

# On the using of two-carrier planetary gear trains with two compound and four external shafts as change-gears

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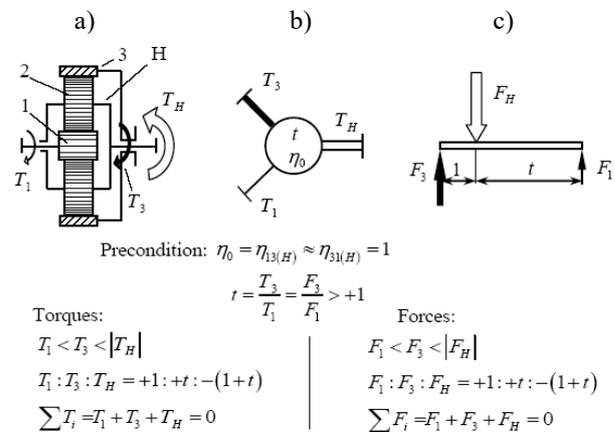
**Abstract.** An overview of all possible structural schemes of two-carrier planetary gear trains (PGTs) with two compound and four external shafts is made. One of possible application of these PGTs is as change-gears. A few cases of this application are presented and investigated through the torque method. Kinematical possibilities of PGTs in question as function of parameters of component simple PGTs are discussed.

## 1 Introduction

Due to their indisputable qualities, planetary gear trains (PGTs) are increasingly used in industry. Of the two-carrier PGTs, those with three outer shafts are mainly used [1]. As gear trains with a variable transmission ratio (change-gears), mainly three-, four-, and recently five-carrier planetary gears are used, which allow a large number of transmission ratios [2-4]. Between these two large groups are the two-carrier PGTs with two compound and four external shafts, which are convenient for changing the speed ratio (such as two-speed or reversing mechanisms) [1]. The capabilities of the latter have been relatively little studied, although there are cases where exactly such a speed change is required (drives of technological machines, of small ships and boats, etc.) [5-7].

This paper is a part of a project investigation with aim to make a systematic study of the different possible structural schemes of two-carrier PGTs with two compound and four external shafts and to find the most suitable ones for a specific application.

The investigation is focused on compound PGTs consist of the most common used simple (one-carrier) PGT (with one external meshing, one internal meshing, and one-rim planets – Fig. 1) as building element. For Kinematic and power analysis the torque method is used. It is very easy for work if the simple PGT is depicted by the symbol of Wolf-Arnaudov – as circle with three external shaft which teen corresponds with the value of their torques (Fig. 1b). In Fig. 1c the lever analogy of the PGT is presented. It allows easy understanding and clary presenting the torques and efficiency calculations [1, 8]. The ratio of forces on the lever is the same as the ratio on the shafts of PGT. This ratio is presented by the torque ratio  $t > 1$  (between the unidirectional torques  $T_3$  and  $T_1$ ).



**Fig. 1.** The most often used PGT (with one external meshing, one interna meshing, and one-rim planets) and it torques: 1 – sun gear; 2 – planets; 3 – ring gear; H – carrier (a); the symbol of Wolf-Arnaudov (b); and lever analogy (c).

In the most common case of three planets ( $k = 3$ ) this ratio varies from 2 to 12 ( $t = 2 \div 12$ ) [1].

## 2 Structural analysis

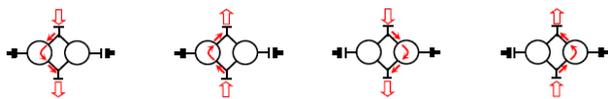
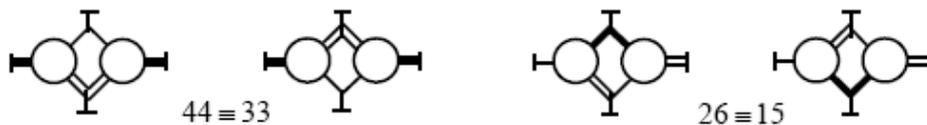
Fig. 2 shows the structural scheme of a two-carrier PGT with two compound and four external shafts. Combination of two PGTs with three shafts gives 36 variants (Table 1) but analysis shows only 12 unrepeatable [1, 9].

