ANALYSIS OF POWER-SPLIT SYSTEMS

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Abstract

On Czech Technical University in Prague was derived the matrix method for calculation of single and nested planetary gear sets and for calculation of other types of mechanical power-split systems. The power of matrix method lies in its easy implementation in computer calculations. In this article is shown computer program "SunGear" dedicated for calculation of power-split systems and complete analysis of mechanical stepped planetary gearboxes developed in Matlab® environment.

1 Introduction to matrix method

All known analytical methods for calculation of kinematics of planetary gear sets (PGSs) are based on Willis formulae. The matrix method for calculation of PGSs nested from single PGSs was introduced by prof. Šalamoun in 70's of last century [1]. In 2007 this method was further elaborated for calculation of reduced or Ravigneaux PGSs [2]. In 2010 the usage of matrix method for any type of mechanism was introduced [3].

Writing the Willis formulae for each set of nested planetary gear set, we obtain the system of linear algebraic equations; i.e. we obtain the matrix of kinematics. The rows belong to the sets and mechanisms working together in complex power-split system. The columns represent external and internal rotating shafts. Very often are used relative speeds, preferably related to the input, in such case the vector of right side is assigned to input shaft.

The derivation of coefficients of kinematics, torques and efficiency for usage of matrix method for single, nested and other power-split mechanisms was briefly described in [3]. More deep description with extensive number of calculated examples can be found in [4]. Anyone can easily describe and calculate kinematics of any power-split mechanism, when the derived coefficients listed in Table 1 will be used.

Table 1: COEFFICIENTS OF KINEMATICS OF PGS AND OTHER TYPES OF MECHANISMS

	Sun gear (driving part)	Spider	Ring gear (driven part)	Not present
Single PGS	1	$i^r - 1$	$- i^r$	0
CVT, TC	$- \nu$	0	1	0

For momentary parameters we can, by analogy with kinematical parameters, set the system of algebraic homogenous equations. For every PGS or CVT or other types of mechanisms we can write the equations of torque and power equilibrium. All moments act on elements externally. It means that on one position of the shaft which belongs to one element and on the other position of the shaft which belongs to another element we have two moments with equal size but different sense. In matrix of torques for every PGS belong two equations (one of torque equilibrium, second resulting from power equilibrium) and equations of torque equilibrium of multiple torque shafts. The columns belong to different elements of PGS and other mechanisms included in investigated mechanism (e.g. sun gear, spider, ring gear, driving sprocket of CVT, pump of torque converter, etc.). Similarly to matrix of kinematics the preferable results are in relative torques, related to the input. Therefore the vector of right side belongs to input shaft. The coefficients for PGS derived from equation of torque and power equilibrium are demonstrated in Table 2.

Table 2: COEFFICIENTS OF MATRIX OF TORQUE FOR SIMPLE PGS

	Sun gear	Spider	Ring gear
1st equation	$i^r \cdot \left(\eta^r \right)^{\pm 1}$	0	1
2nd equation	$1 - i^r \cdot \left(\eta^r \right)^{\pm 1}$	1	0

2   Computer program SunGear

Accordingly to the explanation in previous chapter, the program „SunGear" was developed in frame of Master thesis work [5] which is able to perform calculations of powersplit systems and complete analysis of mechanical stepped planetary transmissions. The program was developed in the Matlab® environment (Release 2009b) with use of additional Symbolic Math Toolbox™.

SunGear consists of more than sixty subfunctions (over 8000 lines of code) placed in the file called *SunGear.m*. All components (Figures, Panels, Button Groups etc.) are created programmatically, i.e. the GUIDE Layout Editor was not used. The main function, *SunGear*, opens a blank GUI with the *File* and *Help* menu. The menu item *New* can be expanded and the user can choose between two kinds of projects, either a *Planetary gearbox* or a *CVT gearbox*. Selecting the item *Program Help* in the *Help* menu an instruction in form of diploma thesis in *pdf* format is opened.

2.1   Calculation of stepped planetary transmission

The user inputs data very intuitively through carefully elaborated system of figures equipped with pop-up menus, buttons, check- and edit boxes. The most significant is the figure enabling the editing of particular planetary gear trains which comprises the graphical representation of actual connection.

