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KINEMATIC OPERATING MODES OF TWO-SPEED TWO-CARRIER PLANETARY GEAR TRAINS WITH FOUR EXTERNAL SHAFTS

Summary

Two-speed planetary gear trains with four external shafts, composed of two simple planetary gear trains, are considered in this paper. The labelling system of these trains is defined and all possible variants are determined. Planetary gear trains are divided into three different design groups, and characteristics of trains of each group are given. Possible power flows through the train at both gears for every group are described. An example of determining the function of transmission ratios of two-speed planetary gear trains by means of the torque method is shown. By research of kinematic schemes (design concepts) all train variants which can be created with an input and an output shaft on opposite sides of the train are identified, as well as those train variants where the aforementioned is not possible and their power input has to be placed between the brakes. All train variants where ideal torque ratios influence a change in the operating mode within the same gear are identified. A review of kinematic operating modes (reduction, multiplication, rotational direction of the output in relation to the input shaft) of all possible variants of the considered trains is given.

Key words: two-speed planetary gear trains, transmission ratio, ideal torque ratio

1. Introduction

In some cases, in common machinery two-speed transmissions are required [1–8]. One suitable solution could be a mechanism obtained by connecting two simple planetary gear trains type 2k-h, variant A [1]. A simple planetary gear train type 2k-h, variant A, is shown in Fig. 1. It is appropriate to show a simple planetary gear train with the Wolf-Arnaudov symbol in which the train shafts are shown with different width lines and a circle [7-16]. Sun gear shaft 1 is shown by a thin line, ring gear shaft 3 by a thick line and the carrier shaft S by two parallel lines. Planetary gear train shafts are loaded with torques whose ratio is also shown in Fig. 1. Torques on the ring gear shaft T_3 and on the carrier shaft T_S are given as a function of the ideal torque ratio t and the torque on the sun gear shaft T_1.

The ideal torque ratio t, under the condition that basic efficiency $\eta_0 = 1$, is constant, and thus ratios of the three ideal shaft torques T_1, T_3 and T_S are also constant, regardless of the following:

- how many degrees of freedom F the gear train has, i.e. whether $F = 1$ or $F = 2$;
- which of the three shafts of the gear train is fixed when $F = 1$;
- the direction of power-flow i.e. whether the gear train acts as a reducer or a multiplier when $F = 1$, or as a collector or distributor when $F = 2$;
- whether the gear train operates independently or as a part of a compound multi-carrier planetary gear train.
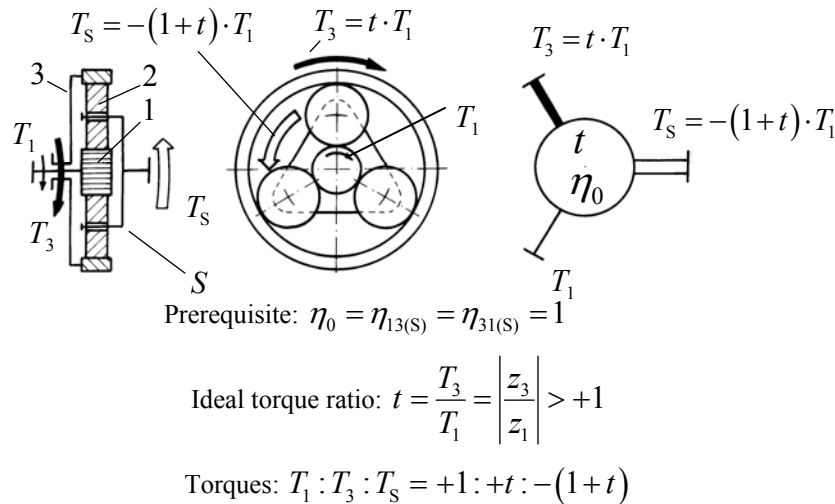

$$\text{Prerequisite: } \eta_0 = \eta_{13(S)} = \eta_{31(S)} = 1$$

$$\text{Ideal torque ratio: } t = \frac{T_3}{T_1} = \left|\frac{z_3}{z_1}\right| > +1$$

$$\text{Torques: } T_1 : T_3 : T_S = +1 : +t : -(1+t)$$

Fig. 1 The most often used single-carrier planetary gear train and its torques [3]