If the input and output are invariable, for working with one degree of freedom ( $F = 1$ ) one of the external shafts must be locked. Locking with braces different shafts two speed ratios obtain. In Fig. 2 possible working modes depend on input, output, and both brakes positioning are shown.

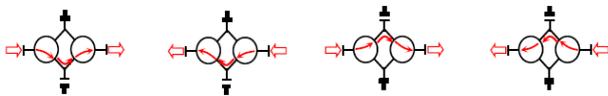
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**Table 1.** Possible variants of two-carrier PGTs with two compound and four external shafts.

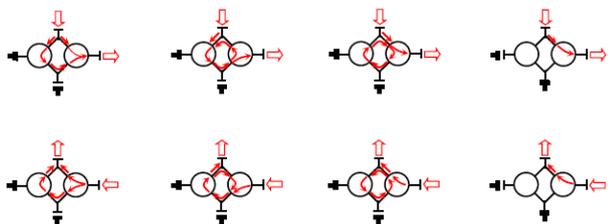
	...1	...2	...3	...4	...5	...6
1...	11	12 ≡ 21	13 ≡ 31	14 ≡ 41	15 ≡ 51	16 ≡ 61
2...	21 ≡ 12	22	23 ≡ 32	24 ≡ 42	25 ≡ 52	26 ≡ 62
3...	31 ≡ 13	32 ≡ 23	33	34 ≡ 43	35 ≡ 53	36 ≡ 63
4...	41 ≡ 14	42 ≡ 24	43 ≡ 34	44	45 ≡ 54	46 ≡ 64
5...	51 ≡ 15	52 ≡ 25	53 ≡ 35	54 ≡ 45	55	56 ≡ 65
6...	61 ≡ 16	62 ≡ 26	63 ≡ 36	64 ≡ 46	65 ≡ 56	66



a) Brakes on both single shafts;



b) Brakes on both compound shafts;



c) Brake on a single and on a compound shaft.

**Fig. 2.** Possible location of both brakes.

In case c) one of component PGT works as closed differential (with two degree of freedom –  $F = 2$ ) and internal division or internal circulation of power is possible depends on parameters of component RGTs.

### 3 Suitable arrangements for operating as two-speed change-gear

#### 3.1. Reversible planetary gear train with possibility for equal speed ratios in both directions

Figure 3 shows a possible arrangement and the structural scheme of PGT with brakes on both single shafts [1]. When the train works as a reducer the input is the compound shaft connecting sun gears of component PGTs and the output shaft connects the carrier of the first and the ring gear of the second component PGT. In the figure ideal torques and speed ratios are determined.

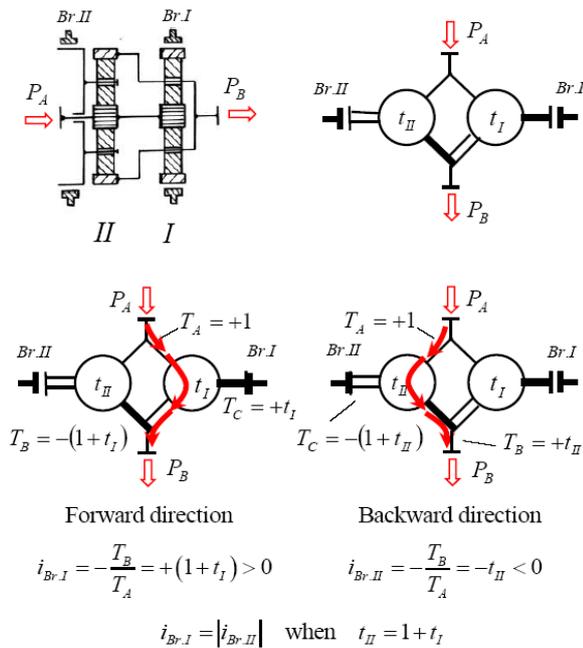
In both cases one of the component PGT operates. When power (moving) transmits from sun gear to the carrier – input and output rotate in one direction (“Forward direction” in Fig. 3). When power (motion) transmits from sun gear to the ring gear – input and output rotate in opposite directions (“Backward direction” in Fig. 3). Both ratios ( $i_{BrI}$  and  $i_{BrII}$ ) depend on parameters (torque ratios  $t_I$  and  $t_{II}$ , respectively tooth numbers ratios) of component PGTs. In case of equal torque ratios