The planetary gearbox can be compound from four single planetary gear sets. The challenging fact is that single planetary gear set can be designed in various forms. A new system how to find an algorithmisation of this problem was found. Lévai [6] categorized 12 mostly used simple planetary gear sets – see Figure 1. Plus were included the schemes of united planetary gear sets. Every planetary gear set was drawn on one layer. By determining the overlap of all layers the scheme depicted below on Figure 1 was found. With help of this scheme we are able to define any type of single planetary gear set.
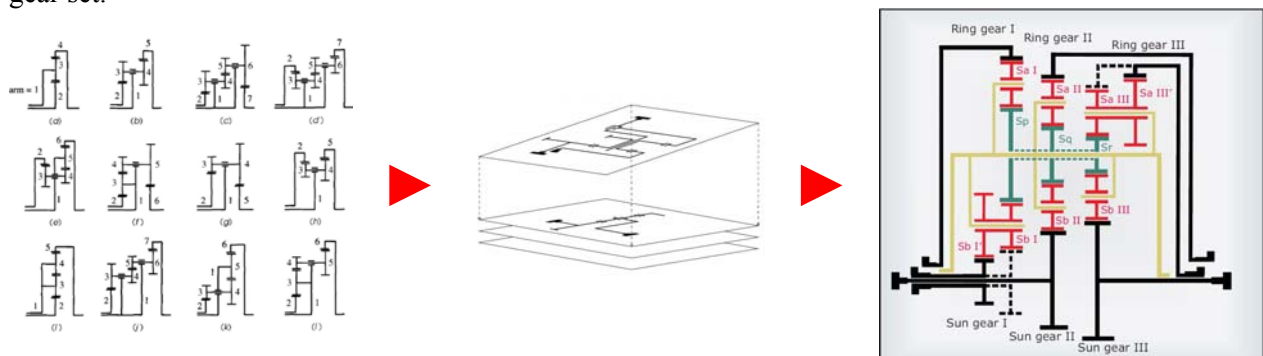

Figure 1: The procedure, how the general scheme covering existing single and united PGS was found. Left Figure presents 12 mostly used single PGSs, next were defined missing schemes – mainly the united PGS and their overlap was done. Right window represents the resulting general scheme.

When choosing the appropriate gear wheels and their number of teeth, immediately the chosen scheme is highlighted. This was achieved by using two overlapping *axes* components. The lower one comprises the background figure and the upper one the graphical features (lines) representing the particular gear wheel. The example of single planetary set with one sun wheel, spider and planet wheel is depicted on Figure 2.
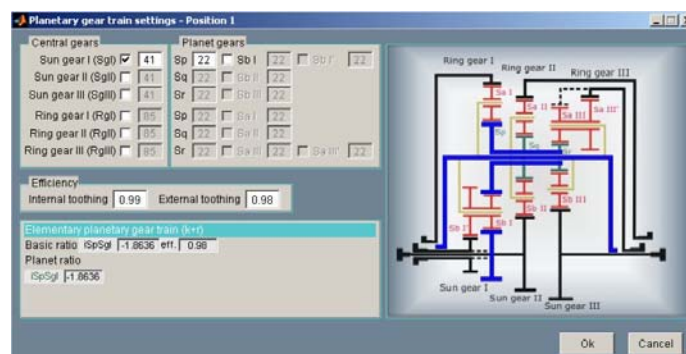

Figure 2: Example of definition of PGS in SunGear [5].

The basic ratio and planet ratio are evaluated based on the entered number of teeth of the gearwheels. In case we know only basic ratio (without knowing the number of teeth of the gearwheels), the fields showing the *basic ratio* and *planet ratio* are editable and can be anytime changed. This is indicated by a red exclamation mark below the cyan zone and by highlighting the particular edited field. By editing any values in the panels above, for example by changing any tooth numbers, all changes on the information panel will be canceled and newly recalculated.

