Design of Compliant Bistable Mechanism for Rear Trunk Lid of Cars

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Abstract. In traditional rear trunk lid designs, extra devices (e.g., hydraulic actuators and spring mechanisms) are employed to compensate the lid weight and reduce the efforts for both opening and closing it. Such devices often consist of a number of parts, thus leading to high costs for manufacture, assembly and maintenance. In this paper, we designed a compliant bistable mechanism to keep the lid's two states and compensate the lid weight, which leads to a system that requires only a small input force to switch between the two states. In the design, the pseudo-rigid-body model (PRBM) was employed to model the compliant mechanism, a particle swarm optimizer was used to optimize the PRBM parameters, and promising results were presented and discussed. The use of complaint mechanism can lead to reduction of the costs for manufacture, assembly and maintenance.

Keywords: trunk lid, compliant bistable mechanism, particle swarm optimizer.

1 Introduction

The rear trunk of a car is its main storage compartment. The rear trunk lid is the movable cover that shelters the things placed in the trunk. It is always required for the lid to steadily stay at two different positions, i.e., the open and closed states. Due to the weight of the lid, extra devices are often employed to reduce the efforts for both opening and closing it thus improving its use comfortableness. Such devices, e.g., hydraulic actuators and spring mechanisms, consist of a number of parts [1-2], thus leading to high costs for manufacture, assembly and maintenance.

In recent years, the research of compliant mechanisms has attracted a lot of attention in both academia and industry. A compliant mechanism, which utilizes the deflection of flexible segments rather than from articulated joints to achieve its mobility, provides many advantages over its rigid-body counterparts such as increased precision and reliability, ease to be miniaturized, and reduced part count (thus decreases the costs for manufacture, assembly and maintenance) [3]. A compliant mechanism also offers an economical way to achieve bistability [3] because the

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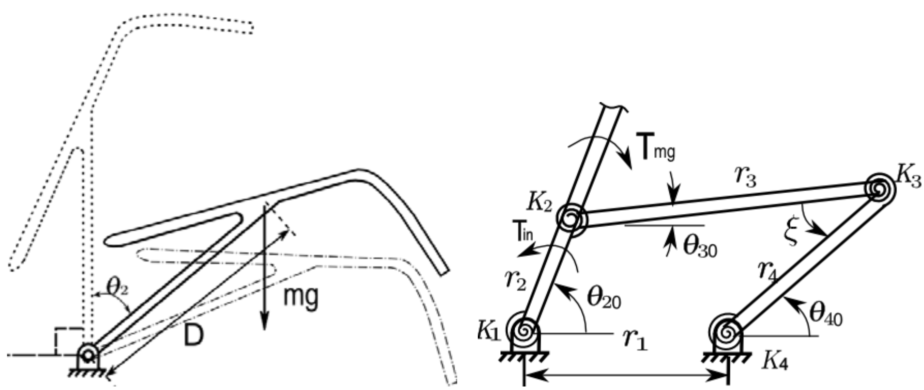
flexible segments store potential energy as they deflect. There has been a large amount of work done on different types of bistable compliant mechanisms [4-10].

Considering the trunk lid is required to steadily stay at two different positions, a bistable compliant mechanism could satisfy this requirement well. Furthermore, the bistable characteristics of the design must also compensate the weight of the lid to improve its use comfortableness.

In this paper, we designed a compliant bistable mechanism to keep the lid's two states and compensate the lid weight, which leads to a system that requires only a small input force to switch between the two states. In the design, the pseudo-rigid-body model (PRBM) [3] was employed to model the compliant mechanism and a particle swarm optimizer (PSO) [11] was used to optimize the PRBM parameters. The rest of the paper is organized as follows: Section 2 defines the design problem and presents the PRBM of a compliant four-bar mechanism; Section 3 optimizes the compliant mechanism; Section 4 discusses the results and concludes the main contribution and limitation of the work.

2 Problem Definition

To design a bistable compliant mechanism for rear trunk lid, its requirement should be well stated. First, the trunk lid could stably stay in the position when it is open or closed. Second, the trunk lid should have adequate range of motion, making it convenient to use. In this work, we assume the range of the trunk lid's motion is 75º. Third, for pursuing comfortableness, one can open or close the lid with a small force.



(a) (b)

Fig. 1. (a) Model of trunk lid: opened position (dotted line); closed position (dot-dash); (b) PRBM of complaint four-bar mechanism

Fig. 1(a) shows a traditional trunk lid that rotates around a pivot, with the dotted line corresponding to the opened position and the dot-dash line to the closed position. And the weight (mg) of the lid is simplified at its center of mass with a distance of *D* to the pivot. Here, we adopt a compliant four-bar mechanism to assist opening and closing the lid, which contains a link corresponding to the lid. So that in the process of lid closing (θ_2 increases from zero to a certain angle), part of the positive work done by gravity will be stored in the compliant segments of the mechanism, thus only a small input load is required to compensate the residual positive work.

