

Synthesis of Efficient Powersplit CVT/IVT System

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ABSTRACT

The target of the work is to find out the algorithm of definition of the ratios of mechanical part of complex powersplit CVT/IVT system with regard to the highest achievable efficiency. The presented synthesis is focused on powersplit systems, which will consist of a CVT part, differential and eventually by-pass gear. The algorithm will be programmed and become an integral part of the program Sungear developed on Czech Technical University in Prague for analyses and synthesis of planetary stepped transmissions and CVT/IVT powersplit systems. The article will mainly present the algorithm of definition of efficient powersplit system.

For the search of the efficient powersplit system we assume that the following parameters are given:

- a. Spread and efficiency of used CVT system.
- b. Total spread of the whole powersplit CVT/IVT mechanism.
- c. Optional: Ratios of the used CVT system.
- d. Optional: Ratios of the whole powersplit CVT/IVT system.

The more kinematic parameters will be given, the more constraints of mechanism are defined and the less optimization capabilities will remain. If all four points a) up to d) will be given for a known structure, the mechanism will be totally constrained, i.e. the ratios of mechanical part can be directly calculated. The search of the most efficient mechanism is replaced with search of the best combination of differential, bypass ratio and CVT system.

When only the parameters in the first two points a) and b) will be given (optionally with c) or d)) then not only the topology, but also the ratios of the remaining mechanical part are searched for. In our study the parameters are searched in order to satisfy only one target: to obtain the highest possible efficiency. For the total efficiency the amount of the power transmitted through the CVT is decisive. In the study is demonstrated, that the total spread depends exponentially on the amount of power transmitted through the CVT part, and the total efficiency depends linearly on the amount of power transmitted through the CVT part. The bigger total spread is demanded, the lower total efficiency of the system will be obtained. In case of a mechanism, where will be demanded a total spread bigger than the given spread of the CVT part a solution is searched which includes shiftable (more mode) mechanical part. For shifting are searched preferably such combinations, where the clutch will be actuated in the point when both shafts rotate at the same speed. In the current state the algorithm is capable to find out the best ratios for combination of CVT part, differential with 2 DOF and 4 shafts with eventual combination of by-pass gear ratio. The results will be presented with help of schemes of possible real configurations.

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1. INTRODUCTION

The transmissions play an important role in the driveline. Their parameters are decisive for the overall efficiency. The trend of usage of modern downsized engines [1], has strong impact on the parameters of transmissions. Especially wide spread is highly demanded. The optimum ratios can help to reduce the fuel consumption of the engine (allowing the engine to work in the most efficient field). On the other hand the efficiency of the transmission itself is important to keep the achieved efficient

functioning of the Internal Combustion Engine. Currently the development in the field of transmissions is very dynamic, and new combinations of several gearbox systems are explored. The example how to optimize the integral drivetrain with powersplit transmission can be found in [6].

In the present article we will focus on the synthesis of powersplit CVT or IVT systems. There have been published a lot of studies concerning different solutions of efficient wide

spread Variable Transmissions, e.g. [2], [3], [4]. To our knowledge no one treats the methodology of design of powersplit CVT/IVT systems. A part of the methodology can be found in [5]. In [7] was presented the system for complete analysis of stepped and continuous powersplit transmissions and several rules leading to the synthesis of powersplit systems.

In this article we present the approach based on the analytical derivation of kinematics and torque ratios for mechanisms consisting from two DOF differential with four or three external shafts, variator, and eventually additional gears. Right now, only frictional CVT's can be taken into account, the hydrostatic and hydrodynamic CVT'S will be goal of next research.

2. ANALYTICAL MODEL OF POWERSPLIT MECHANISM

Since the mechanism will be optimized based on the efficiency calculation, firstly the approach of efficiency estimation will be presented. Further will be derived a more general model of powersplit mechanism with differential with 4 external shafts. Next in separate chapters are shown the results of derivation for 2 DOF, 3 external shafts differential (the mechanism with input-coupled variable shunt, or output-coupled variable shunt).