The basic efficiency is calculated from the number of gearwheels in mesh and type of gearmesh. Used efficiencies in *Efficiency* panel are of course editable. Similarly the basic efficiency can be also edited, but only for case of single PGS.

The input data are stored in matrices or cell arrays and are written and read by other subfunctions by means of *setappdata/getappdata* functions. The handles of graphical components are called by very fast function *findobj*. The program ensures permanent checking of input values, in the case of inputting an invalid value a warning window pops up and appeals to the user for changing of the value. *SunGear* also provides saving of the current figure with all components and actual settings in a **.fig* file, which can be subsequently reopen and edited. The central wheels and main planet gears are labeled with numbers, which accompany each of them from data input to result table.

After definition of the number of nested planetary gear sets and its composition, the working scheme for different speeds is defined. For every planetary set corresponds a panel, which comprises a set of control objects that manage connection between gearbox members, namely *Direct* check box and specific functions like *Input, Output, Reaction, Link A, Link B* and *Link C*. The user can choose according to the actual connection in a gear the appropriate position of a gear wheel. If a position is not occupied by any of gear wheels in a particular PGS, the option *None* has to be selected. The example of input window is depicted in Figure 3. For each speed it is possible to define its name, input angular speed and input torque, since all subsequent calculations are related to the unit inputs.
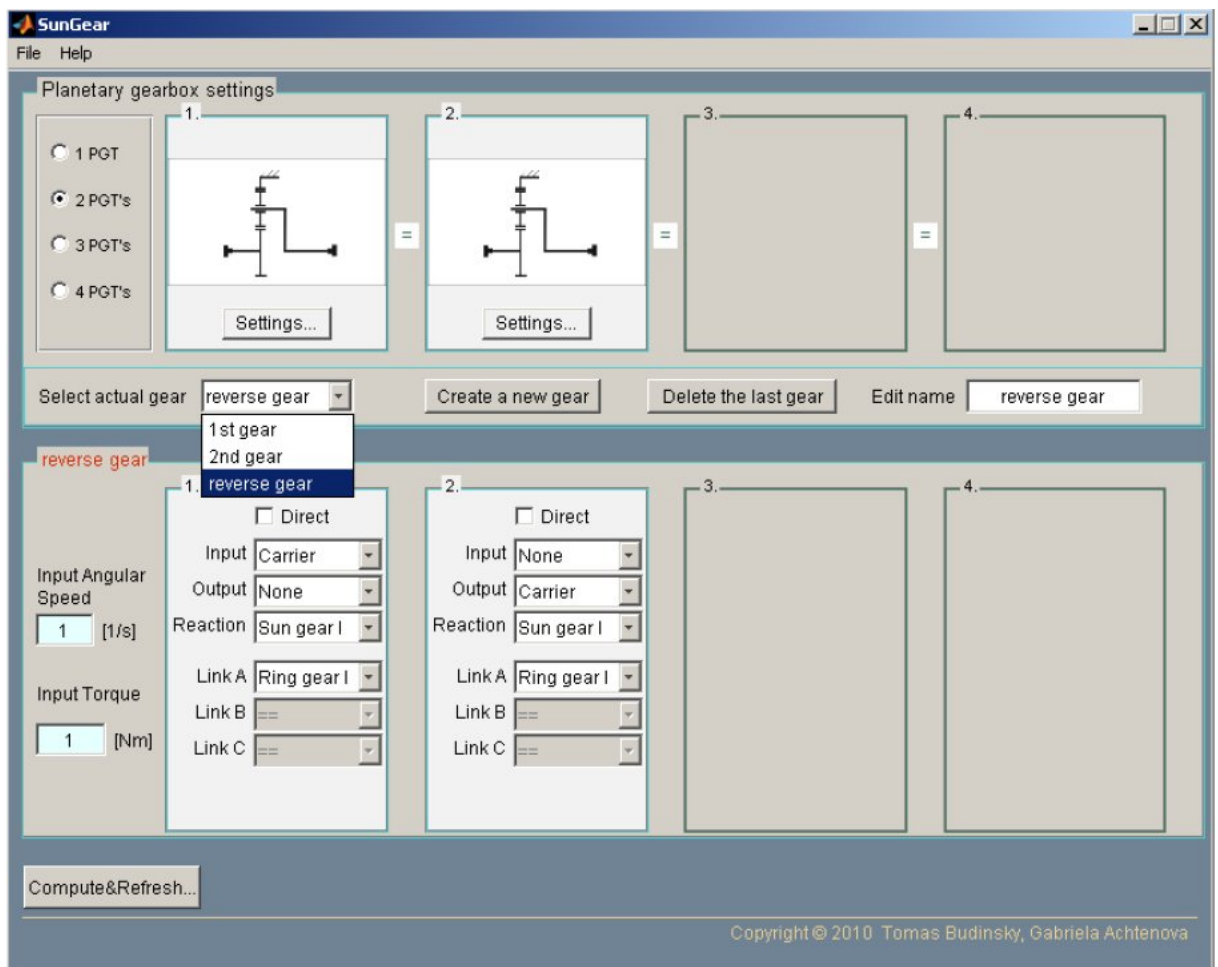