By joining two shafts of one component planetary gear train with two shafts of the other component planetary gear train a mechanism with four external shafts that can operate as a two-speed planetary gearbox is obtained (Fig. 2). The component planetary gear train will be referred to as the component train and the obtained mechanism with four external shafts will be referred to as the compound train.
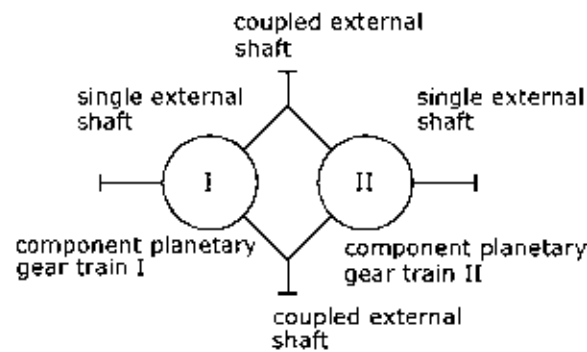

Fig. 2 Planetary gear train with four external shafts (compound train)

By situating the brakes on two shafts a braking system is obtained in which the alternating activation of the brakes shifts the power flow through the planetary gear train, which causes a change in the transmission ratio.

Some planetary gear trains of this type are described in [1, 4, 6, 7, 8, 9, 10]. Possible power flows for planetary gear trains of the considered type are analysed, and functions of the transmission ratio at both gears for some trains of this type are deduced in [9]. In [1], 15 kinematic schemes of the considered type are presented and achievable values of transmission ratios and efficiencies of both gears are given. A computer program for the selection of an optimal variant of similar multi-speed planetary gear trains is described in [11]. Shifting capabilities charts for all possible two-speed planetary gear trains are given in [10].

Papers by S. Troha and D. Karaivanov [7, 8, 12] have preceded this paper and pursue similar subjects. In [12], the basis of application of the lever analogy is suggested, on which the torque method is founded. Schemes of one-speed two-carrier trains with three external shafts are systematically and symbolically shown. Specific ways of connecting a component gear train for getting a two-carrier and a three-carrier train are shown. A way for determining transmission ratio of a one-speed two-carrier train by a reduced ideal torque ratio is depicted. A methodology for determining the efficiency of one-speed trains, which is suitable for computer implementation, is suggested. A multi-criteria selection methodology (multi-criteria optimization) of one-speed trains which can also be applied to multi-speed trains is suggested. Possible research directions regarding planetary trains are given.

In [7], a systematization of two-speed planetary trains is provided, but an unambiguous way of the labelling of two-speed two-carrier planetary trains is not defined. The number of all different variants is not determined. An example of a structural analysis of one train is given, in which specific torques on the shafts, power flows through the train, functions of transmission ratios and efficiency function for both gears for that train are determined. Transmission ratio functions and functions of the ratio of two transmission ratios are graphically shown, which allows a clear insight into kinematic capabilities of that train. Expressions for transmission ratios of some variants are given, and some characteristics of certain train variants are described. Detailed and extensive research of capabilities of two-speed two-carrier trains conducted from 2006 to 2011 [10], from which applicable original scientific results were derived, preceded the concisely written, four-page paper [7]. Some of these results are systematically and unambiguously presented in this paper.

In [8], a method of optimal selection of a two-speed two-carrier planetary train according to several criteria is presented. Based on that method a computer program for the selection of the optimal variant according to three criteria (minimal pitch diameter of greater crown, maximal efficiency and minimal backlash) is created. Users of the program DVOBRZ1, which was developed as a part of the first author's PhD dissertation [10], will receive the optimal two-carrier two-speed variant and its basic parameters easily. However, that program is available only to the first author of this paper. To help the designers who do not possess the program for the selection of an adequate train variant and its basic parameters an overview of operating modes of all possible two-speed train variants is given here.

The basic aim of this paper is to systematically review kinematic operating modes of the considered planetary gear trains in order to help designers to select the appropriate two-speed planetary gear train by means of operating mode tables and transmission ratio functions.