2.1. Efficiency Estimation

The estimation of efficiency is made for a mechanism with unknown topology. Therefore we are not capable to do the accurate calculation. For estimation we take into account the efficiency of the CVT only. We suppose that the efficiency of variator is much lower than that of the mechanical parts of powersplit mechanism, so we expect an error in order of approximately 2 to 5 % (depending on the complexity of the mechanical part). This expectation will be confirmed later.

The efficiency is defined as ratio of output and input powers.

$$\eta_{CVT} = \frac{|P_{output}|}{P_{input}} \quad (1)$$

The lost power in the mechanism can be expressed with help of input power.

$$|P_{Lost}| = P_{input} \cdot \xi = P_{input} \cdot (1 - \eta) \quad (2)$$

Since we stated that only the losses in the variator will be taken into account we can write the following equation, where α denotes the CVT input shaft and I denotes the input to the whole mechanism.

$$|P_{Lost}| = P_{\alpha} \cdot (1 - \eta_{CVT}) = P_I \cdot (1 - \eta) \quad (3)$$

The ratio between the power on the input shaft of the whole mechanism and the input shaft of the variator defines the relative input power to the CVT: $\mu_{\alpha I}$

$$\mu_{\alpha I} = \frac{P_{\alpha}}{P_I} = \frac{1 - \eta}{1 - \eta_{CVT}} \quad (4)$$

From previous equation results the following dependence of total efficiency.

$$\eta = 1 - \mu_{\alpha I} \cdot (1 - \eta_{CVT}) \quad (5)$$

From this equation we can read, that the higher power will flow through CVT mechanism, the lower total efficiency will be; the higher efficiency of CVT, the higher total efficiency of the complete mechanism. We cannot influence the efficiency of the CVT with the topology of the complete mechanism, but we can influence the amount of relative power on the input shaft of the CVT. When we will derive the equations of kinematics for different mechanisms, it is important to derive also the expression for relative power on the CVT input shaft. These equations will play crucial role in proposal of efficient powersplit mechanism.

2.2. Powersplit Mechanism with 2 DOF, 4 External Shafts Differential

In this chapter will be derived the basic equations of kinematics of the mechanism depicted in Figure 1. The search of the optimal mechanism will be made based on the given kinematic parameters - like spread of the CVT (eventually completed with minimal or maximal ratio), desired spread of the whole mechanism (eventually completed with minimal and maximal ratios). Therefore the derivation of kinematics will be made with objective to define the dependence between total spread and CVT kinematic parameters.

The optimization of parameters will be done with respect to achieve the highest efficiency. With regard to the estimations made in previous chapter the relative power on the CVT input shaft will be derived also.

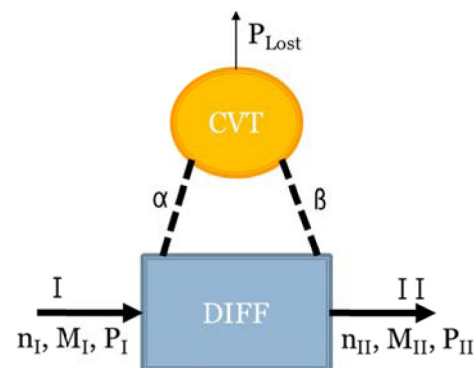


Figure 1. Scheme of powersplit mechanism with 4 shafts differential with 2 DOF.

The differential has 2 DOF and 4 external shafts, which leads to 4 - 2 independent equations of kinematics:

$$\begin{aligned}\omega_I &= i_{I,\alpha}^\beta \cdot \omega_\alpha + i_{I,\beta}^\alpha \cdot \omega_\beta \\ \omega_{II} &= i_{II,\alpha}^\beta \cdot \omega_\alpha + i_{II,\beta}^\alpha \cdot \omega_\beta\end{aligned}\quad (6)$$

The ratios in every kinematic equation are mutually dependent as demonstrated by Willis [8].

$$\begin{aligned}i_{I,\alpha}^\beta &= 1 - i_{I,\beta}^\alpha \\ i_{II,\alpha}^\beta &= 1 - i_{II,\beta}^\alpha\end{aligned}\quad (7)$$