$$t_I = t_{II} \tag{1}$$

the difference of absolutely values of speed ratios will be 1

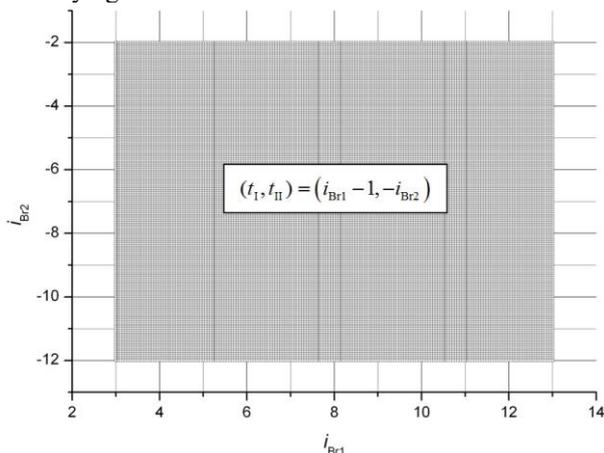
$$i_{Br.I} = |i_{Br.II}| + 1 \quad (2)$$

This structural scheme gives easy possibility to obtain equal speeds in both directions (see Fig. 3). This is appropriate for boat transmission, for example [6].



**Fig. 3.** Reversible PGT (variant 36  $\equiv$  45, resp. 36  $\equiv$  63 and 45  $\equiv$  54 from Table 1).

Torque method analysis allows develop a methodology for optimal choice of parameters (torque ratio) of component PGTs in which a desirable speed ratio of compound PGT occurs [10]. Software has been developed that can determine the possible combinations of  $t_I$  and  $t_{II}$  values that give desired values of the two transmission ratios  $i_{Br.II}$  and  $i_{Br.I}$ . From this database, the optimal combination can be selected according to one or more criteria (minimum overall dimensions, maximum efficiency, desired ratio of the dimensions of the two planetary stages, minimum reduced clearances to the input shaft, etc.). One of the main points of this methodology is kinematical possibility of the structural scheme determining. Figure 4 shows a diagram of possible speed ratios  $i_{Br.II}$  and  $i_{Br.I}$  if torque ratios  $t_I$  and  $t_{II}$  are varying from 2 to 12.



**Fig. 4.** Possible speed ratios  $i_{Br.II}$  and  $i_{Br.I}$  if torque ratios  $t_I$  and  $t_{II}$  are varying from 2 to 12 (for the PGT from Fig. 3).

### 3.2 Reversible planetary gear train with different speed ratios in both directions

Figure 5 shows a possible arrangement and the structural scheme of PGT with brakes on both compound shafts [1]. In both cases the component PGTs operate as in series connected PGTs. The power (motion) passes through one of the compound shafts when the other is locked by a brake. In the figure the power paths, if the train is working as a reducer, are shown.

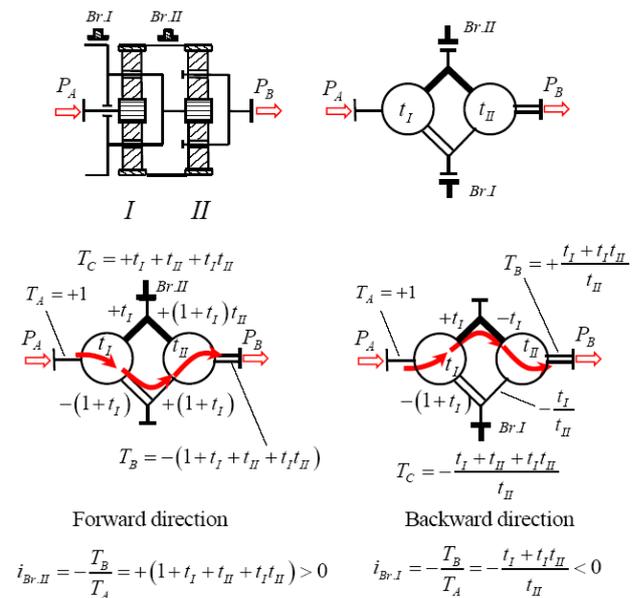
The formulae for gear ratio in both directions show a significant difference between its values.