2. Structures of planetary gear trains and their labelling

Two component trains can be joined in a whole in 12 different ways, called the planetary gear train with four external shafts [7-10]. To each of 12 structural schemes an alphanumerical label (S11…S56) is attached, which indicate the ways of connecting the shafts of the main elements of both component trains (Fig. 3). In every presented scheme it is possible to put brakes as well as the driving and the operating machine on external shafts in 12 different ways (V1…V12), which will be here called layout variants (Fig. 4).
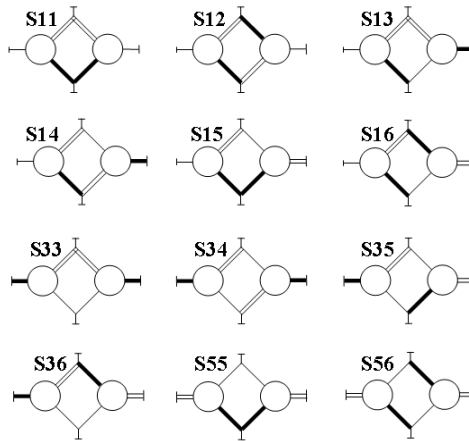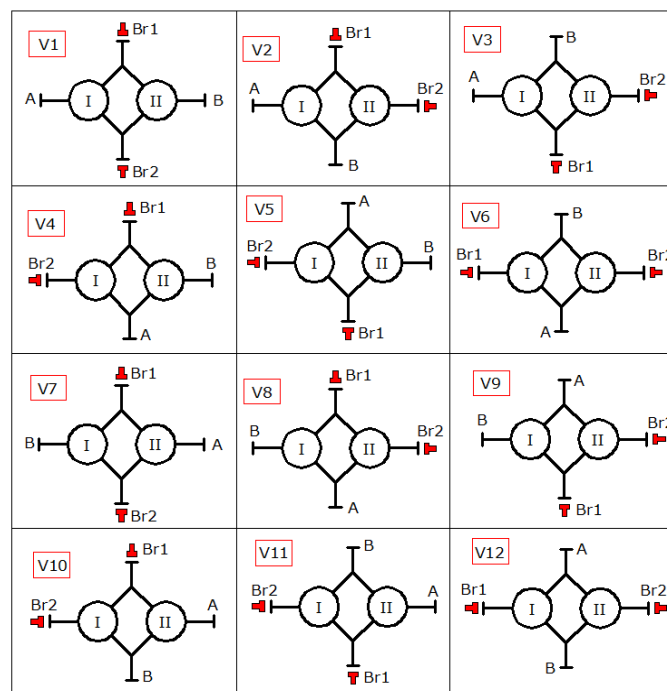
Fig. 3 Systematization of all schemes of two-carrier planetary gear train with four external shafts

A – input shaft ; B – output shaft ; Br1, Br2 – brakes ; V1-V12 – layout variants

Fig. 4 Systematization of all layout variants of two-carrier planetary gear train with four external shafts

The analysis of 12 structural schemes and 12 layout variants shows that there are some different layout variants within the frame of the same scheme, which result in the identical compound train. It has been established that there are:

- 12 different compound trains with brakes on the single shafts of which each of them has a power input and a power output determined by label V6 or V12 (24 variants)
- 12 different compound trains with brakes on the coupled shafts of which each of them has a power input and a power output determined by label V1 or V7 (24 variants)
- 36 different compound trains with brakes on the coupled and the single shaft (72 variants)

Each of 120 variants of two-speed gearboxes has specific shifting capabilities.
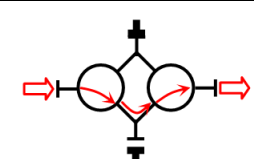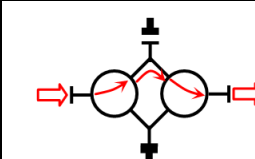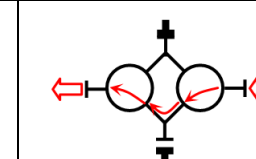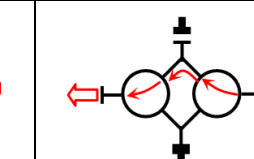
On the basis of the labels of the structural schemes (S11…S56) and the labels of the layout variants (V1…V12) shown in Fig. 3 the label of the compound train can be defined. The label of the compound train contains a label of the structural scheme and a label of the layout variant. If needed, the label of the compound train can contain a label of the brake turned on as well. An example of such a label is S16V2Br2.

