Applied Mathematical Modelling 38 (2014) 5456–5470

Contents lists available at ScienceDirect

Applied Mathematical Modelling

journal homepage: www.elsevier.com/locate/apm

Modeling the angular capability of the ball joints in a complex mechanism with two degrees of mobility

Petre Alexandru, Ion Vişa, Cătălin Alexandru *

Transilvania University of Braşov, Bd. Eroilor nr. 29, 500036 Braşov, Romania

ARTICLE INFO

Article history:
Received 20 September 2012
Received in revised form 21 December 2013
Accepted 15 April 2014
Available online 26 April 2014

Keywords:
Linkage mechanism
Ball joint
Angular capability
Guiding system

ABSTRACT

The paper puts forward a complex linkage mechanism with two degrees of mobility and three kinematic loops, which is used for the guiding (suspension and steering) system of the vehicles. The geometric parameters and the coordinates frames that define the mechanical system are presented, as well as the specific kinematic functions. For this complex mechanical system, the angular capability of the ball (spherical) joints is defined by two angles. The equations for these angles have been determined by matrix algebra tools, considering the transformation matrices between the bodies reference frames. The diagrams of the angular capability of the ball joints, which are represented in angular coordinates, describe the form, orientation and size of the sockets from the spherical casings. Wears, shocks, functional locks or the compromising of the joint strength can occur if scarce sockets are implemented. The risk points, in which the angular parameters have maximum values, have been determined, the simulation being performed for a real system (vehicle).

1. Introduction

Ball joint is used in countless applications, wherever rotational motion must be allowed to change the alignment of its rotation axis. The angular capability of the ball joints was a permanent concern and challenge from a theoretical as well as constructive point of view, the references pointed here giving an image of these developments.

Ball joint is modeled using dual-number coordinate-transformation matrices in [1]. The joint consists of concave and convex spherical surfaces engaged to prevent translations but allowing three degrees of freedom, all of which are rotations. An extended Denavit–Hartenberg notation which allows the independent parameters of the spatial mechanisms with ball joints to be derived for analysis and synthesis purposes is presented in [2]. A similar modeling is presented in [3], the interference-free region with maximum ball-retention capability of a socket in a spherical pair being determined analytically. Extended Denavit–Hartenberg notation was used to model binary mechanisms with spherical pairs, simplifying their design and study. The dimensional synthesis of a 3-RPS parallel manipulator according to the limitation on the range of motion of the ball joints is presented in [4]. In [5], ball joints based on a ball and socket configuration were developed for parallel kinematic machines. Four prototypes are implemented using point, rolling, sliding and aerostatic contact mechanisms, each with a magnetic preload between the ball and the socket. Closed-form solutions to the problem of defining the attachment of a ball joint in a spatial linkage are analyzed in [6], with the aim to minimize the opening angle of the

* Corresponding author. Tel./fax: +40 268472496.
E-mail address: calex@unitbv.ro (C. Alexandru).

http://dx.doi.org/10.1016/j.apm.2014.04.032

socket, maximizing in this way the ball retention capability. A kinematic analysis and optimization technique required for the optimal attachment of a ball joint to the ground pivoted link of an RSSR spatial four-bar linkage is developed in [7].

For a synthesized RSSR mechanism, the closed form equation describing the spherical trajectory of the ball in the socket as well the design and manufacturing issues of the ball joints are presented in [8]. Another important subject consists in the analysis of the limit on the range of motion of the ball joint due to the socket, with application in a practical manipulator [9]. The physical constraint was expressed as the maximum angle between the axis of symmetry of the ball joint and the link. A method well-suited to the automated computer optimization of the structural attachment of ball joints in spatial linkages is developed in [10], the main objective being to determine an optimal ball joint attachment such that the opening angle of the ball joint is minimized. A method of studying joint geometry is presented in [11], relating the geometry of contacting surfaces to motion capability in the joints of spatial linkages.