At  $t = 2 \div 12$

$$i_{Br.II} = 9 \div 169$$

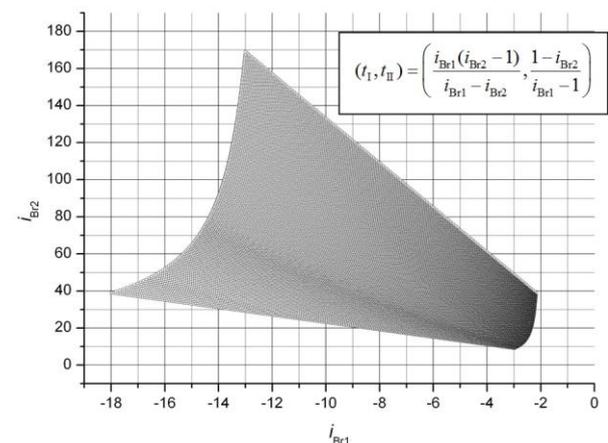
$$i_{Br.I} = 2,166 \div 18$$

This makes the PGT suitable for technological machines with a faster reverse idle.



**Fig. 5.** Reversible PGT (variant 26  $\equiv$  15, resp. 26  $\equiv$  62 and 15  $\equiv$  51 from Table 1).

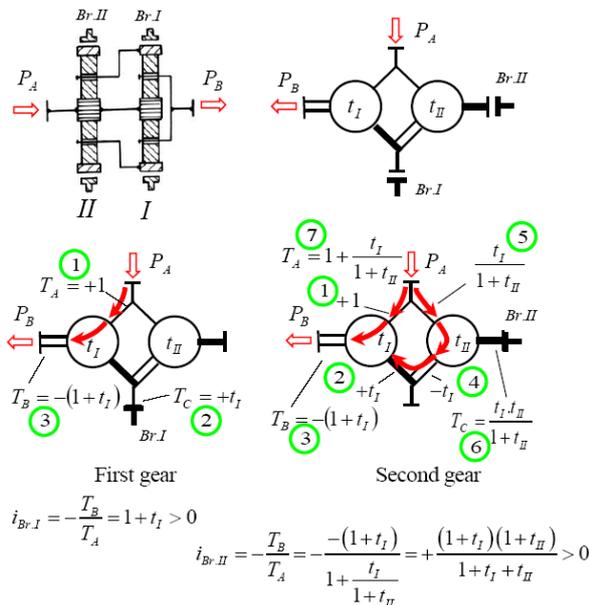
By the above-mentioned software a diagram of possible speed ratios  $i_{Br.II}$  and  $i_{Br.I}$  if torque ratios  $t_I$  and  $t_{II}$  are varying from 2 to 12 is created too (Fig. 6).



**Fig. 6.** Possible speed ratios  $i_{Br.II}$  and  $i_{Br.I}$  if torque ratios  $t_I$  and  $t_{II}$  are varying from 2 to 12 (for the PGT from Fig. 5).

### 3.3 Planetary gear train with different speed ratios in one direction

Figure 7 shows a possible arrangement and the structural scheme of PGT with one brake on single shaft and other brake on a compound shaft [1]. When the train works as a reducer the input is the compound shaft connecting sun gears of component PGTs and the output is the carrier of the first stage. As on both gears the output shaft rotates in one direction, this PGT is suitable to work as two-speed change-gear or to be a part of complex multispeed change-gear (automatic transmission).

