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Kinematic and sensitivity analysis and optimization of planar rack-and-pinion steering linkages

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Abstract

In this paper, the combined kinematic and sensitivity optimization of a rack-and-pinion steering linkage is performed. This steering linkage is the most common steering system used in passenger cars. Although, the steering linkage has received a lot of attention for the minimization of the steering errors, no attempt has been made so far to investigate the sensitivities of optimum dimensions relative to variation of link lengths. The kinematic optimization of the linkage is carried out using three homogenous design parameters. The objective of the proposed optimization is to minimize maximum steering error during cornering. This is followed by a sensitivity analysis to predict how the steering error is affected by manufacturing tolerances, assembly errors, and clearances resulting due to wear. Since the optimized kinematic error is very sensitive to the variations of the linkage parameters, the kinematic and post-optimal sensitivity optimization of the steering linkage is performed in an integrated manner. The methodology proposed in this work helps the designers of rack-and-pinion steering linkage to choose the linkage parameters whose maximum steering error (MSE) and sensitivity are minimum.

Keywords: Rack-and-pinion steering linkage; Steering error; Kinematic optimization; Post-optimal sensitivity; Cognates

1. Introduction

Among the steering linkages, rack-and-pinion steering linkage is the most widely used in passenger cars. It consists of two steering arms, two tie rods, and a rack. The linkage has two common configurations, namely, central take-off and side take-off, as shown in Fig. 1. In central take-off (CTO) configuration, the tie rods and the rack are connected at the middle of the rack as depicted in Fig. 1a, while in side take-off (STO) configuration, these connections are at the rack ends as shown in Fig. 1b. Each of the above configurations can be either trailing or leading type, as shown in Fig. 2a and b, respectively [1].

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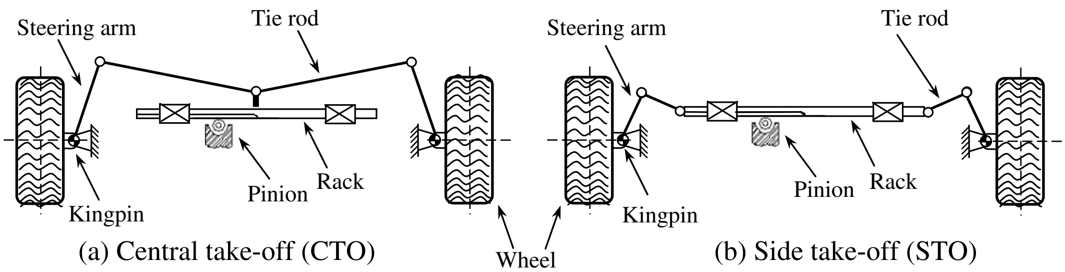

Fig. 1. Rack-and-pinion steering linkage and its configurations.

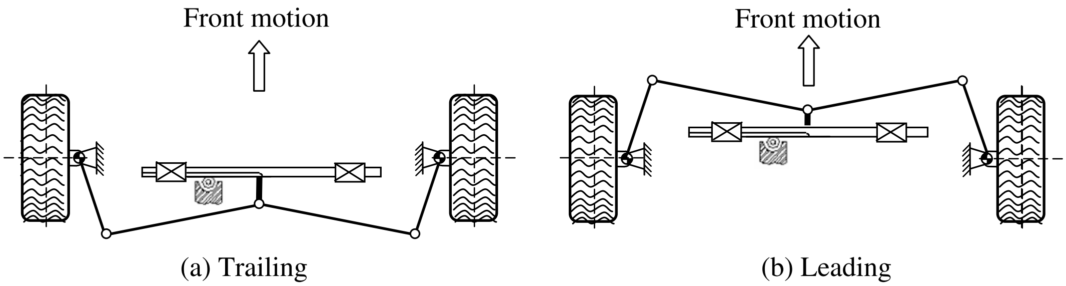

Fig. 2. Trailing and leading type of rack-and-pinion steering linkages.

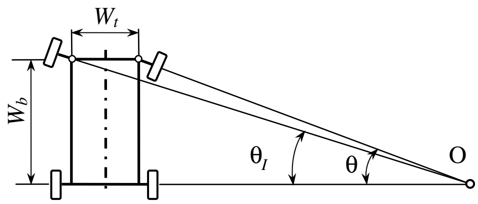

Fig. 3. Ackermann condition for a vehicle when turning.

In order to provide pure rolling to the road wheels and to reduce wear and tear of the tires, a steering linkage must handle the vehicle so that it follows Ackermann principle (see Fig. 3). This principle states that during low speed cornering when free from lateral inertia forces, the verticals drawn from the centers of the wheels should meet at the center of bend, i.e., point O of Fig. 3. For a two-wheel steering vehicle, this point must lie on the common axis of the rear wheels [1]. Referring to Fig. 3, the relation between the inner wheel angle, θ_{I}, and the outer wheel angle according to Ackermann principle, $\theta_{\mathrm{OA},}$ is given as

$$\theta_{\mathrm{OA}}(\theta_{\mathrm{I}}) = \tan^{-1}\frac{1}{\cot\theta_{\mathrm{I}} + \frac{W_{\mathrm{t}}}{W_{\mathrm{b}}}} = \tan^{-1}\frac{1}{\cot\theta_{\mathrm{I}} + 1/w_{\mathrm{b}}} \tag{1}$$

where $w_{\mathrm{b}} = W_{\mathrm{b}}/W_{\mathrm{t}}$ is the normalized expression of the wheel base, W_{b}, with respect to wheel track, W_{t}. In reality, Eq. (1) is never satisfied for every radius of orientations. Hence, there are efforts to synthesize the linkage so that Ackermann principle is satisfied for any orientation of the wheels as closely as possible. In order to do that, it is necessary to obtain the angle θ_{O} for a given value of θ_{I}. Hence, an appropriate kinematic model of the steering linkage is essential. In addition, the kingpin inclination and caster angles that provide compliance to the steering linkage with the suspension system have little influence on the motion transmission of the steering linkage. As a result, the real rack-and-pinion steering linkage, which is spatial in nature, can be modeled as a planar linkage for the investigation of Ackermann condition. Such a simplification of the steering system has been also used by other researchers, e.g. [2,3].