Meshing Efficiency Analysis of Two Degree-of-Freedom Epicyclic Gear Trains

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The concept of potential power efficiency is introduced as the efficiency of an epicyclic gear train (EGT) measured in any moving reference frame. The conventional efficiency can be computed in a carrier-moving reference frame in which the gear carrier appears relatively fixed. In principle, by attaching the reference frame to an appropriate link, torques can be calculated with respect to each input, output, or (relatively) fixed link in the EGT. Once the power flow direction is obtained from the potential power ratio, the torque ratios are obtained from the potential power efficiencies, the particular expression of the efficiency of the EGT is found in a simple manner. A systematic methodology for the efficiency analysis of one and two degree-of-freedom (DOF) EGTs is described, and 14 ready-to-use efficiency formulas are derived for 2DOF gear pair entities (GPEs). This paper includes also a discussion on the redundancy of the efficiency formulas used for 1DOF GPEs. An incomplete in the efficiency formulas in previous literature, which make them susceptible to wrong application, is brought to light. [DOI: 10.1115/1.4033693]

Introduction

Several methods for determination of efficiencies in EGTs are proposed [1–25]. Most of these analyses are performed based on the principle of equilibrium of torques. Merritt [1] and Macmillan and Davies [2,3] deduced independently the efficiencies for all the epicyclic inversions of a GPE. In particular, these efficiencies have been related to the gear ratio $N_{i,j}$ and to the mechanical efficiency $\eta_{c(i-j)}$ of the GPE when operating with a fixed carrier. Merritt approach [1] is based on the fact that the torques acting on the links and the power loss are independent of the observer's motion. Pennestri and Freudenstein [4] adopted the formulas which are used for the estimation of efficiency in epicyclic inversions and 2DOF differential gearing, deduced by Merritt [1] and Radzimovsky [6], respectively. They embodied the formulas deduced by Merritt and Radzimovsky, in their systematic method for mechanical efficiency analysis of EGTs [4]. In particular, Radzimovsky [5] presented relationships that, given the efficiencies of the gear train when one of the input shafts is fixed and the speed ratios, the overall efficiency in a 2DOF differential gear train is determined. Yu and Beachley [7] introduced analytical methods for the efficiency analysis of gearing with 2DOFs. del Castillo [8] used the virtual gear tooth ratios and the gearing power to obtain formulas for the efficiency of epicyclic trains. Chen and Angeles [9] applied the concept of virtual power ratio for the mechanical efficiency analysis of one-carrier EGTs. Chen and Liang [10] applied Chen and Angeles method [9] to find formulas for efficiency of 2DOF gear trains. The three limitations of the virtual power method are the uncertainty regarding the number of equations, the need for ad hoc reasoning in the application of the power ratios, and the lack of generality. Pennestri et al. [11] expended the ready-to-use formulas proposed by Pennestrì and Freudenstein [4], to apply them to power split transmissions with EGTs. Mantriota and Pennestrì [14] proposed and experimentally validated a load-dependent losses model for EGTs. Hsieh and Tsai [16] used Merritt approach to select the most efficient clutching sequences associated with epicyclic-type automatic transmission. Duan and Yang [17] analyzed the meshing efficiency of 3K-type planetary gear train, while Hsieh and Tang [21] analyzed the meshing efficiency of 2K–2H type epicyclic gear reducer.

In GPEs, the power developed may differ from that being transmitted. This unique characteristic, which is a result of the relative motion of the gears, is present in some GPEs and has a significant effect on the efficiency. Although analytical expressions were developed for the efficiency of GPEs [4,6,11,12], the relationships involved are not always reliable. They did not take into account, when originally derived, all the possible working conditions.

In the design of EGTs, mechanical efficiency is one of the important consideration factors. The torque and power distributions have significant effect on the efficiency of EGTs. However, the efficiency analysis due to various inversions of a GPE is still not thoroughly explored. In this study, the principle of equilibrium of torques will be applied to show how the efficiency of an epicyclic GP is related to the efficiency of a conventional GP and its kinematic inversions and to identify the efficiency characteristics of 1 and 2DOF GPEs.

General Pair Entity (GPE). The GPE is defined as an entity consisting of a pair of meshing gears and a carrier. A gear or a carrier can be shared by different entities. The EGTs are composed of two kinds of GPEs: the external GPE (planet-sun GP) and the internal GPE (planet-ring GP). A GPE has three basic members that can input or output power, including the carrier as in Fig. 1. A GPE has 2DOFs, i.e., two constraints must be given, otherwise the relationships among the three members are independent. For example, if two of the three members are given as inputs, then the other can be determined as the output. It is also possible to have one input and two outputs, and knowing any two values makes it possible to calculate the third.

Planet Speed Ratio. The term "planet speed ratio" will be used here to denote the relative speed ratio between any two links of a GPE with respect to the carrier [26]. The planet speed ratio between links p and j can be written as

$$N_{p,j} = \frac{\omega_j - \omega_c}{\omega_p - \omega_c} \quad \text{for} \quad j = p, q, \text{ and } c \tag{1}$$

where link j is any link in the GPE, and ω_p, ω_j, and ω_c denote the speeds of the links p, j, and carrier c, respectively. From Eq. (1),

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Contributed by the Power Transmission and Gearing Committee of ASME for publication in the JOURNAL OF MECHANICAL DESIGN. Manuscript received January 15, 2016; final manuscript received May 20, 2016; published online June 13, 2016. Assoc. Editor: Hai Xu.