Innovative design of eight-bar linkage motorcycle suspension based on mechanism regeneration method

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Abstract. Motorcycles have high requirements on operation agility, steering accuracy and braking stability when running at high speed, and the core structure that determines the above performance lies in the suspension system. Therefore, this study uses the mechanism regeneration method to analyze the Duolever multi-bar linkage scissor front suspension of BMW and the eight-bar linkage rear suspension of Honda, and the topology matrix and generalized kinematic chain of the mechanism are obtained. Under the condition of meeting the design constraints, 12 kinds of eight-bar ten-pair combined kinematic chains can be gotten. After specifying the link types in turn, 17 feasible new eight-bar linkage motorcycle suspensions are finally realized. This study provides an efficient method for the independently design of the motorcycle suspension topology.

1. Introduction

Riders have the requirement of stable direction, agile manipulation and accurate steering feedback when riding at high speed [1-2]. What’s more, they have the performance pursuit of high-efficiency braking and stable direction keeping when braking. For these reason, the motorcycle suspension needs a breakthrough in structure to meet higher requirements. Traditional periscope shock absorber relies on the up and down expansion of the shock absorber to absorb the ups and downs from the road surface when the vehicle is running, so as to achieve the effects of stabilizing the vehicle’s body and reducing the vibration. At the same time, however, the shock absorber needs to bear the lateral and longitudinal forces generated when the vehicle turns or brakes. What’s worse, and the shock absorber will be distorted laterally and longitudinally, which will easily cause instability in high-speed driving.

Therefore, major enterprises have designed suspensions with superior performance [3], expecting to form a front suspension with coordinated control of steering and vibration reduction and a more stable rear suspension [4-5]. For example, the Duolever multi-bar linkage scissor front suspension [6] mounted on BMW K1200 and K1300 not only ensures the stability and accuracy of riding direction, but also brings excellent comfort and keen feedback. Honda uses similar technology in the rear suspension [7], as shown in Figure 1. However, the suspension structures of these enterprises have corresponding patent protection, and other enterprises must break through the corresponding technical barriers if they want to develop their own core technologies. Therefore, this study uses the mechanism regeneration method [8] to design new types of eight-bar linkage motorcycle suspension based on the existing suspension structure, aiming to realize independent innovation of the suspension structure.
2. Structural analysis of existing motorcycle suspension

The Duolever multi-bar linkage scissor front suspension of BMW shown in Figure 1 (A) is a planar eight-bar linkage mechanism with 10 kinematic pairs, including a fixed link (machine member 1, $K_F$), a moving link connected with wheels (machine member 2, $K_M$), a shock absorber ($K_r$) composed of a cylinder (machine member 3, $K_Y$) and a piston (machine member 4, $K_I$), and four swing arms (machine member 5, $K_{L1}$; machine member 6, $K_{L2}$; machine member 7, $K_{L3}$; machine member 8, $K_{L4}$) which have 9 revolute pairs ($J_R$: a, b, c, d, e, f, g, h, j) and 1 prismatic pair ($J_P$: k). The eight-bar linkage rear suspension of Honda shown in Figure 1(B) is also an eight-bar linkage mechanism with 10 kinematic pairs, including a fixed link (machine member 1, $K_F$), a moving link connected with wheels (machine member 2, $K_M$), a shock absorber ($K_r$) composed of a cylinder (machine member 3, $K_Y$) and a piston (machine member 4, $K_I$), and two swing arms (machine member 5, $K_{L1}$; machine member 6, $K_{L2}$), and sliding assemblies with splined holes (machine member 7, $K_{L3}$; machine member 8, $K_{L4}$) which has 8 revolute pairs ($J_R$: a, b, c, d, e, f, g, h) and 2 prismatic pairs ($J_P$: j, k). The corresponding degrees of freedom are as follows:

\[
F_a = 3(N_L - 1) - 2(N_{JR} + N_{JP}) = 3*(8-1) - 2*(9+1) = 1
\]  
\[
F_b = 3(N_L - 1) - 2(N_{JR} + N_{JP}) = 3*(8-1) - 2*(8+2) = 1
\]  

In Equations (1) and (2), $N_L$ is the number of machine members, $N_{JR}$ is the number of revolute pairs, and $N_{JP}$ is the number of prismatic pairs. Therefore, it can be seen that both suspensions are mechanisms with only one degree of freedom, that is to limit the up-and-down jumping of motorcycle wheels in the direction perpendicular to the ground, so as to ensure the driving stability of the wheels. The difference is that the machine members 7 and 8 in (A) can separate the steering system from the vibration damping system in the front suspension, while the machine members 7 and 8 in (B) are used for the rear wheel transmission shaft. If the machine members 7 and 8 are deleted from the two mechanisms, it will become a planar six-bar linkage mechanism with seven kinematic pairs, which is similar to that in reference [8]. And more connecting links can ensure the motorcycle to have more stable and flexible performance when driving at high speed. Therefore, this study takes the Duolever multi-bar linkage scissor front suspension of BMW in Figure 1(A) as the original mechanism to carry out mechanism regeneration design. The topology matrix $M_F$ of the mechanism is as follow:
3. Generalized kinematic chains and determined design constraints

According to the generalizing principles and rules, the fixed link 1 is released and generalized into a quaternary link, and the moving link 2 connected with wheels is generalized into a ternary link. The prismatic pair between the cylinder 3 and the piston 4 is transformed into a revolute pair and generalized into a binary link, the swing arm 5 is generalized into a ternary link, and the swing arms 6, 7 and 8 are generalized into binary links. The generalized kinematic chain is obtained as shown in Figure 2.