3.   Analysis of the operation of compound trains with different layout variants

The considered compound trains can be divided into three different groups depending on the layout of brakes on the shafts. The first group consists of the compound trains with brakes on the coupled shafts. The second group consists of the compound trains with brakes on the single shafts. The third group consists of the compound trains with brakes on the coupled and the single shaft. All compound trains within separate groups have some specific common characteristics which are described in the following paragraphs.
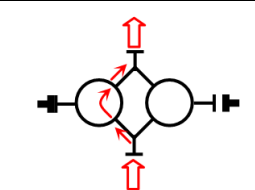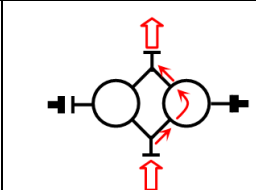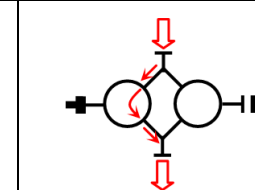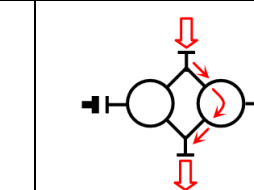
The compound train with brakes on the coupled shafts (layout variants V1 and V7) is symbolically shown in Table 1. When the brake on the upper coupled shaft is turned on, the power is transmitted through the lower coupled shaft, and when the brake on the lower coupled shaft is turned on, the power is transmitted through the upper coupled shaft. Input and output of power are on the single shafts. This is a case in which two component trains are serially joined and both operate with one degree of freedom. Each of the component trains is taking part in the changing of the energy parameters at both gears.

Table 1 Possible power flows through the train with brakes on the coupled shafts

V1Br1	V1Br2	V7Br1	V7Br2

The compound train with brakes on the single shafts (layout variants V6 and V12) is symbolically shown in Table 2. When the left brake is turned on, power is transmitted through the left component train (component train I), and when the right brake is turned on, power is transmitted through the right component train (component train II). Input and output of power are on the coupled shafts. In this case, whatever the brake is turned on, only one component train operates actively while the other operates idly. Therefore, the transmission ratios of the compound train are equal to the transmission ratios that the component trains accomplish.
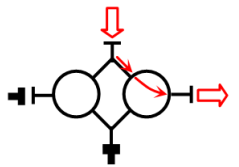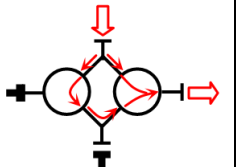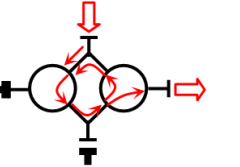
Table 2 Possible power flows through the train with brakes on the single shafts

V6Br1	V6Br2	V12Br1	V12Br2

Symbols and possible power flows of the compound train with brakes on the coupled and the single shaft (layout variant V5) are shown in Table 3. Compound trains with layout variants V2, V3, V4, V5, V8, V9, V10 and V11 belong in that group. When the coupled shaft is locked (brake Br1 turned on), power is transmitted through one component train while the

other component train operates idly. When the brake on the single shaft is turned on (brake Br2 turned on), power is transmitted through both component trains. In the case of power transmission through both component trains the internal power branching or internal circulation of power in the compound train is possible, depending on the structure of the compound train [9, 10]

Table 3 Possible power flows through the train with brakes on the coupled and single shaft

V5Br1	V5Br2 power branching	V5Br2 internal circulation of power	

By creating kinematic schemes i.e. design concepts of all 120 train variants an insight into the arrangement of gears, shafts and brakes is obtained [10]. It is established that all of 120 train variants can be designed (some more easy than others). A possibility of locating the input and the output shaft on opposite sides of the train is investigated in particular. It is established that some of the train variants, because of their concepts (arrangement of brakes), cannot have input and output on opposite sides of the train. Those variants have input and output between the brakes. For each of the three train groups, variants which cannot be achieved with the input and output shaft on opposite sides of the train are given as follows:

For trains with brakes put on the single shafts, the train variants are the following: S15V6 S15V12, S16V6, S16V12, S35V6, S35V12, S55V12, S55V6, S56V12 and S56V6.

For trains with brakes on the coupled shafts, the train variants are the following: S55V1, S55V7, S56V1 and S56V7.