To simplify the notation we will introduce the constants a_1, b_1, a_2, b_2 instead of the ratios $i_{I,\alpha}^\beta, i_{I,\beta}^\alpha, i_{II,\alpha}^\beta, i_{II,\beta}^\alpha$. Although the ratios are dependent, we will keep the general form of equations.

$$\omega_I = a_1 \cdot \omega_\alpha + b_1 \cdot \omega_\beta \quad (8)$$

$$\omega_{II} = a_2 \cdot \omega_\alpha + b_2 \cdot \omega_\beta \quad (9)$$

The kinematic parameter of the CVT can be calculated with help of the [equation \(10\)](#)

$$\nu_{CVT} = \frac{\omega_\beta}{\omega_\alpha} \quad (10)$$

The kinematic parameter of the mechanism can be calculated as follows:

$$\nu = \frac{1}{i} = \frac{\omega_{II}}{\omega_I} = \frac{a_2 \cdot \omega_\alpha + b_2 \cdot \omega_\beta}{a_1 \cdot \omega_\alpha + b_1 \cdot \omega_\beta} = \frac{a_2 \cdot \nu_{CVT} + b_2}{a_1 \cdot \nu_{CVT} + b_1} \quad (11)$$

For efficiency optimization we need to determine the relative power on shaft α . The relative power can be calculated with help of relative torque and ratio of shaft α .

$$\mu_{\alpha,I} = m_{\alpha,I} \cdot i_{\alpha,I} \quad (12)$$

We will determine the ratio between shaft α and input shaft I from [equation \(8\)](#).

$$i_{\alpha,I} = \frac{1}{a_1 + b_1 \cdot \nu_{CVT}} \quad (13)$$

The estimation of torque on shaft α related to the input shaft I we obtain from the equation of power equilibrium on the differential.

$$\begin{aligned}P_I + P'_\alpha + P'_\beta + P_{II} &= 0 \\ T_I \cdot n_I + T'_\alpha \cdot n_\alpha + T'_\beta \cdot n_\beta + T_{II} \cdot n_{II} &= 0\end{aligned}\quad (14)$$

On the shafts α and β should be established the torque equilibrium, it means:

$$\begin{aligned}T'_\alpha &= -T_\alpha \\ T'_\beta &= -T_\beta\end{aligned}\quad (15)$$

Introducing [equations \(8\), \(9\)](#) and [\(15\)](#) into [equation \(14\)](#) we obtain the following form of equation of power equilibrium on the differential.

$$\begin{aligned}\omega_\alpha \cdot (T_I \cdot a_1 - T_\alpha + T_{II} \cdot a_2) + \\ + \omega_\beta \cdot (T_I \cdot b_1 - T_\beta + T_{II} \cdot b_2) &= 0\end{aligned}\quad (16)$$

The [equation \(16\)](#) should be valid for any ω_α or ω_β . Therefore the expressions in brackets should equal 0. When dividing the expressions in brackets with input torque T_I we obtain the equation for relative torque on shaft α and β .

$$\begin{aligned}T_\alpha &= T_I \cdot a_1 + T_{II} \cdot a_2 \quad \left| \div T_I \right. \\ T_\beta &= T_I \cdot b_1 + T_{II} \cdot b_2 \quad \left| \div T_I \right. \\ m_{\alpha,I} &= a_1 + m \cdot a_2 \\ m_{\beta,I} &= b_1 + m \cdot b_2\end{aligned}\quad (17)$$

The expression m denotes the relative output torque. It can be expressed also with help of kinematic parameter and total efficiency.

$$m = \frac{m_{II}}{m_I} = -\frac{\eta}{\nu} \quad (18)$$

When introducing the [equation \(18\)](#) in [equation \(17\)](#), and when using the expression (11) for the kinematic parameter, and [equation \(5\)](#) for dependence between the total efficiency and the efficiency of the CVT only, we will obtain different expressions for relative torque on shaft α as function of total ratio, or of kinematic parameter of CVT. The following equations represent the final derivation.