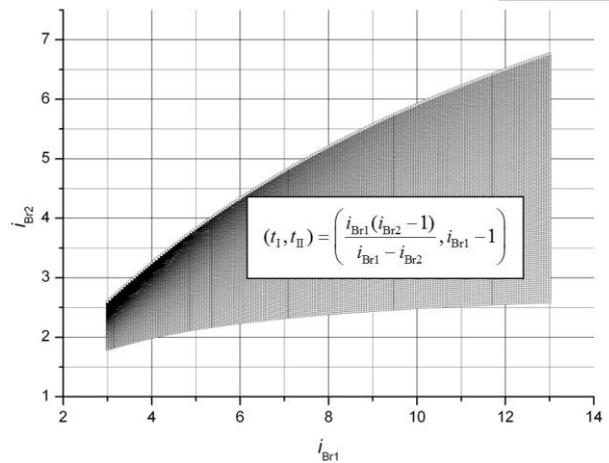


**Fig.7.** Two-speed change-gear (variant  $45 \equiv 36$ , resp.  $45 \equiv 54$  and  $36 \equiv 63$  from Table 1).

On “First gear” only the first component PGT operates with fixed ring gear. On “Second gear” the second component PGT works with fixed ring gear and the first one works as a *summation differential*. In the compound PGT an *internal power division* occurs.

In this example the torques determination in the second case (“Second gear”) is more complicated. The procedure may begin from any of sun gear shafts. In Fig. 7 it begins from the sun gear of first stage and the sequence of procedure is shown by numbers in circles. Determination of the torques in second stage begins from the internal compound shaft – the torque on the carrier is the same as the torque on the ring gear of the first stage (+ $t_I$ ) but with the opposite sign (- $t_I$ ) [1].

In Fig. 8 the kinematic capabilities of this structural scheme are shown.



**Fig. 8.** Possible speed ratios  $i_{Br-II}$  and  $i_{Br-I}$  if torque ratios  $t_I$  and  $t_{II}$  are varying from 2 to 12 (for the PGT from Fig. 7).

### 4 Conclusions

Clarity and simplicity of the torque method of investigation of PGTs allow methodology for analysis and synthesis compound PGTs developing. Through this methodology two-carrier PGTs with two compound and four internal shafts are investigated. Some of possible structural schemes are appropriate to operate as change-gears.

Software has been developed that can determine the possible combinations of component PGTs parameters that give desired values of the two transmission ratios  $i_{Br-II}$  and  $i_{Br-I}$ . From this database, the optimal combination can be selected according to one or more criteria (minimum overall dimensions, maximum efficiency, desired ratio of the dimensions of the two planetary stages, minimum reduced clearances to the input shaft, etc.).

Developed methodology may be a part of a complex methodology for PGTs in question optimization.

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### References

1. K. Arnaudov, D. Karaivanov, *Planetary gear trains* (CRC Press, Boca Raton [FL, USA], 2019)
2. H.W. Muller, *Epicyclic drive trains* (Wayne State University Press, Detroit, 1992)
3. D. Jelaska, *Gears and gear drives* (Chichester [UK]: John Wiley & Sons, Chichester [UK], 2012)
4. S. Milev, *Kinematic and geometric synthesis of planetary gearboxes. Dissertation* (Ruse University “A. Kanchev”, Ruse, Bulgaria, 2019) (in Bulgarian)
5. S. Troha, Ž. Vrcan, D. Karaivanov, M. Isametova, The selection of optimal reversible two-speed planetary gear trains for machine tool gearboxes, *Facta Universitatis-Series Mechanical Engineering*, 18, 1, 121-134 (2020)

6. S. Troha, J. Stefanović-Marinović, Ž. Vrcan, M. Milovančević, Selection of the Optimal Two-Speed Planetary Gear Train for Fishing Boat Propulsion, *FME Transactions*, 48, 397-403 (2020)
7. S. Troha, D. Karaivanov, Ž. Vrcan, K. Marković, A. Šoljić, Coupled two-carrier planetary gearboxes for two-speed drives, *Machines Technologies Materials*, **15**, 6, 212-218 (2021)
8. K. Arnaudov, D. Karaivanov, *Torque method for analysis of compound planetary gear trains* (LAP Lambert Academic Publishing, Beau Bassin [Mauritius], 2017)
9. S. Troha, *Analiza varijanti mjenjačkoga zupčaničkoga planetnog pretvarača. Dissertation* (Tehnički Fakultet, Sveučilište u Rijeci, Rijeka [Croatia], 2011) (in Croatian)
10. D.P. Karaivanov, S. Troha, Optimal Selection of the Structural Scheme of Compound Two-Carrier Planetary Gear Trains and their Parameters, 339-403 in: Radzevich, S.P., (Editor), *Recent Advances in Gearing: Scientific Theory and Applications*, Springer, 1<sup>st</sup> ed. (2022)