For trains with brakes on one single and one coupled shaft there is no train variant which can have an input and an output shaft on opposite sides of the train. In Fig. 5, a kinematic scheme of one train with a shaft on its opposite sides is shown as an example (S36V6, Fig. 5a) as well as one variant which cannot have an input and an output shaft on opposite sides (S15V12, Fig. 5b).
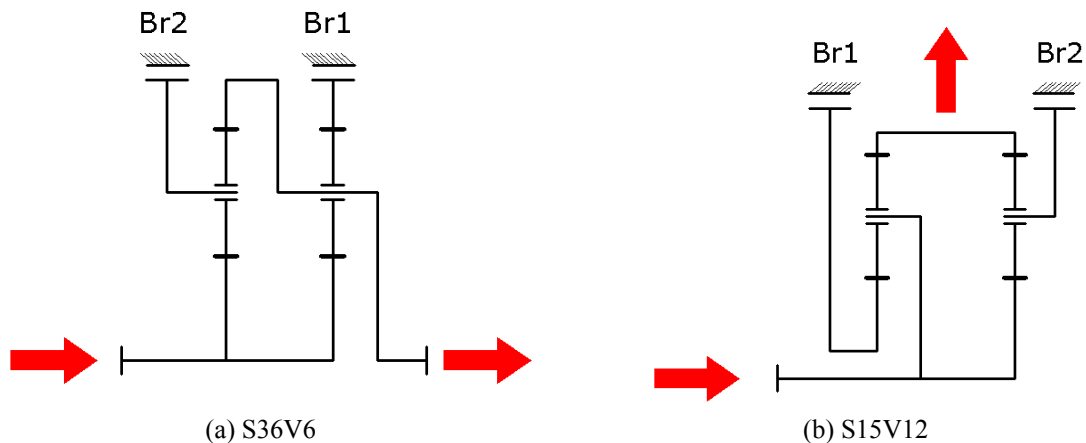

(a) S36V6   (b) S15V12

Fig. 5 Kinematic scheme of train S36V6 with input and output on opposite sides (a), kinematic scheme of train S15V12 which cannot have input and output on opposite sides (b).

4. Structural analysis and operating modes of the compound trains

Using the torque method [7-17], for every individual variant of the two-speed compound train, specific ideal torques on shafts are determined in [10]. The torque method is chosen because of its advantages over other methods which can determine the transmission ratio (Kutzbach method, Willis method, Swamp method, etc.) The most commonly used methods are the Kutzbach graphical method described in [2, 5, 18, 19, 20] and the Willis method described in [2, 5, 18, 19, 20]. The Kutzbach graphical method is clear but the values of rotational speed from which the transmission ratio is obtained have to be measured and depend on drawing accuracy. The Willis method gives precise results but the procedure of determining the transmission ratio demands more calculations, in which mistakes can easily happen. The torque method is clear, precise and accurate and allows the designer to obtain transmission ratio functions, which contain ideal torque ratios t_I and t_{II}, in a faster and simpler way. Beside transmission ratios, this method allows the determination of power flows through the train, torque on the shafts and efficiency.

For both gears, the flows of the power transmitted through the compound train are also determined in [10]. On the basis of the specific output and the specific input ideal torque $\overline{T}_A$ and $\overline{T}_B$ functions of transmission ratio i for both gears (Fig. 6) are obtained according to the following expression

$$i = -\frac{T_B}{T_A} = -\frac{\overline{T}_B}{\overline{T}_A} \qquad (1)$$

where:

T_B - ideal torque on the output shaft,

T_A - ideal torque on the input shaft,

$\overline{T}_A$ - specific ideal torque on the output shaft,

$\overline{T}_B$ - specific ideal torque on the input shaft.
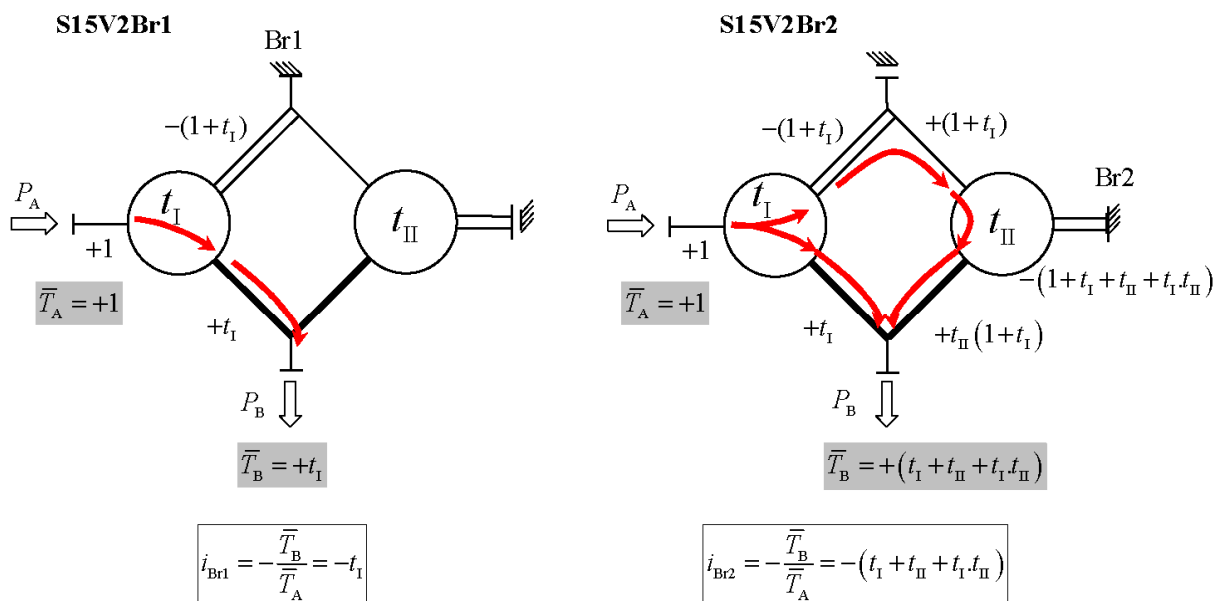
Fig. 6 Structure analysis of compound train S15V2