Figure 3: Window for definition of actual connection of PGSs of planetary mechanism for the chosen speed [5].

The main calculation algorithm is working in a cycle scanning the input data of planetary gearbox connection and implementing basic ratios as a calculation variable for creating moderate matrix that is finally enumerated with well-known technique – briefly described in Chapter 1.

After pressing *Compute&Refresh...* button, the *compute* function is called, which besides the figure initialization and definition, provides the connection checking for all connected gears. If any connection discrepancies are found, a dialog window shows up and the user is advised to check the connection settings.

For correctly input gearbox a new result window pops up, consisting of two main panels enabling the graphical and numerical representation of the results. The result window is resizable to better visualize the details on the plots. There are also several controls available that enable export or simply enhance displaying of results. For velocity diagram of planetary gearbox is also available the possibility of mouse position scanning. The example of result window for six speed planetary gearbox is shown on the following Figure. The button *ShowData* expends the table presenting the result values of kinematics, torques and efficiencies for all calculated speeds.
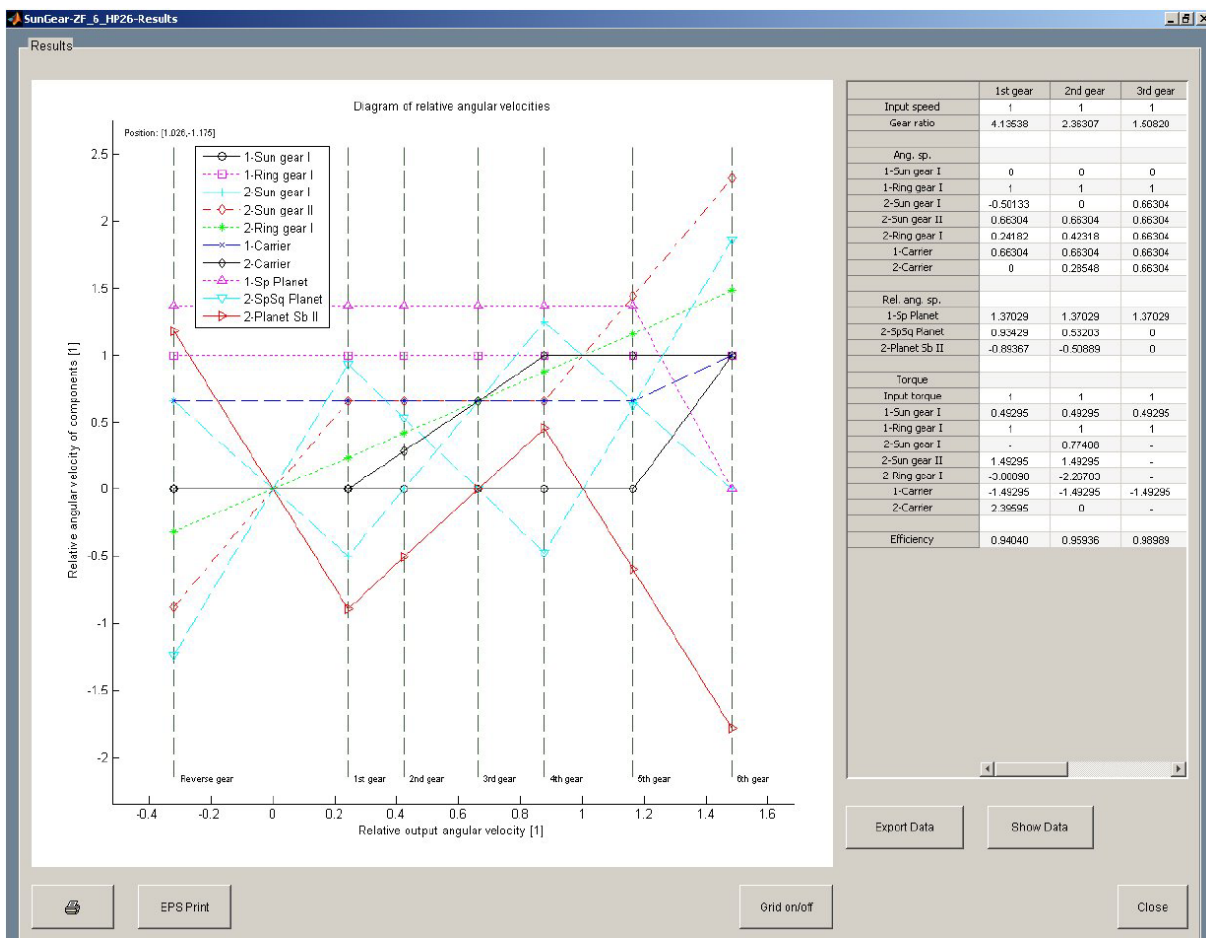

