Mechanism and Machine Theory 92 (2015) 64–85

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Dynamics of chain drives using a generalized revolute clearance joint formulation

C. Pereira [a], J. Ambrósio [b,*], A. Ramalho [c]

[a] Polytechnic Institute of Coimbra, R. Pedro Nunes, 3030-199 Coimbra, Portugal
[b] LAETA, IDMEC, Instituto Superior Técnico, University of Lisbon, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[c] University of Coimbra, R. Luís Reis dos Santos, 3030-788 Coimbra, Portugal

ARTICLE INFO

Article history:
Received 17 May 2014
Received in revised form 27 April 2015
Accepted 30 April 2015
Available online xxxx

Keywords:
Chain drives
Multibody dynamics
Clearance revolute joints
Contact mechanics
Continuous contact force model

ABSTRACT

Roller chain drives can be modeled as a constrained dynamic system composed of a large number of rigid bodies, links, rollers and sprockets, interconnected by multiple ideal or clearance revolute joints. Here, the methodology described for a clearance revolute joint, usually used in the contact between the pin link/bushing link and the bushing link/roller pairs, is generalized to describe the roller/sprocket tooth surface contact pair. Regardless of whether the clearance revolute joint is used for roller–sprocket or bushing–sprocket engagements, depending on the chain type, the contact conditions are defined as a function of the tooth geometry. The methodology describing the tooth profile and allowing for the contact detection uses a tooth fixed coordinate system to evaluate all quantities required by the contact force model. As the contact phenomenon is herein described using the continuous contact force method, the contact force in each contact pair is available at any time during the dynamic simulation.

1. Introduction

Chain drives have been recognized as one of the most precise and effective forms of power transmission in mechanical systems [1]. However, not only due to the complexity of the system itself, composed of a large number of contacting bodies, but also due to the complex interactions between them, their complete dynamic behavior has only been studied in the last few decades [2–5]. Due to their discrete nature, chain drives are characterized by complex dynamic behavior dominated by the impacts between the chain links and sprockets and by the fact that even when the driving sprocket of a chain runs at a constant speed, the speed of the chain itself is not constant but is subject to periodic fluctuations resulting from the geometry of the chain wrapping around a polygon rather than a circle [3,6]. The combined effect of polygonal action and the occurrence of impacts between rollers and sprockets, at the moment of their engagement, lead to the discontinuities in the system velocities giving rise to transversal and longitudinal vibrations on the spans of the chain [7]. These phenomena are responsible for part of the noise emitted by mechanical devices that use chains and, ultimately, for the wear of chain drive, being their characterization of crucial importance for the development of better transmission designs.

Previous works, using continuous and discrete models as well as experimental measurements, addressed partially the chain drive dynamics [1,3,4,7–9]. With the development of more advanced dynamic analysis methodologies efforts were made to better understand the complexities of the motion of these chain drives [3]. Integrated models that describe the complex dynamics of the roller chain drive, including the detailed description of the non-trivial geometry of the sprocket surface and of the dynamics associated with the polygonal effect, the compliance of the chain, i.e., flexibility of links, transversal and longitudinal vibrations, friction effects, and impact forces between chain and sprockets, has been proposed by Kim and Johnson [10], Veikos and Freudenstein [11,12] and

* Corresponding author at: LAETA, IDMEC, Instituto Superior Técnico, Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal.
E-mail addresses: candida@isec.pt (C. Pereira), Jorge.ambrosio@tecnico.ulisboa.pt (J. Ambrósio), amilcar.ramalho@dem.uc.pt (A. Ramalho).

http://dx.doi.org/10.1016/j.mechmachtheory.2015.04.021
0094-114X/

Pedersen and co-workers [3]. Issues such as the efficiency loss due to friction [5], the chain link flexibility [3,13] or the influence of the chain tension [4,5] on the chain drive dynamics has been addressed in the framework of such models. It is the general understanding in these works that the chain efficiency as a transmission is mostly influenced by the tension, its flexibility and by the non-thermal friction losses.

However, in most of these models the intentional clearances required to allow relative motion between links and sprockets and to permit the link component assemblage as well and the dimensional variations due to manufacturing tolerances, machining imperfections, material deformations and mechanisms' wear, which invariably exist in all mechanical systems [14–16] were neglected. It is well known that the dynamic effects of clearances in joints have a profound influence on the dynamic response and service life of mechanical systems, particularly if the joints operate without lubricant, since internal impact forces and impulsive forces are generated [4,16–18]. However, due to cumulative effects, it is in a mechanical system with a greater number of contacting bodies, such as roller chain drives, that this issue assumes a crucial role [19]. The flexibility of the chain can also be associated with the existence of the clearances between its constitutive elements. This issue attracted recently a sprawl of attention in order to understand the effects of the contact force models and friction in clearance joints, being these translation [20,21], revolute [16,22] or just general contact pairs [23].

The knowledge of the peak contact forces developed in the contact process and their transmission throughout the system is very important for the dynamics of mechanical systems and has consequences in the engineering design process, namely to define the minimum level of suitable tolerances that will allow the roller chain to achieve the required performance [4,16]. The importance of the correct characterization of the chain dynamics is of particular interest in the description of the meshing dynamics and, in the process, for devising improved designs for this type of transmissions. The optimization of the tooth profile geometry is one of the forms pursued for such improvement and that requires reliable chain drive models [24]. Therefore, the revolute clearance joint formulation is adopted to perform this work, in which the mathematical models that describe the key elements of roller chain drives as planar multibody mechanical systems with multiple revolute clearance joints are presented.

2. Roller chain drive modeling

A chain drive is composed, at least, of a chain wrapped around driving and driven sprockets. The chain is made of alternating inner roller and outer pin links, assembled on pivots by bearing pins, which are alternately spaced throughout the length of the chain, as illustrated in Fig. 1. A roller link consists of two sets of rollers and bushings, the latter being press-fitted into the two side members, called link plates. The pin link has two link plates into which the two pins are press-fitted. When assembled, the two pins fit into the bushings of the two adjacent roller links. If the chain is of a bushing type instead of a roller chain, the roller element does not exist. Therefore, the chain can be modeled as just an assemblage between pin links and bushing links. The distance between the centers of adjacent joint members is defined by the pitch of a roller chain, as shown in Fig. 1.

Based on the description provided, the roller chain can be understood as a multibody system composed of a collection of rigid bodies, i.e., links, interconnected with ideal kinematic joints or clearance revolute joints that constrain the relative motion between the adjacent links in different directions [25]. Each roller chain connection consists of an assemblage of a pin link with a bushing link and a roller. However, if the clearance is considered, the connection between an inner link and an outer link forms a multirevolute clearance joint involving the assemblage of two revolute joints, one constituted by the bushing link/pin link pair and the other formed by the roller/bushing link pair, as shown in Fig. 2.

Moreover a chain drive consists of one or more chains whose links engage with one driving sprocket and one or more driven sprockets. The chain engagement on the sprocket results in the contact between the rollers and the sprocket surface. The geometry of the sprocket tooth profile is such that each contact pair can be modeled as an instantaneous revolute clearance joint in which the contact geometry is variable, depending on the region of the sprocket tooth in which contact occurs. The dynamic analysis of roller chain drives is therefore a complex issue, since its behavior is characterized by multiple, simultaneous contacts/impacts. This work proposes to address all contacts in the roller chain drive in a unified form using a generalized revolute clearance joint formulation to represent them.

The kinematic restrictions between any two bodies can be represented by a set of kinematic constraints or by contact force relations [14,17,25]. Due to the function and construction of a roller chain drive the contacts that occur with roller, pin and bushing require

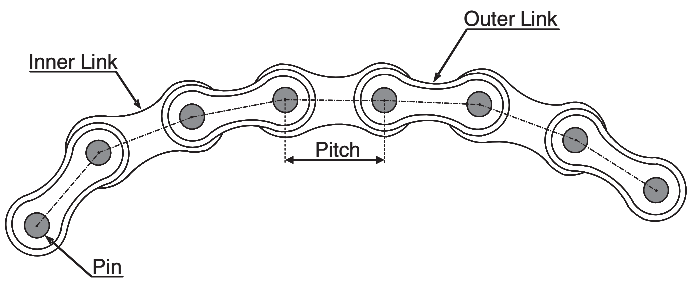

Fig. 1. Roller chain links.