The structural analysis and power flows through the compound train S15V2 are shown in Fig. 6. At every shaft, a corresponding specific ideal torque is given. Specific ideal torques are expressed as functions of ideal torque ratios of the component trains. The figure shows that at gear Br1 only one component train is actively operating, and at gear Br2 two component trains are actively operating.

The design concept of this compound train is presented in Fig. 7. On the left-hand side of the figure the power flow through the compound train at gear Br1 is shown. On the right-hand side of the figure power flow through the compound train at gear Br2 is shown.
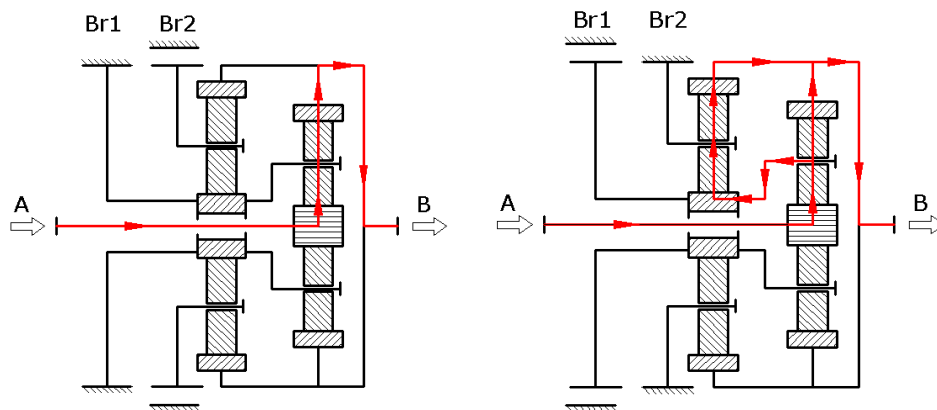
Fig. 7 Design concept and power flows through compound train S15V2

In Fig. 8, the influence of ideal torque ratios on the transmission ratios of both gears is graphically shown. The figure shows that in the whole domain of ideal torque ratios the transmission ratio at gear Br2 is greater than the transmission ratio at gear Br1.
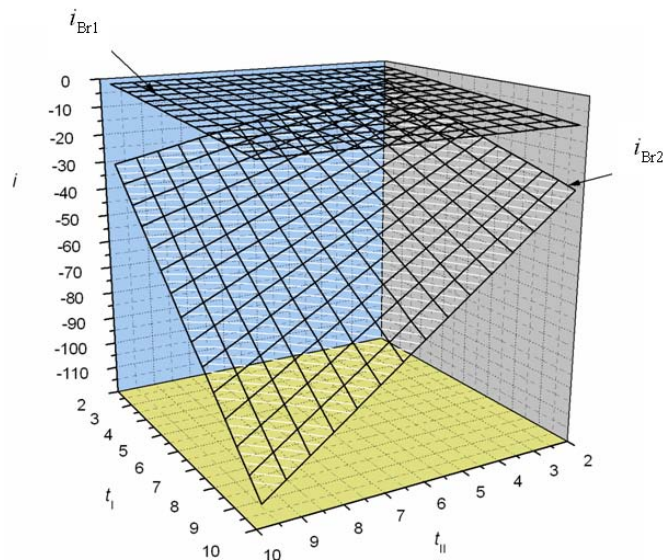
Fig. 8 The influence of ideal torque ratios on transmission ratios of compound train S15V2

By analyzing the functions of transmission ratios, data about the operating modes of all variants is obtained and given in Tables 4, 5, 6a and 6b. In these tables, the operating mode (reduction, multiplication, rotational direction of output in relation to input shaft) is expressed for every possible variant with only brake Br1 turned on and with only brake Br2 turned on.