![Generalized kinematic chain of Duolever front suspension of BMW.](image)

According to the functional requirements of motorcycle front suspension, the following design constraints can be determined as the basis of regeneration mechanism. Firstly, the total number of links and kinematic pairs should remain unchanged, that is, the new mechanism must also be a planar eight-bar linkage mechanism with 10 kinematic pairs. Secondly, there must be a shock absorber composed of double-connecting links \( K_p \), and one end of the shock absorber should be connected with the fixed link. Thirdly, there must be a fixed link \( F \) attached to the vehicle’s body, and it should be a multi-pair link. Fourthly, there must be a moving link \( W \) connected with the wheels and not to the fixed link. Lastly, the moving link, the fixed link and the shock absorber connected with the wheels should be different links.

4. Combined kinematic chain

In the kinematic chain, the number of various link types and the number of kinematic pairs should meet the following requirements:

\[
2n_2 + 3n_3 + 4n_4 + \ldots + n_n = P
\]

\[
2n_2 + 3n_3 + 4n_4 + \ldots + n_n = N
\]

\[
n_{\text{max}} = P - N + 2
\]

In Equations (4), (5) and (6), \( n_2, n_3, n_4, \ldots, n_n \) respectively represent the number of binary links,
ternary links, quaternary links and N-pair links. \( n_{\text{max}} \) indicates the link type with the largest number of kinematic pairs in the kinematic chain. \( N \) represents the total number of links in the kinematic chain, and \( P \) represents the total number of kinematic pairs, then \( n_{\text{max}} = 4 \). 16 different kinematic chains can be obtained from the three types of eight-bar ten-pair assortment scheme: (1) \( n_2 = 4, n_3 = 0, n_4 = 0 \); (2) \( n_2 = 5, n_3 = 2, n_4 = 1 \); (3) \( n_2 = 6, n_3 = 0, n_4 = 2 \). However, in this design, there must be a shock absorber composed of double-connecting links. After eliminating all types that do not include two binary links connected together, 12 possible combinations are shown in Figure 3.

5. Regenerative kinematic chain

According to the constraint conditions specified above, the special treatment is carried out, and three ternary links and three quaternary links, namely (a), (b), (c), (k), (m) and (n) in Figure 3, are selected from the link types with the largest number of kinematic pairs to design the regenerative kinematic chain.

Firstly, designate the shock absorber \( (K_F) \). If there must be a shock absorber composed of double-connecting links, six kinds of non-isomorphic mechanisms can be obtained, as shown in Figure 4(a1), (b1), (c1), (k1), (m1) and (n1).

Secondly, designate the fixed link \( (F) \). When one end of the shock absorber is connected to the fixed link through the revolute pair, seven kinds of non-isomorphic mechanisms can be obtained, as shown in Figure 4(a1-1), (b1-1), (c1-1), (c1-2), (k1-1), (m1-1) and (n1-1).

Thirdly, designate the moving link connected with the wheels \( (W) \). If the moving link connected with the wheels is limited to a multi-pair link and cannot be connected with the fixed link, six kinds of non-isomorphic mechanisms can be obtained, as shown in Figure 4(a1-1-1), (b1-1-1), (c1-1-1), (c1-2-1), (c1-2-2) and (n1-1-1). The remaining multi-pair links in (k1-1) and (m1-1) are connected with the fixed link \( (F) \), and cannot be designated as the moving link \( (W) \).

Lastly, designate the remaining four swing arms \( (L_1, L_2, L_3, L_4) \). There is no design restriction on the swing arms, so the remaining four unspecified links are called swing arms. Then, six feasible specialized kinematic chains are obtained, as shown in Figure 4.

According to the same method, 13 different regenerative kinematic chains can be obtained: 4, 1, 4, 1, 1 and 2 in Figure 3(d), (e), (f), (g), (h) and (j) respectively. Figure 3(g) shows the Duolever multi-bar linkage scissor front suspension of BMW in Figure 1(A). Figure 4(b1-1-1) shows the eight-bar linkage.
rear suspension of Honda in Figure 1(B). Therefore, the remaining 17 types are new eight-bar linkage motorcycle suspension mechanisms.

6. New suspension mechanisms of the motorcycle
According to the 17 new motorcycle suspension mechanisms designed in the previous section, one of the ternary links (c1-2-2) and the quaternary links (n1-1-1) with the largest number of kinematic pairs is selected respectively, and the regenerated design mechanism is shown in Figure 5.
7. Conclusion
On the basis of analyzing the advantages and disadvantages of existing motorcycle suspensions, in order to break the technical barriers of enterprises, this study uses the mechanism regeneration method to design and develop new types of suspensions. Based on the suspension of planar eight-bar linkage with 10 kinematic pairs, the corresponding topology matrix is analyzed, and 12 kinds of combined kinematic chains that meet the requirements are obtained. Furthermore, the constraint conditions of the new suspension mechanisms are established, and the corresponding link types are specified in turn. Finally, 17 kinds of new eight-bar linkage motorcycle suspension mechanisms are designed. These new structures can provide theoretical and practical basis for independent design of motorcycle suspension system.

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