Figure 4: Results window of a six speed planetary gearbox [5].

2.1 Calculation of CVT modul

If the user selects *CVT Gearbox* option in the menu bar, a new panel will show up as shown in Figure 5. In the left side of the panel the particular position of PGT inside a CVT gearbox can be selected. There are two possibilities:

- Input split,

- Output split.

If any option is selected, accordingly, the panels on the right side will be moved. This freature ensures graphical deployment of the units inside a CVT gearbox. The CVT unit can be either purely mechanical or hydrodynamic. The particular option can be selected in the pop-up menu.

The CVT unit must be defined by its operational limits. The admissible values are from +100 till -100. The user can define the number of computational points, which can be defined from 4 till 500. In contrast the torque conversion (or efficiency) of hydrodynamic torque converter (TC) are not constant in its operational range. The data import is provided by pushing *Load data* button. The input data are written in *.mat files, which can be obtained by the CVT data generator *generatorcvt.m* located in the same folder as *SunGear* program.
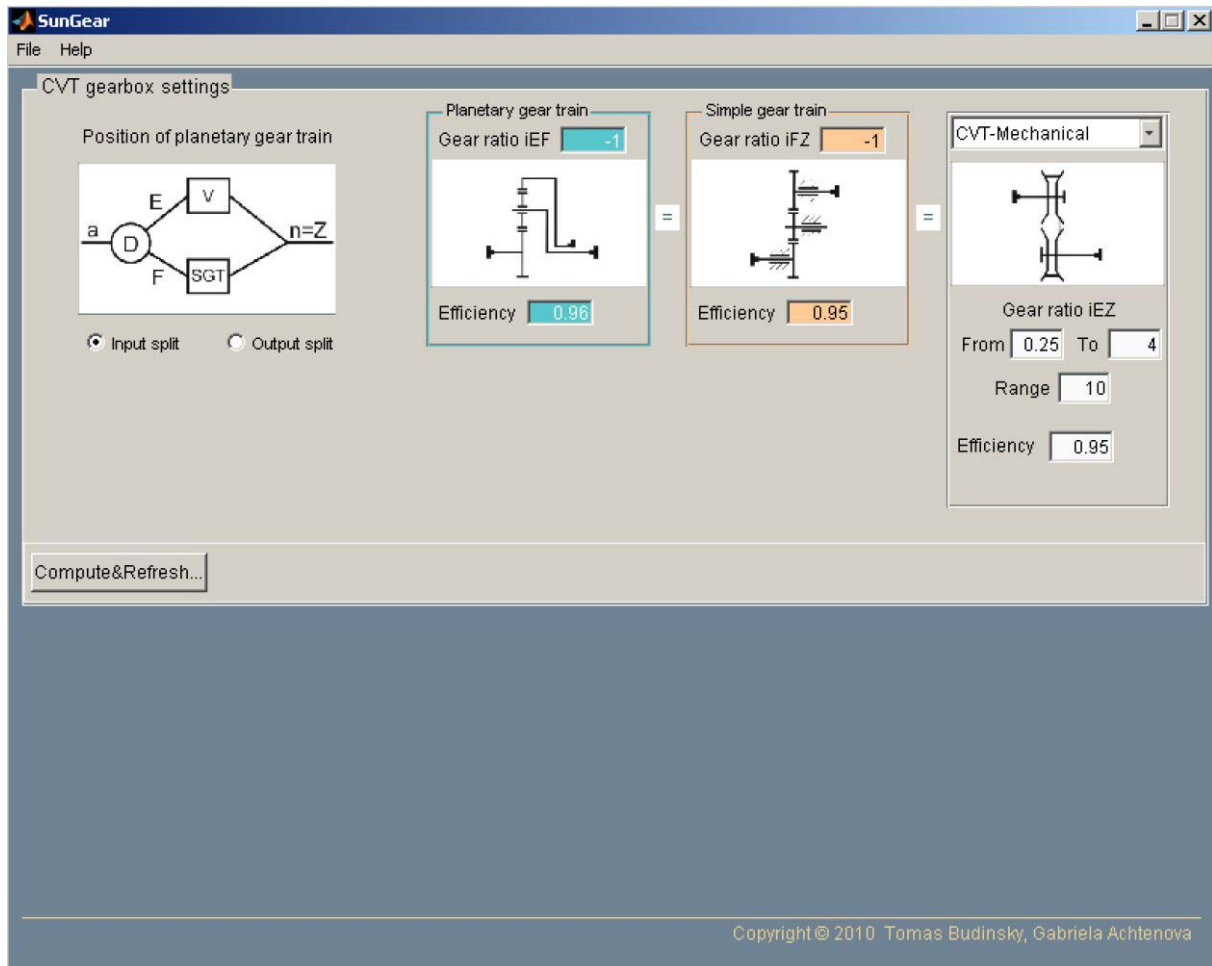

Figure 5: CVT Gearbox settings [5].

The CVT-modul uses the symbolic representation to be able to calculate derivatives of some expressions that are crucial for calculation of efficiency values. Since for a CVT-modul the number of calculations is much higher (depends on CVT-unit range), a graphical waitbar is shown during the computation process.

A CVT gearbox results are substantially different; the calculated values of total gear ratio, total torque ratio and total efficiency are evaluated for all values of variator gear ratio in the whole operational range. The *Print* button invokes *printsettingCVT* function which ensures the opening of the *Print Preview* figure with use of a small trick. Since the print functions would print the whole results

window, the plot is made one more time in an another figure (*figure_fake)* that is invisible for the user, but enables programmatic settings of appropriate look for the print preview window. In the print preview other parameters can be set, such as paper format, color, orientation... The *EPS Print* button uses the same trick for exporting the plot as an EPS file, which achieves, if printed on a PostScript printer, the highest quality results. Considering further postprocessing of results, *SunGear* enables exporting of data to a *.txt file, which can be imported in other environments.