The PRBM of the complaint four-bar mechanism is shown in Fig. 1(b). Link r_1 is the ground or fixed link while link r_2 corresponds to the trunk lid. The moment (T_{mg}) is generated by the lid weight and exerts on link r_2. In Fig. 1(b), r_i denotes the length of the links, K_i the stiffness of torsional spring, θ_i the angle of the links to the horizontal axis, T_{in} the moment required to actuate the lid. In the next section, for given r_i, K_i and θ_{i0}, we will deduce the relationship between θ_2 and T_{bar}, where T_{bar} is T_{in} neglecting the lid weight.

3 Methods

In this section, based on the PRBM, we will deduce the expression of T_{bar} with respect to θ_2. Then by adding T_{bar} to T_{mg}, we can get the resultant moment. Due to its simplicity in implementation and high computational efficiency in performing difficult optimization tasks, we use a PSO [11] to optimize the parameters of PRBM.

3.1 Moment

In the PRBM, the moment needed to drive a complaint four-bar mechanism is:

$$T_{bar} = K_1\psi_1 + K_2\psi_2\left(1-\frac{d\theta_3}{d\theta_2}\right) + K_3\psi_3\left(\frac{d\theta_4}{d\theta_2}-\frac{d\theta_3}{d\theta_2}\right) + K_4\psi_4\frac{d\theta_3}{d\theta_2} \tag{1}$$

where ψ_i is the change of angle θ_i as θ_2 increases:

$$\begin{aligned}
\psi_1 &= \theta_2 - \theta_{20} \\
\psi_2 &= \theta_2 - \theta_{20} - (\theta_3 - \theta_{30}) \\
\psi_3 &= \theta_4 - \theta_{40} - (\theta_3 - \theta_{30}) \\
\psi_4 &= \theta_4 - \theta_{40}
\end{aligned}$$

and kinematic coefficients [3] are:

$$\frac{d\theta_3}{d\theta_2} = \frac{r_2\sin(\theta_4-\theta_2)}{r_3\sin(\theta_3-\theta_4)}, \frac{d\theta_4}{d\theta_2} = \frac{r_2\sin(\theta_3-\theta_2)}{r_4\sin(\theta_3-\theta_4)}$$

We can see that $T_{bar} = 0$ when $\theta_2 = 0$. Thus, we consider $\theta_2 = 0$ as the opened position (corresponding to the dotted line in Fig. 1(a)). But since we have fixed the gravity of trunk lid on r_2, that the value of T_{mg} under the condition of θ_2 in Fig. 1(b) is not zero means this position is not stable. In this case, we rotate the PRBM together with the horizontal axis, to the position that r_2 is at the same position of trunk lid's open position in Fig. 1(a). At this position, T_{mg} equals zero and corresponds to a stable equilibrium position. In this paper, we consider that the mass of the lid m=10 Kg, and the distance D=0.6 m. Then the moment exerted by the lib weight is:

$$T_{\mathrm{mg}} = mgD\sin\theta_2 \tag{2}$$

To enhance the load capacity and improve the performance, two identical bistable mechanisms will be employed and symmetrically mounted on both sides of the lid to support the lid weight, thus each bistable mechanism will compensate half of the lid weight. The moment at the pivot can be expressed as:

$$T_{\mathrm{in}} = T_{\mathrm{bar}} - T_{\mathrm{mg}} / 2 \tag{3}$$

This will be used to optimize the parameters of PRBM in the next subsection.

3.2 Optimization

PSO a population-based and stochastic optimization technique inspired by sociological behavior of bird flocking and fish schooling, which was first developed by Kennedy and Eberhart [12] in 1995. In PSO, the population is called the swarm, the individuals are called the particles, and each particle represents a potential solution for the problem being solved. Each particle "flies" through the solution space according to the previous experiences of its own and the particles within its neighborhood in search of better solution. PSO had been successfully applied to a wide variety of optimization tasks including artificial neural network training, job-shop scheduling, multi-objective optimization problems, etc.

Considering the assembly of the mechanism to the lid, we employ a partially compliant configuration which has two traditional rigid pivots, i.e., K_1=0 and K_2=0. The length of the fixed link (r_1) is set to 0.35 m. Then, the parameters to be optimized are: [r_2, r_3, r_4, θ_{20}, K_3, K_4]. The constraints of the optimization include: (a) Because r_2 is fixed to the trunk lid, the motion range of θ_2 must be no less than 75°; (b) The maximum stress in the compliant segments must be less than the yield strength of the material; (c) The values of K_i are also limited due to the implementation difficulty.

To facilitate the optimization, we formulated an ideal bistable behavior of T_{in} (denoted as T_{target}) with respect to θ_2 as:

$$T_{\mathrm{target}} = \frac{40\theta_2^3 + 85\theta_2^2 + 40\theta_2}{\theta_2^2 + 0.42\theta_2 + 1.2} \tag{4}$$

The curve for T_{target} is plotted in Fig. 2. Then the fitness function of the optimization can be written as:

$$
\begin{aligned}
\text{min} \quad & T_{\text{error}} = T_{\text{target}} - T_{\text{in}} \\
\text{s.t} \quad & 0 \le r_i \le 0.5m, (\ i = 2,3,4\ ) \\
& 0 \le \theta_i \le 110^\circ, (i = 3,4) \\
& 75^\circ \le \theta_2 \le 110^\circ \\
& 0 \le K_i \le 20 N \cdot m / rad, (i = 1,2,3,4)
\end{aligned}
\tag{5}
$$

In the optimization, the swarm size was set to 40 and the maximum iteration is 10000. Each particle is a 6-dimensional vector representing the PRBM of a candidate compliant four-bar mechanism design.

4 Results and Discussion

The optimized results of the parameters are given in Table 1. Using the results in Table 1, T_{in} is plotted in Fig. 2. The corresponding PRBM is also presented in Fig. 3(a). From Fig. 2, we can see that T_{in} approximates T_{target} well before the unstable equilibrium position (the second position where T_{target}=0). Although T_{in} is not equal to zero when θ_2 >75º, the sign of T_{in} is negative and the trunk lid can be stopped by the lower part of the trunk to maintain the position. In summary, the design is acceptable for the trunk lid. The maximum value of T_{in} is about 5 Nm, which represents a comfortable moment for users to open and close the lid.

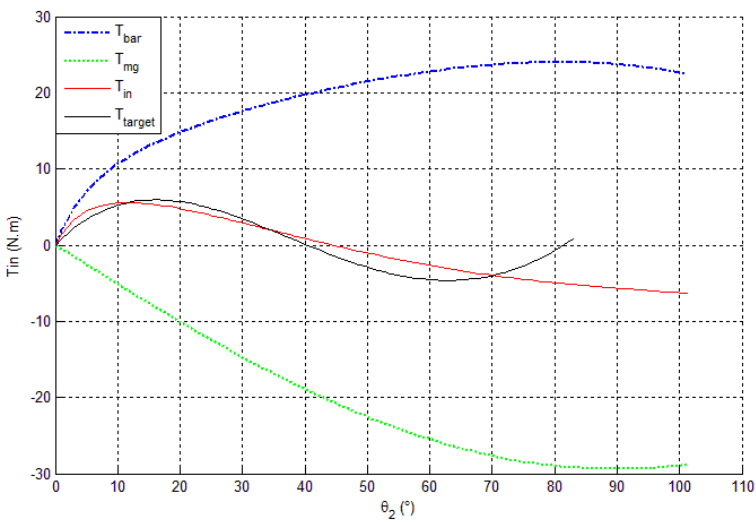


Fig. 2. The curves of T_{in}, T_{mg}, T_{bar} and T_{target}

Table 1. Optimized parameters

r_2 (m)	r_3 (m)	r_4 (m)	θ_{20} ($^\circ$)	K_3 (Nm/rad)	K_4 (Nm/rad)
0.37	0.4	0.39	12	0.38	16.5

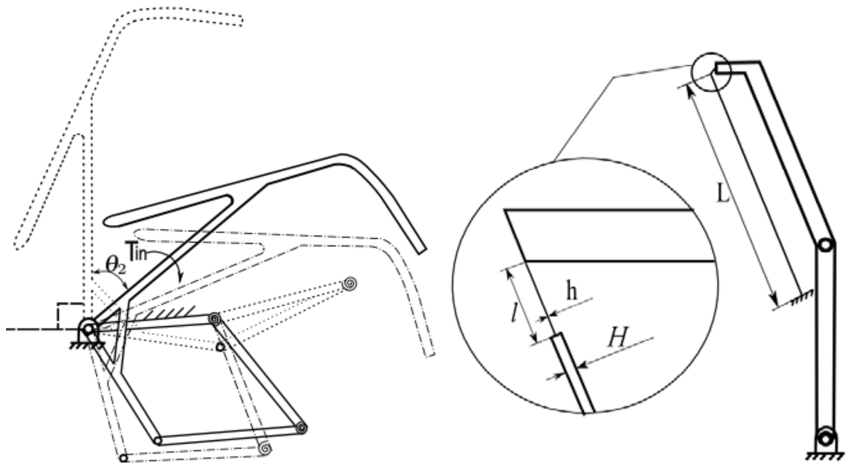


Fig. 3. (a) The PRBM of the optimized compliant four-bar mechanism and the trunk lid; (b) The implementation of the PRBM (ocantilevered segments and small-length flexural pivots)

Finally, a rigid-body replacement method [13] was used to finalize the bistable compliant mechanism from the PRBM. There are two flexural pivots in the PRBM. Because for K_3 is much smaller than K_4, we adopt a cantilevered segment for K_4 (with b, H and L are the out-of-plane thickness, the in-plane thickness and the length, respectively), and a small-length flexural pivot for K_3 (with b, h and l are the out-of-plane thickness, the in-plane thickness and the length, respectively). We set the out-of-plain thickness b for both compliant segments to 0.03 m, so they can be fabricated from a single layer of material [14]. Titanium was selected due to its high ratio of yield stress to elastic modulus (σ_y/E). In the following, the dimensions of the two segments are determined using their stiffness listed in Table 1.

$$K_3 = \frac{EI}{l} = \frac{Ebh^3}{12l} \tag{6}$$

$$K_4 = \gamma K_\theta \frac{EI}{L} = \frac{\gamma K_\theta Ebh^3}{12L} \tag{7}$$

where l=0.02 m, γ = 0.85, K_θ = 2.85, $L = r_4 / \gamma$ = 0.459 m. The in-plain thicknesses are:

$$h = 0.3\times10^{-3}\,\text{m},\ \ H = 2.3\times10^{-3}\,\text{m}$$

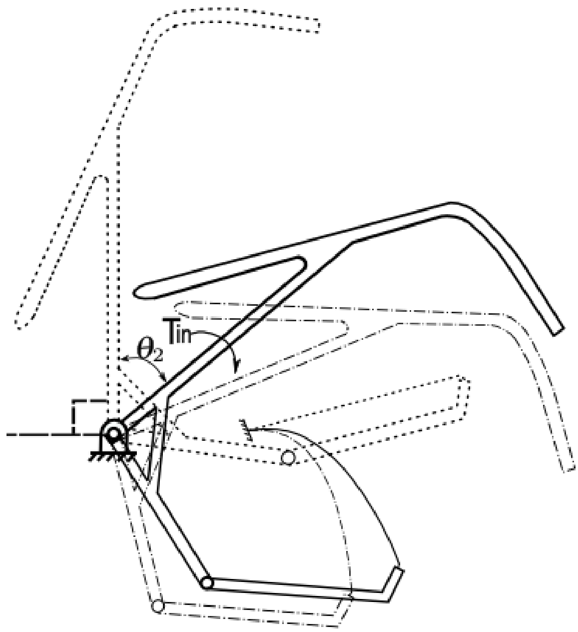


Fig. 4. The resultant design both at its open position (dotted line) and closed position (dot-dash)

It is also necessary to evaluate the stress level of the compliant segments. For given maximum rotation angle of the lid (r_2 in the PRBM), the maximum rotation angles of ψ_3 (corresponding to K_3) and ψ_4 (corresponding to K_4) are 66° and 90°, respectively. For the cantilevered segment, bending dominates its load, thus we have

$$\sigma_{\max} = \frac{M_{\max} H / 2}{I} = \frac{K_4 \psi_4 H}{2I} = 979.9 \text{ MPa} \tag{8}$$

For the small-length pivot, both tension stress and bending stress are considered:

$$\sigma_{\text{bend}} = \frac{M_{\max} h/2}{I} = \frac{K_3 \psi_3 h}{2I} = 972.7 \text{ MPa} \tag{9}$$

$$\sigma_{\text{pull}} = \frac{F}{A} = \frac{(K_3 \psi_3 / r_3) \div \sin(\xi)}{bh} = 7.6 \text{ MPa} \tag{10}$$

where angle ξ is marked in Fig. 1(b). The maximum stress in total is:

$$\sigma_{\max} = \sigma_{\text{bend}} + \sigma_{\text{pull}} = 927.7 + 7.6 = 935.3 \text{ MPa} \tag{11}$$

In summary, the maximum stress in the compliant segments is less than the yield stress of Titanium (σ_y = 1170 MPa), thus the design can meet the requirements of the lid design.

5 Conclusion

In this paper, we designed a compliant bistable mechanism to keep the lid's two states and compensate the lid weight, which leads to a system that requires only a very small force to switch between the two states. In the design, the pseudo-rigid-body model (PRBM) was employed to model the compliant mechanism, a particle swarm optimizer was used to optimize the PRBM parameters, and promising results were presented and discussed. The use of complaint mechanism can lead to reduction of the costs for manufacture, assembly and maintenance.

Nevertheless, this design could be improved in our future work by further reducing the lengths of the links and decreasing the stress level in the compliant segments. Also, trying other types of bistable compliant mechanisms for the design is also of our interests.

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