The modeling and functionality of the ball joints is also approached considering the implementation in the suspension and steering system of the motor vehicles. In [12], the angular capability of the ball joints (called "ball joint travel") is approached considering a SLA suspension mechanism. The ball joint travel is defined as the angular displacement between the two connected parts, quantifying in fact the amount of swing angle of the ball stud relative to the ball housing. The simulation was performed for a ground severe durability test, using a multi-body system model in ADAMS. The purpose was to study the effects of the stiffness characteristics of the bushings between the control suspension arms and the car body on the ball joint travels. The ball joint travel sensitivities to considered design variables are important to ensure reliable designs of ball joints. It should be noted that in this study the ball joint travel limits serve only as indicators, and the angular capability is defined/measured by a single angle per joint.

Another important issue in the field is the accurate identification of the geometric parameters in the suspension elastokinematic models. The deviations due to the elastic deformations of the compliant joints (bushings) in a pseudo-McPherson suspension system are approached in [13], a comprehensive method based on homogeneous coordinates and operators being developed for determining the precise position and orientation of joints (using a portable coordinate measuring machine). Other methods proposed for elastokinematic parameter identification in order to achieve correlation are based on the analysis of wheel motion under quasi-static load cases, by using statistical design of experiments techniques [14,15].

From the literature review, it can be seen that the studies about the ball joints applications in vehicle suspension and steering systems are less oriented towards the mathematical modeling of the angular capability, the optimal design of the form, orientation and size of the of the sockets from the spherical casings, and also the determination of the risk points, in which the angular parameters have maximum values.

Under these terms, in the present paper, the angular capability of the ball joints in a complex guiding (suspension and steering) system is approached with the aim of describing/determining an algorithm to find the optimal form, orientation and size of the sockets from the spherical casings, which allows avoiding/minimizing wears, shocks and functional locks. The correlation of the motions in the suspension and steering mechanisms, which have functional interdependences, represents another important aspect, the maximum travels of the suspension being coupled with the maximum steer rotations to delimit the extreme socket size.

The guiding system of the front wheel approached in this paper is defined by 56 geometric parameters (lengths, coordinates, and angles), having two driving elements, which correspond to the suspension and steering actuatings. Although the geometric system is presented as a rigid one, the adaptability for considering the elasticities in joints or deviations is very simple, by adding the deviations to the nominal values of the parameters. The spatial–geometric generality of the model/system and the adaptability for considering the deviations due to the elasticities represent important characteristics of the paper. For the 56 geometric parameters and the two independent kinematic variables, there is presented the full-allure of the relative motion in the ball joints (between bolts and spherical casings).

Thus, the following original elements, which differentiates the paper in relation to other works, can be formulated: defining the whole system in a general geometric–spatial model; combining the two kinematic actuatings on the entire working cycle of the suspension and steering system; marking the limit stroke points with their effect on the angular displacements in the ball joints; easy and direct integration of the deviations due to the elastic deformations in bushings; representing the angular displacements (i.e. the angular capability of the ball joints) on the entire working cycle of the kinematic variables, as well the size and orientation of the sockets from the spherical casings; a more complex and realistic modeling of the angular capability in the ball joints by using a pair of two angles for each joint. The model presented in this paper and the specific data are based on the careful analysis of a significant number of constructive variants of wheel guiding systems (suspension and steering), which have been generalized in a general spatial system.

2. Geometric modeling of the mechanical system

The application from the present paper is performed for a complex mechanical system, with two degrees of mobility and three kinematic loops, which is used for the guiding (suspension and steering) system of the motor vehicles. The scheme shown in Fig. 1 is for a quarter-car model, which corresponds to the left wheel of the vehicle, the right part being simetrically disposed relative to the longitudinal–vertical plane of the vehicle. A double-wishbone mechanism is used for the front wheel suspension. The suspension mechanism M_0MNN_0 uses two control arms (lower arm – 1, and upper arm – 3) to hold the wheel carrier (2) and control its movements. In the four-bar steering mechanism E_0ECA, the motion is transferred from