Figure 6 represents the result window of calculated powersplit mechanisms consisting of planetary differential and hydrodynamic TC. The graph represents comparison of characteristic of TC itself and resulting characteristic of powersplit mechanism.
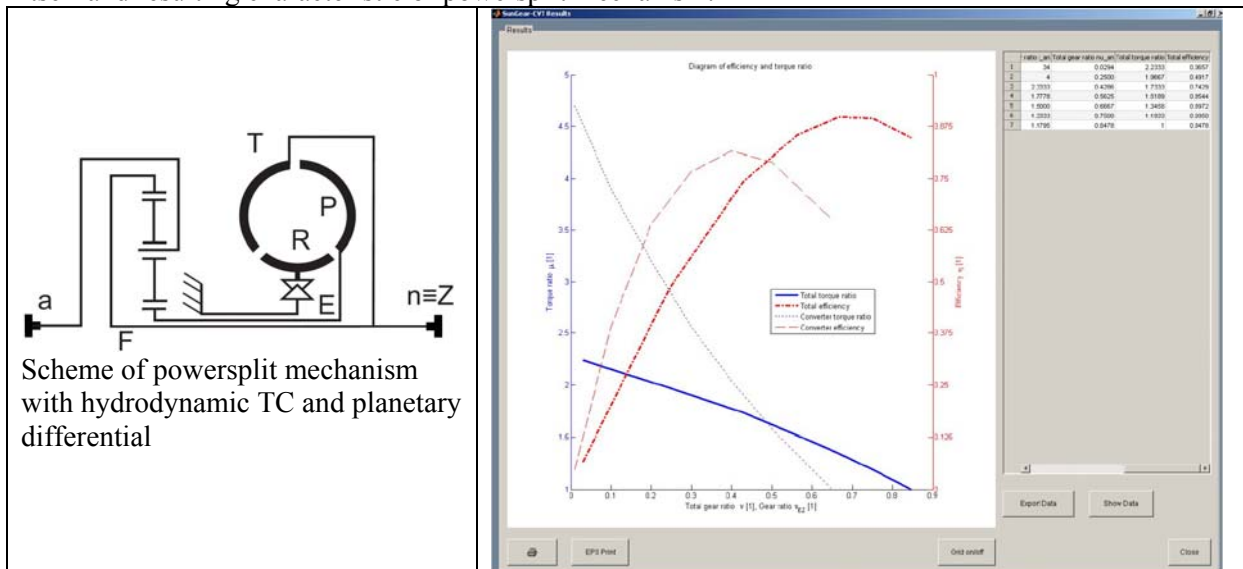

Figure 6: Scheme and computational results of powersplit mechanism [5].

3 Graphical User Interface (GUI) Programming

The first sketch of *SunGear* was created in MATLAB GUIDE. The layout has been changing throughout the programming work, since some features turned out to be not user friendly. The gearbox deployment and gear connections were not separated.

There are several techniques that can be used for programming GUI in Matlab®. *SunGear* uses *subfunctions* to divide the whole program code. Each *subfunction* begins with its own definition header. They follow each other and can occur in any order, as long as the primary function appears first. *Subfunctions*, in contrast to alternative technique utilizing *Nested functions*, has been chosen due to following advantages:

- Subfunctions cannot access variables used by other subfunctions. This feature disables existence of unwanted processes if same symbols of variables are used. The only way, if declaration of global variables will not be considered, is to pass them as arguments.

- Subfunctions are visible to the primary function or to other subfunctions in the same file. Therefore, any function calling from any position is possible.

Matlab® uses for designing GUIs the so-called *Handle Graphics*. The main idea of this technique is that every object in the Figure window (axes, lines, text, etc.) has a handle (a number), by means of which the object can be easy identified and its properties eventually changed [7]. To find any particular object, the most used technique is the use of *findobj* command. Other methods used in *SunGear* include passing handles as arguments to the corresponding subfunction and saving handle as an application data. The second one very often used for saving any other data, each as results or input data in a matrix form. Very rarely the *UserData* property as a *Data-Sharing Method* is used, since it is limited to one variable.

4 Results

The program for analysis of stepped planetary gearboxes and power-split continuously variable transmissions was built with help of Matlab and Symbolic Math Toolbox. The article describes the concept of program and user interface.

The whole program was programmed without using any object-oriented program techniques, however their usage will be considering in the future works. In the current Matlab releases this kind of programming is already highly elaborated and its implementation would be surely advantageous leading to better clarity of code.

List of abbreviations

CVT   Continuously Variable Transmission
GUI   Graphical User Interface
PGS   Planetary Gear Set
TC   Torque Converter

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