Optimization Design of Shaper Mechanism Based on Nonlinear Programming Model

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Abstract. Due to the lack of the optimization algorithm or model which could be used to optimize the complicated plane linkage mechanism (like a shaper mechanism), a nonlinear programming model which could solve this problem was proposed in this work, whose objective function was the minimum initial velocity of the cutting tool in the shaper mechanism, and the length of the linkages in the shaper mechanism was regarded as the constraint conditions. Subsequently, a typical shaper mechanism was chosen as the example to be optimized via this nonlinear programming model. The optimization results revealed that this model could acquire an appropriate optimization scheme effectively and the optimization scheme was reasonable.

1. Introduction
With the advancement of computer science and programming language, an increasing number of intelligent algorithms or models had been applied in the machinery industry field, especially for the optimization design of a mechanism, which had aroused the attention of a host of scholars in recent years actually [1-2]. According to the available literatures, a large quantity of optimization algorithms and models which were utilized to optimize the size of the components in a certain mechanism had been reported, such as multi-objective programming model (MOOM) [3-4], differential evolution [5], Monte Carlo method [6], particle swarm optimization (PSO) [2] and so on, all of which had been proved to be effective and efficient to carry out an appropriate optimization scheme for some simple plane linkage mechanisms like slider-crank mechanism [3] and four-bar linkage mechanism [5]. Nevertheless, the investigations on the optimization algorithms and models which had the capacity to be used to propose a proper optimization scheme for complex linkage mechanisms, such as the actuator of a shaper mechanism, were inadequate. Therefore, an optimization model which could be used to optimize the length of the linkages in a six-bar shaper mechanism was established via utilizing a nonlinear programming model, which was the main contribution of this work.
2. Rules of establishing optimization model

While optimizing the design of a shaper mechanism, several critical issues needed to be considered: 1) it was widely acknowledged that the cutting tool of the shaper mechanism needed to move smoothly during the process of cutting metal. Furthermore, the impact load which would occur when the cutting tool contacted with the metal should be limited to a lower level as much as possible, which revealed that the initial velocity of the cutting tool should be as low as possible; 2) due to some special limitations of working conditions, the length of the linkages in the shaper mechanism should be controlled within a certain range. According to the analysis which had been mentioned above, some of the constraints couldn’t be described as a linear function, and they were nonlinear functions actually. Thus, a nonlinear programming model should be presented to solve this problem.

2.1. Establishing objective function

Assuming that the initial velocity of the cutting tool was $v_0$, and there were $n$ independent optimization variables which may exert an effect on the initial velocity of the cutting tool, all of which could be written as a column vector as Equation 1.

$$L = [l_1, l_2, \ldots, l_n]^T (i = 1, 2, \ldots, n)$$ (1)

Where $l_i$ was the independent variable, and the length of the linkages in this shaper mechanism would always been regarded as the independent variable. Therefore, the initial velocity of the cutting tool $v_0$ could use a function like Equation 2 to express.

$$\min v_0 = f (l_1, l_2, \ldots, l_n) (i = 1, 2, \ldots, n)$$ (2)

Where $l_i$ was the element of vector $L$. The main purpose of this optimization model was to make $v_0$ as low as possible, thus, Equation 2 could be regarded as the objective function of this nonlinear optimization model.

2.2. Establishing constraint conditions

As a matter of fact, a large number of factors which could exert an influence on the length of the linkages in the shaper mechanism, such as the value of pressure angle and the condition of forming an oscillating guard bar mechanism, which would limit the length of the linkages into a certain range. Providing that the minimum value of a linkage was $l_{imin}$, and the maximum value of a linkage was $l_{imax}$, the constraint conditions of this nonlinear optimization model could be written as Equation 3.

$$l_{imin} \leq l_i \leq l_{imax} (i = 1, 2, \ldots, n)$$ (3)

3. Example analysis

3.1. Optimization problem definitions

This work chose a shaper mechanism like Figure 1 as the example to illustrate how to use the nonlinear programming model to optimize this shaper mechanism.
As shown in Figure 1, Component 1, 3 and 4 were linkages, and Component 2 was a slider. Besides, Component 5 represented the cutting tool of this shaper mechanism. Component 1 was the original move part which would rotate contraclockwise, whose angular velocity $\omega_1$ was a constant. At the beginning of the motion, the angle $\theta_1$ was equal to 0. The range of the size of the linkages in Figure 1 would be introduced in Section 3.2. We intended to know the value of the length of the linkages in Figure 1 when the initial velocity of Component 5 was the lowest.

3.2. Determining constraint conditions
Taking the conditions of forming this mechanism and the value of pressure angle into consideration, the range of the size of the linkages in Figure 1 could be written as follow: $AB \in [100mm, 200mm]$, $CD \in [500mm, 700mm]$, $DE \in [100mm, 200mm]$, $AC \in [200mm, 300mm]$ and $HE \in [500mm, 600mm]$, all of which could be regarded as the constraint conditions of this nonlinear programming model.

3.3. Determining objective function
The initial velocity of Component 5 could use graphical method of vector equation to solve. Since the graphical method of vector equation was a mature mechanism kinematic analysis theory, the expression of the initial velocity of Component 5 $v_0$ would be given directly and the process of acquiring this expression was omitted, which could be written as Equation 4.

$$\text{Min } v_0 = \frac{AC}{BC} - \frac{(AB / BC) \cdot \tan \theta \cdot (AB^2 / BC^2) \cdot CD \cdot \omega_1}{(DE \cdot BC)^2 - (H \cdot BC + CD \cdot AC)^2}$$ (4)

Where $\omega_1$ was a constant and $\tan \theta$ could be written as Equation 5.

$$\tan \theta = \frac{(H \cdot BC - CD \cdot AC) \cdot (DE \cdot BC)^2 - (H \cdot BC + CD \cdot AC)^2}{(DE \cdot BC)^2 - (H \cdot BC + CD \cdot AC)^2}$$ (5)

In Equation 4 and 5, $BC$ was equal to $(AB^2 + AC^2)^{1/2}$. As shown in Equation 4 and 5, there were 5 independent variables in Equation 4, including $AB$, $CD$, $DE$, $AC$ and $H$. The range of them had been proposed in Section 3.2. Therefore, Equation 4 could be regarded as the objective function of this nonlinear programming model.
3.4. Solutions & Results

Using Python programming language to program the code which could solve this nonlinear programming model and running these codes in PyCharm, the optimization results were attained. The comparison results between the original design and the optimization design which was acquired via using this nonlinear programming model were shown in Table 1.

|                | AB/mm | CD/mm | DE/mm | AC/mm | H/mm | \(v_0\)/(mm·s\(^{-1}\)) |
|----------------|-------|-------|-------|-------|------|-------------------------|
| Original design| 125   | 600   | 150   | 275   | 575  | 102                     |
| Optimization design | 100   | 630   | 103   | 300   | 500  | 0                       |

As shown in Table 1, this nonlinear programming model presented an optimization design scheme. In this scheme, the initial velocity of the cutting tool was 0. It was an ideal circumstance, because the impact load which would occur when the cutting tool contacted with the metal would be the lowest.

4. Conclusion

This work proposed an optimization design model for optimizing the shaper mechanism based on nonlinear programming model. The optimization results of the example demonstrated that this model could acquire the optimization design scheme effectively. Furthermore, the design scheme of the shaper mechanism which was calculated via this model was better than the original design scheme, which provided a new solution for the similar optimization problems in the machinery industry field.

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