a large output force is obtained through the mechanism via the singular position of the linkages. Thus, a small change in the link angles can lead to dramatic changes in the output force. This characteristic of the mechanism is critical for harsh conditions such as those observed in industries. To increase the robustness of the mechanism, it is necessary to maintain a high generating force for a wide range of workspaces.

Various methods were developed to design link mechanisms to achieve different objectives. Olson et al. [10] reviewed previous synthesis methods. Hansen [11] presented a method of synthesizing a planar mechanism using a multilevel approach. Kong [12] synthesized a translational parallel mechanism with three legs to satisfy certain conditions. Pucheta and Cardona [14] formed an atlas of kinematic chains and developed a method of designing a mechanism with prismatic and revolute joints. Lu and Leinonen [13] proposed two types of methods for type synthesizing a planar mechanism. Birglen [15] proposed a method of synthesizing a self-adapting finger linkage. An optimal linkage mechanism should be carefully determined to obtain a high performing FCU.

Further, optimizing the dimensions of linkages in certain mechanisms is an important step. Shiakolas et al. [16] proposed a new optimization method to reduce the square sum of errors in a four-bar linkage. Lin and Hsiao [17] optimized a five-point double-toggle mechanism to reduce the link length while maintaining the output force. Mundo et al. [18] synthesized a cam-linkage mechanism to follow a precise trajectory. Mundo et al. [19] optimized a five-bar linkage mechanism with a noncircular gear to follow the desired path. Pennock and Israr [20] designed the link lengths of a six-bar linkage mechanism wherein an adjustable pivot is employed. Huang et al. [21] defined a design parameter for a five-bar double-toggle clamping mechanism and optimized the link lengths of the mechanism using a genetic algorithm. Kim et al [22] applied new methodology for optimizing crank-rocker four-bar linkage structure to follow both specific trajectory and velocity. Kafash and Nahvi [23] implemented new optimization function for path generation of four-bar linkage, which has lower number of optimization variables. The dimensions should be optimized with respect to an appropriate cost function to better design the FCU.

We propose a toggle mechanism for the FCU wherein a high output force is maintained for a wide range of workspace. The optimization method presented in this paper is as follows. First, the toggle mechanisms were extensively reviewed including four-bar and six-bar linkage mechanisms. Second, mechanisms that are feasible for toggle operations are selected from each possible structure of the linkage mechanisms. Each feasible mechanism was optimized to generate a high output force in a pre-defined workspace. Finally, we selected a mechanism wherein the output force is maximum in the pre-defined workspace by comparing the optimization result. For the verification, experiments were conducted using the optimized mechanism.

The rest of this paper is organized as follows. In Section 2, details about the determination of possible toggle-linkage mechanisms and selection of design alternatives for the FCU are presented. Dimension optimization of each design alternative and selection of an optimal design alternative are presented in Section 3. Prototype manufacturing and experimental analysis are presented in Section 4. Finally, in Section 5, the conclusions of this study are presented.

2. Type synthesis of FCU

2.1. Design constraints of FCU

The objective of this study is to develop an FCU using an electric actuator. Fig. 1 shows an example of an electrically actuated FCU. To design such an FCU, certain constraints exist because of practical reasons. In this study, the following design constraints are considered.

1. The linkage mechanism must be a closed chain.
2. The total degrees of freedom (DOFs) of the mechanism should be one.
3. The radial force applied to the input joint should be small when clamping.

The first constraint is needed for force amplification using singular points. The second one was set because no additional DOFs are needed to achieve the clamping task. Additional DOFs in the FCU may cause a problem because of the redundancy in the mechanism. Hence, the mechanism should be a single DOF system. The third constraint was set because of practical problems. Because of the large output force, the reaction force applied along the input joint can be quite high. A high radial force along the input joint may cause serious problems for the actuator such as fracture of the gearbox and fatigue failure along the joint. The design alternatives for the FCU were obtained by considering the constraints.

2.2. Determination of specialized kinematic chain for FCU

The specific kinematic chains for FCU design were selected by using Yan's approach [24]. But we are going to skip generalization step and start with synthesizing atlas of kinematic chain since we already decided to use toggle linkage mechanism for FCU. From design constraint and structure of Tünkers FCU [8], design requirements of FCU are as follows: