Mechanism and Machine Theory 73 (2014) 218–243

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Analysis of the transmission ratio and efficiency ranges of the four-, five-, and six-link planetary gear trains

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A R T I C L E I N F O

Article history:
Received 17 October 2012
Received in revised form 30 October 2013
Accepted 8 November 2013
Available online 7 December 2013

Keywords:
Planetary gear train
Gear train efficiency
Transmission ratio
Planetary speed reducer
Kinematic inversion
Isomorphism

A B S T R A C T

The objective of the present work was the conjoint analysis of the efficiency and transmission ratio ranges that can be achieved with all the possible constructive solutions of four-, five-, and six-link planetary gear trains. We started from the graphs of these trains to determine all the structurally distinct kinematic inversions. We then obtained all the constructive solutions resulting from every possible combination of gear type and configuration. The result was thus the set of structurally and constructively different planetary gear trains. Next, we obtained the range of transmission ratio that can be achieved with each train, and the efficiency as a function of the transmission ratios within that range. This analysis revealed which trains allow both high transmission ratios and high efficiency, and are thus potentially most useful in the design of power transmission applications. They included a series of high efficiency trains whose potential utility had not as yet been investigated. Additionally, the study led to some interesting conclusions about the relationship between efficiency and transmission ratio in six-link planetary gear trains.

1. Introduction

In the recent past, several researchers have focused their efforts on determining all the possible different structural forms of planetary gear trains (PGTs), with some of the recent work in this line being that of [1–4]. Knowledge of the different types of PGT is of interest both scientifically and technologically. In particular, it could lead to the design and construction of more efficient implementations of such trains. In this regard, PGT efficiency must be understood as a generic and global concept. This is because, given a certain transmission ratio, the designer would like to be able to select from all matching PGTs those that have the right combination of efficiency and simplicity of construction. Few studies have addressed this important issue. Of particular interest among those that have are [5,6,4], although this last does so from a qualitative standpoint.

As noted above, one important question in this field is to find an efficient way to select planetary gear trains that allow a high transmission ratio without excessively sacrificing efficiency and without having recourse to great structural complexity. This issue is dealt with explicitly in [5,6]. Another interesting work in this line is [7] in which a worm gear and a planetary gear train are combined to reduce the transmission ratio. The resulting gear drives, however, have relatively low efficiency. Finally, also worthy of note is the methodological approach taken in [8]. This study presents a procedure to assess the sensitivity of certain characteristics of a planetary gear train – the efficiency and the transmission ratio – with respect to small variations in the design parameters. However, the method is only applied to a particular train by way of example rather than by performing an exhaustive analysis of numerous gear trains.

The present work addresses the problem of determining the set of planetary gear trains with the greatest efficiency for a given transmission ratio. This problem is solved comprehensively and conclusively by analyzing, for a given PGT, all the possible

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0094-114X/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.mechmachtheory.2013.11.001

constructive solutions with all the possible types of gears. For the results to be practical, the analysis is focused on trains with at most six links, since, with more links, the complexity of the construction would increase drastically. The results are of great practical interest, showing that there are a significant number of reducer trains with high efficiency that will allow transmission ratios in the range 1/20 to 1/100 to be attained. The results are similar for the case of increaser gear trains.

One key point that needs to be taken into account in analyzing and estimating the efficiency of a PGT is its structure. This is determined by the number and type of links, and by the kinematic pairs between them. In particular, the links of PGTs are of three types which in the present work we shall call suns, arms, and planets. The planets are links that undergo a planetary motion. Each planet is linked to its respective arm by a turning pair and to other members by gear pairs. The arms have a rotational movement around the PGT's principal axis, and are characterized by having at least one turning pair with a planet; they may also have gear pairs with other members. Finally, the suns are links that only have gear pairs with other links and also have a rotational movement around the PGT's principal axis. Suns and arms are central links since they rotate around the central axis of the PGT, whereas the planets are non-central links since they have a planetary motion. Fig. 1(a) shows a scheme of an 8-link PGT. Links 1, 2, and 3 are the suns; links 4 and 5 are the arms; and links 6, 7, and 8 are the planets of the PGT. Finally, the structure of a PGT is completely defined by its list of circuits. Each circuit is the set of three links that it is involved in each gear pair. These three links are the sun and the planet that are linked by the gear pair, and the arm that makes it possible that kinematic link. Therefore, the number of circuits is equal to the number of gear pairs. For example, the circuits of the PGT shown in Fig. 1(a) are (1, 6, 4), (1, 7, 4), (2, 6, 4), (2, 8, 5), (3, 7, 4) and (3, 8, 5), where the order of the links in each circuit is sun, planet and arm.

A PGT can also be represented as a graph in which each vertex corresponds to a link of the train, and each edge corresponds to a kinematic pair between the links corresponding to the vertices at the ends of the edge. In this paper, we shall use the graph representation introduced in [1] in which the vertices of the graph are drawn in three rows. The top row corresponds to the arms, the central row to the planets, and the bottom row to the suns. The kinematic pairs are represented by solid edges for the turning pairs and dashed edges for the gear pairs. For the sake of simplicity only those turning pairs linking the planets with the suns and/or arms are included in the graph representation proposed in [1]. Fig. 1b shows the graph representing the train of Fig. 1(a).

There can be a great diversity in the constructional solutions adopted for a given PGT, i.e., different constructional solutions based on the same underlying structure (given by its graph) and the same inversion. The inversion is the triplet: input link, output link, and ground link. The notation used for the inversions will be (X,Y-Z) where X is the input link, Y the output link, and Z the ground link. The structure of a PGT is defined by the set of links of the train and by the relationship of the pairs that link each of these members to the others.

The number of the different constructional solutions depends on how the links are designed. In the present work, a constructional solution of a PGT will be understood to be the set of types of gear pairs used – external or internal – and the specific form in which each link is constructed. In particular, in this work we shall focus on the constructive solution adopted for each planet. Therefore, the expression “simple planet” will be used for a planet constructed with a single gear and “double planet” for one constructed with two gears.

Fig. 1(a) shows a particular constructive solution of the PGT whose graph is shown in Fig. 1(b). This solution results from choosing the inversion 1,5–2 of the graph, so that the input link is the sun 1, the output link is the arm 5, and the ground link is the sun 2. Additionally, this constructive solution is characterized by having two simple planets (planets 6 and 8) and a double planet (planet 7), and for having chosen external gears for the gear pairs between the links 1–6, 1–7, 3–7, and 3–8, and internal gears for the 2–6 and 2–8 pairs. All the possible combinations of external and internal gears and of the constructive form adopted for each planet give rise to the set of constructive solutions of a PGT.

In [1], the graphs of planetary gear trains of one degree of freedom that had a maximum of nine links were identified and enumerated. The PGTs enumerated in that work formed the starting point for the present study. Fig. 2 shows the graphs of the 4- to 7-link PGTs obtained in [1]. The links in the graphs are labeled as follows: first label the suns, then the arms, and finally the

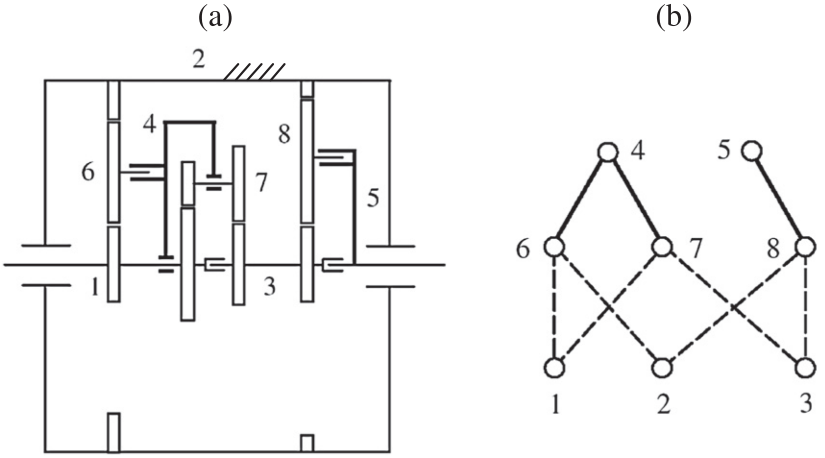

Fig. 1. (a) Constructive solution of an 8-link planetary gear train, and (b) its representation in the form of a graph.