Some variants at both gears operate as a reducer and some as a multiplier with the retention of or the shift in the rotational direction of the output shaft when changing the gear.

Also, other variants operate as a reducer at one gear and as a multiplier at the other with or without the retention of rotational direction when changing the gear. At all compound trains with brakes on the single shafts the operating mode is independent of the value of ideal torque ratios of the component trains. At some compound trains with brakes on the coupled shafts the change in the value of ideal torque ratios can cause a switch from reduction to multiplication within the same gear. These are the following compound trains: S11V1, S12V1, S33V1, S55V1, S11V7, S12V7, S33V7 and S55V7.

At some compound trains with brakes on the coupled and single shaft the change in the value of ideal torque ratios can cause a shift in the rotational direction of the output shaft and also a switch from reduction to multiplication and vice versa. These are the following compound trains: S11V4, S11V5, S33V4, S33V5, S36V8, S55V4, S55V5, S11V10, S11V11, S33V10, S33V11, S36V2, S55V10 and S55V11.

The review of operating modes of all compound trains can considerably reduce the time needed to find an adequate variant of the compound train. For example, if the designer is looking for a compound train which operates as a reducer in one gear with the same rotational direction of the input and output shaft and as a multiplier with the opposite rotational directions of the input and output shaft in the other gear, the tables direct him to the analyses of schemes which meet the required condition. The variants which meet this condition are the following: S15V6, S35V6, S56V6, S12V12, S14V12, S34V12, S36V1, S14V11, S34V2 and S56V9.

When the variants with the required operating modes are identified, the functions of transmission ratios are to be determined by means of the method previously shown (the torque method) and it should be verified if any of the selected variants can achieve the required values of transmission ratios. By inserting the values of the demanded transmission ratios into the transmission ratio function, obtained by the expression (1), the values of ideal torque ratios of the component gear trains can be determined. These values have to be within the interval limited by the design $t \in (2,12)$. If the values of the ideal torque ratios are not within that interval, the train cannot be created. On the basis of the determined ideal torque ratios the number of teeth of all gears in accordance with the synthesis condition (mounting condition and coaxiality condition) [1, 8, 17] of the planetary gear set can be determined.

Table 4 Operating modes of compound trains with brakes on single shafts

Label of the train variant	At gear Br1:		At gear Br2:		Output shaft rotates in the opposite direction from the rotational direction of the input shaft with the brake turned on:	
	red.	mul.	red.	mul.	Br1	Br2
S11V6	●		●		●	
S12V6	●			●	●	
S13V6	●		●		●	
S14V6	●			●	●	
S15V6	●			●		●
S16V6	●		●			●
S33V6	●		●		●	
S34V6	●			●	●	
S35V6	●			●		●
S36V6	●		●			●
S55V6		●		●	●	●
S56V6		●	●		●	●

Label of the train variant	At gear Br1:		At gear Br2:		Output shaft rotates in the opposite direction from the rotational direction of the input shaft with the brake turned on:	
	red.	mul.	red.	mul.	Br1	Br2
S11V12		●		●	●	
S12V12		●	●		●	
S13V12		●		●	●	
S14V12		●	●		●	
S15V12		●	●			●
S16V12		●		●		●
S33V12		●		●	●	
S34V12		●	●		●	
S35V12		●	●			●
S36V12		●		●		●
S55V12			●		●	●
S56V12				●	●	●

