An Approach to Power-Flow and Static Force Analysis in Multi-Input Multi-Output Epicyclic-Type Transmission Trains

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This study contributes to the development of a systematic methodology for the torque and power-flow analyses of multi-input multi-output (MIMO) epicyclic gear mechanisms (EGMs) with or without reaction link based on the concept of fundamental circuit. The studies on power-flow analysis of EGMs are mostly done in the context of efficiency formulations. In the opinion of the authors, the design process of the MIMO mechanism involves not only finding the configuration that provides the correct velocity ratios but also meeting other kinematic requirements and ensuring that the two inputs have a mutually constructive nature. To demonstrate the analysis, a new motor/generator integrated hybrid transmission design is used to show how the torque acting on each link of an epicyclic gear train (EGT) can be systematically solved in terms of input torque(s) and/or controlled output torque. This paper presents a unification of kinematic and torque balance approaches for the analysis of MIMO epicyclic-type transmission trains. The results presented are meant to deepen the knowledge as to how and why a MIMO epicyclic-type transmission should operate in a certain way under the given conditions. In the process, this paper explores the theoretical bases of operation of the Toyota Hybrid System and the root cause of some confusion in the field of EGTs.
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1 Introduction

Due to the fact that the function of an automotive transmission mechanism is to provide proper torques and velocities for a vehicle, it is essential to identify the relations among the velocity ratio, torque distribution, and the power flow in an EGM.

The studies on power-flow analysis of EGMs are mostly done in the context of efficiency formulations [1–3]. Pennestri and Freudenstein [1,2] used the same fundamental circuits (FCs) proposed earlier in their kinematic work [4] for a complete static force analysis. Hsieh and Tsai [3] applied a similar formulation in conjunction with their earlier kinematic study [5] to determine the most efficient kinematic configuration for one-degree-of-freedom (DOF) automatic transmission gear train. Kahraman et al. [6] used the concept of kinematic units (KUs) developed by Liu and Chen [7] for analyzing speeds of any typical one-degree-of-freedom automatic transmission gear train. They also performed a complete static force (power-flow) analysis. The work by Del Castillo [8] further generalizes the efficiency formulations of gear trains formed by single- or double-planet arrangements. A review of formulas for the mechanical efficiency analysis of two DOF epicyclic gear trains is presented by Pennestri and Valentini [9].

The arrangement used in the Toyota Hybrid System (THS) [10] is a basic epicyclic gear train (EGT). The basic EGT consists of a sun gear, a ring gear, a carrier, and several planets. It is shown in Fig. 1(*a*). The carrier is connected to an engine crankshaft, the sun gear is connected to a first motor/generator (MG1), and the ring gear is used as the output shaft of the transmission. The output shaft is connected to a final reduction unit followed by a differential gearbox to drive the wheels. In addition, a second motor/generator (MG2) is connected directly to the output shaft of the transmission. Such arrangement allows the engine power to be split into two paths, one through the ring gear to the output shaft (mechanical path) and the other via the sun gear to the generator (electrical path). In this path, the generated electricity is used to drive MG2, which in turn drives the vehicle wheels.

When MG1 acts as a motor, it drives the sun gear backward. Then, the engine and MG1 work together to drive the output shaft as a two-input EGT.

Since the engine is the primary converter on the vehicle, the direct fuel to engine to wheel path is the most efficient energy path on the vehicle. THS possesses many favorable characteristics; however, the potential disadvantages of this design include the need for two electrical motors and a constant split of the engine power. Also, the simultaneous dual motor operation requires sophisticated control systems and intricate custom fabrication [11].

Corey [12] presented a solution technique for finding a total speed and force solution to two-DOF EGTs having no reaction link in the most general case possible. The EGT to be used in Ref. [12] in a new generation of tandem bicycles is shown in Fig. 1(*b*).

Nazim and Hussaini [13] presented a new concept of mobile robot speed control by using two degree of freedom gear transmission made up of a basic EGT. The basic EGT used in Ref. [13] is shown in Fig. 1(*c*).

The concept had only been simulated without regard concerning the validity of the mechanical solutions or the creation of a reliable physical simulation model for the transmission. "The controller is built on the speed mixing capability of a two degree of freedom epicyclic gear train." The car engine and the additional dc motor, "in turn, jointly control the speed of vehicle wheels according to the characteristic equation of the selected epicyclic gear train."

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