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Research paper

Direct analysis of power-split CVTs: A unified method

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ABSTRACT

This paper provides a fast kinematic analysis method for compound power-split CVTs, which consents to identify their functional parameters. Such parameters permit the assessment of power flows, torques and efficiency, and the design of equivalent transmissions by the use of a recently published mathematical model. The same method can easily address either simpler or more complex transmissions by mean of kinematic equivalent parameters, without the need to arrange separate systems of equations. As a case study, we performed the kinematic analysis of the "Voltec" multi-mode GM transmission.

1. Introduction

A new mathematical model for the preliminary design of power-split CVTs has been recently published [1]. It has been shown that a small number of functional parameters rule the operation of any power-split transmission: kinematics, power flows and efficiency can be assessed regardless the actual constructive layout.

In particular, these parameters govern a set of characteristic functions whose graphical representation, named *design-chart*, permits a quick comparison between the main features of different solutions, and can lead to important constructive simplifications, while taking efficiency-oriented choices.

Accordingly, for given target functional parameters, the method [1] leads the designer to choose a specific preliminary constructive concept, among all the possible solutions with one or two planetary gear trains and up to six ordinary gears.

However, despite the method [1] aims to the constructive feasibility of the involved gear sets, for instance it may be difficult to realize exactly the required ratios by means of concrete structures, because actual gear ratios are discrete. Therefore, a quick analysis method is necessary in order to assess the impact of a small variation of the constructive parameters on the transmission functioning, thus obtaining, for the chosen constructive scheme, its actual functional parameters.

This task is conceptually easy, and there are countless examples of similar analysis in literature [2–22]; nevertheless, none seems to provide a reasonably simple unified method in order to address all the possible different constructive solutions, especially when several functioning modes are involved. Accordingly, the main purpose of this article is to provide a unified method for the analysis of such transmissions, by identifying the functional parameters defined in [1].

Therefore, the method presented in this paper can be used to verify how much the target functional parameters will differ from the obtainable ones, but it also permits to analyze the operation of an existing power-split transmission as well

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Nomenclature

An over-lined power or torque symbol refers to real working conditions

A	overall ratio spread
A_j	ratio spread of the jth shaft
i	input of the CVU
j	jth shaft
IN	input of the transmission
o	output of the CVU
OUT	output of the transmission
k_x	fixed speed ratio on the xth shaft of a three port differential
P_j	ideal power transmitted by the jth shaft
p_j	dimensionless ideal power transmitted by the jth shaft
p_i	dimensionless ideal power transmitted by the CVU
T_j	ideal torque applied to the jth shaft
α_j	implicit functional parameter
η	apparent efficiency of the PS-CVT
η_v	apparent efficiency of the CVU
τ	overall speed ratio (ω_{OUT}/ω_{IN})
τ'	normalized overall speed ratio (τ/τ_m)
τ_j	jth speed ratio (ω_j/ω_{IN})
τ_*	overall speed ratio concurrent with the synchronism of one planetary gear train
τ_v	CVU speed ratio (ω_o/ω_i)
$\tau_{\#i}$	overall speed ratio when the "i" shaft is still
$\tau_{\#o}$	overall speed ratio when the "o" shaft is still
$\tau_{i_{\#o}}$	τ_i when the "o" shaft is still
$\tau_{o_{\#i}}$	τ_o when the "i" shaft is still
$\phi^{z}_{y/x}$	generic three-port differential characteristic function
$\psi^{z}_{y/x}$	fixed-z speed ratio of the planetary gear train in a three port differential
Ψ	basic Willis' ratio
ω_j	angular speed of the jth shaft

Subscripts

m	concurrent with the initial overall speed ratio
M	concurrent with the final overall speed ratio
$\#i$	concurrent with the nodal overall speed ratio $\tau_{\#i}$
#o	concurrent with the nodal overall speed ratio $\tau_{\#o}$

as to explore the other possible equivalent designs by mean of the model presented in [1]. As example, we used it with the GM Voltec multi-mode transmission.

2. Theory

A Power-Split CVT (Fig. 1) consists of a Continuously Variable Unit (CVU) of any kind and of a Power-Split Unit (PSU), which is composed by two (or one) planetary gear trains and up to six fixed-ratio joints (Fig. 2).

Regardless the actual constructive layout, kinematics, power flows and efficiency are ruled by few functional parameters, such as the actual working range of each involved device [1], defined by its initial speed ratio τ_{i_m} τ_{o_m} or τ_m and its ratio spread A_i, A_o or A:

$$A_i = \frac{\tau_{i_M}}{\tau_{i_m}} \qquad A_o = \frac{\tau_{o_M}}{\tau_{o_m}} \qquad A = \frac{\tau_M}{\tau_m} \tag{1}$$

Alternatively, the kinematics may be defined as functions of α_i and α_o. Formerly, α_i and α_o represent the normalized overall transmission ratios for which the input or output shaft of the CVU is null (mechanical points or node points):

$$\alpha_i = \frac{A_i - A}{A_i - 1} = \frac{\tau_{\#i}}{\tau_m} \qquad \alpha_o = \frac{A_o - A}{A_o - 1} = \frac{\tau_{\#o}}{\tau_m} \tag{2}$$

They are related to the ratio spreads, but they may not be actual working points.

However, in an analysis study, the working range of each involved device is not known yet. Accordingly, we have to rearrange the relationships presented in [1] using variables that are independent in respect to the latter.