Table 5 Operating modes of compound trains with brakes on coupled shafts

Label of the train variant	At gear Br1:			At gear Br2:			Output shaft rotates in the opposite direction from the rotational direction of the input shaft with the brake turned on:	
	red.	red or mul	red.	red.	red. or mul	mul.	Br1	Br2
S11V1		●			●			
S12V1		●			●		●	●
S13V1	●			●				
S14V1	●			●			●	●
S15V1	●			●			●	
S16V1	●			●			●	
S33V1		●			●			
S34V1			●	●			●	●
S35V1			●	●			●	
S36V1		●		●			●	
S55V1		●			●			
S56V1	●					●		
S11V7		●			●			
S12V7		●			●		●	●
S13V7			●			●		
S14V7			●			●	●	●
S15V7			●			●	●	
S16V7			●			●	●	
S33V7		●			●			
S34V7	●					●	●	●
S35V7	●					●	●	
S36V7		●				●	●	
S55V7		●			●			
S56V7			●	●				

Table 6a Operating modes of compound trains with brakes on coupled and single shaft

Label of the train variant	At gear Br1:			At gear Br2:			Output shaft rotates in the opposite direction from the rotational direction of the input shaft with the brake turned on:		Rotational direction of the output shaft at gear Br2 depends on the relation between ideal torque ratios
	red.	red. or mul.	mul.	red.	red. or mul.	mul.	Br1	Br2	
S11V4			●	●			●		●
S11V5			●	●					●
S12V2	●			●			●		
S12V3	●			●					
S13V2	●			●			●	●	
S13V3	●			●				●	
S13V4	●			●			●		
S13V5			●	●					
S14V2	●			●			●		
S14V3	●			●					
S14V10	●			●					
S14V11			●	●			●		
S15V2	●			●			●	●	
S15V3	●			●					
S15V4	●			●					
S15V11			●	●					
S16V2	●			●			●	●	
S16V3	●			●					
S16V4	●			●					
S16V11			●	●					
S33V4	●				●		●		●
S33V5	●				●				●
S34V2			●	●			●		
S34V3	●			●					
S35V2			●	●			●	●	
S35V3	●			●					
S35V4	●			●					
S35V11			●	●					
S36V3	●			●					
S36V4	●			●					
S36V8	●				●		●	●	
S36V11			●	●					
S55V4	●				●				●
S55V5	●				●				●
S56V3			●	●				●	
S56V5	●			●					

Table 6b Operating modes of compound trains with brakes on coupled and single shaft

Label of the train variant	At gear Br1:			At gear Br2:			Output shaft rotates in the opposite direction from the rotational direction of the input shaft with the brake turned on:		Rotational direction of the output shaft at gear Br2 depends on the relation between ideal torque ratios
	red.	red. or mul.	mul.	red.	red. or mul.	mul.	Br1	Br2	
S11V10	●				●		●		●
S11V11	●				●				●
S12V8			●			●	●		
S12V9			●			●			
S13V8			●			●	●	●	
S13V9			●			●		●	
S13V10			●			●	●		
S13V11	●					●			
S14V8			●			●	●		
S14V9			●			●			
S14V4			●			●			
S14V5	●					●	●		
S15V8			●			●	●	●	
S15V9			●			●			
S15V10			●			●			
S15V5	●					●			
S16V8			●			●	●	●	
S16V9			●			●			
S16V10			●			●			
S16V5	●					●			
S33V10			●		●		●		●
S33V11			●		●				●
S34V8	●					●	●		
S34V9			●			●			
S35V8	●					●	●	●	
S35V9			●			●			
S35V10			●			●			
S35V5	●					●			
S36V9			●			●			
S36V10			●			●			
S36V2			●		●		●	●	
S36V5	●					●			
S55V10			●		●				●
S55V11			●		●				●
S56V9	●					●		●	
S56V11			●			●			

5. Conclusion

In this paper, two-carrier planetary gear trains with four external shafts and two brakes are analyzed. It has been established that these trains, equipped with two brakes, can achieve very different combinations of two transmission ratios. The labelling system of these trains is defined and all variants of such trains are identified. The labelling system allows the unambiguous defining of the train structure and the position of the driving machine, operating machine and brakes on the train shafts. The trains are divided into three different design groups and common characteristics of the trains of each group are given. The train variants whose structure allows the input and the output shaft to be placed on opposite sides of the train are identified as well as those train variants in which this is not possible, so input and output have to be placed between the brakes of the train. It has been investigated for which train variants the magnitude of an ideal torque ratio can cause a change in the operating mode within the same gear. For each train variant, the kinematic operating modes are determined (reduction, multiplication, rotational direction of the output shaft in relation to the input shaft) and the results are presented in the tables. These tables allow insight in the operating mode of each variant and therefore can help the designer not to waste time on analyzing structural schemes which certainly cannot satisfy transmission requirements.

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