Design Method for the Power Shifting Transmission of Parallel Hybrid Electric Vehicle

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Abstract: A novel method of scheme design is proposed for power shifting transmissions of parallel hybrid electric vehicles (HEVs). First, shift sequences considering the path of power flow and shift logics are analyzed based on the graph theory model, abstracted from the degree-of-freedom (DOF) of the schemes. Second, the scheme of gear-pair and shaft, defined as the scheme that ignores the arrangement of synchronizers, is derived from the basic configuration, defined as the scheme of gear-pair and shaft that contains only one of each type of the variable connections, and the numbers of each type of the variable connections. Finally, a multi-parameter scheme, including the arrangement of synchronizers and gear ratios, is designed to optimize the results of synthesis. This method helps to gain a deeper understanding of the systematic design of other fixed gear transmission schemes, such as automated mechanical transmission, dual clutch transmission, and even some novel multi-input transmission.

Key words: hybrid electric vehicle; transmission scheme; novel design method
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Due to their fewer emissions and higher energy efficiency, electric and hybrid electric vehicles (HEVs) have been developed by leading global car manufacturers. Although fully electric vehicles are currently the ultimate goal of the automobile industries, they are currently only available in niche industries[1]. The powertrain can be made more efficient using an electric motor (EM)[2]. Many hybrid architectures of series, parallel, or complex series/parallel types, have been developed by car manufacturers. Due to automated manual transmission (AMT) being not only the most efficient automated transmission but also the most inexpensive one, the parallel architecture, which is usually constitutes an EM and an AMT, is currently almost the most frequently adopted among hybrid electric vehicles[3]. This paper is focused on the parallel HEV, which is called power shifting transmission (PST) in this paper.

Without increasing mechanical complexity, PSTs can provide several internal combustion engine (ICE) gears as well as several EM gears by improving the utilization of mechanical components. Therefore, numerous PSTs have been proposed and produced[4-5]. Researchers recently began to investigate systematic ways to identify optimal configurations and sequences. The topological synthesis of a two degrees-of-freedom (DOFs) fractionated parallel hybrid transmission mechanism was presented in Ref. [1]. An efficient methodology on designing multiple operating DOFs planetary gear trains based on the varying structure theory was proposed in Ref. [6]. An automated modeling and a fast suboptimal control procedure were developed that were able to be used to explore a large number of power-split configurations in Refs. [2,7]. A systematic and automatic synthesizing method was proposed by means of morphological analysis[8]. All of the theoretical layouts of parallel HEVs with three shafts were presented and classified into four

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types in Ref. [9]. However, none of these methods can be applied in designing PSTs, in which the two kinds of powers are coupled together through the same mechanism components.

The basic flowchart of topology design method is shown in Fig. 1. Firstly, the concrete structures of the transmission schemes are sidestepped. Thus, the concrete structures are abstracted into the vertices and the edges based on the DOF of the schemes to study the shift sequences. Secondly, the schemes of gear-pair and shaft are synthesized based on the shift sequences above and the basic configurations. Thirdly, multiple parameters, including the synchronizers' arrangement and gear ratios, is optimally designed for the results of the synthesis.

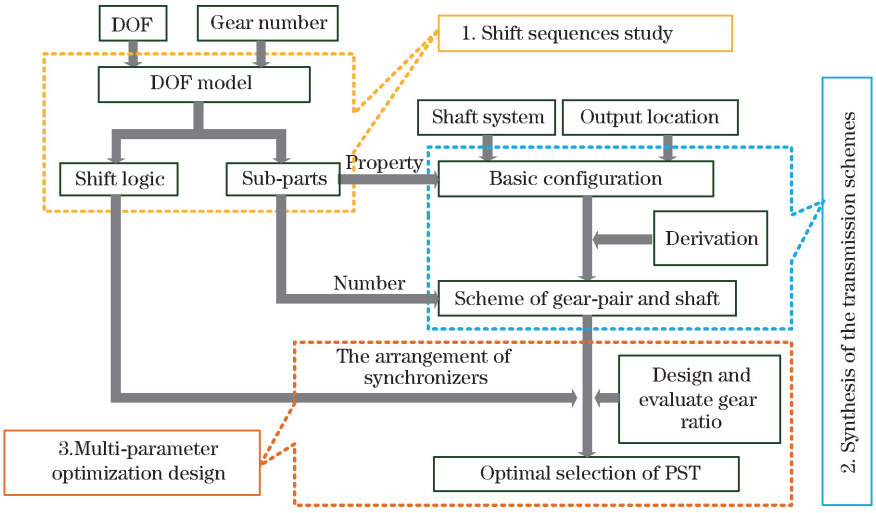


Fig. 1 Basic flowchart of topology design method

1 Shift Sequences Study

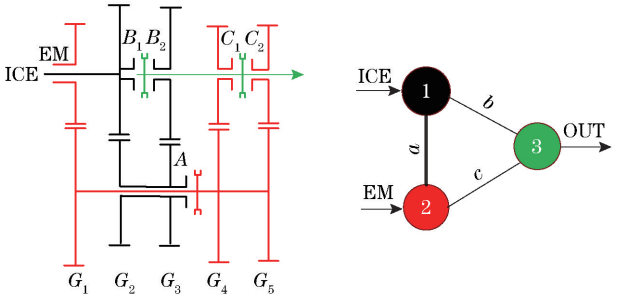
1.1 Define the DOF model

The DOF of transmission is defined as the number of independently and arbitrarily presentable parameters or states for the definite operating condition[10]. Since there are two power sources, the PST contains three DOFs, which are connected with the ICE, the EM, and the output shaft respectively. Two concepts are defined in order to facilitate the study of shift sequences, variable connection, and permanent connection. The variable connection is defined as the gear-pair in which one gear of the gear-pair is permanently connected with the shaft or hollow shaft, and the other is an idler gear. The synchronizers' state determines whether the idler gear is connected to the shaft or not. If both gears of a gear-pair are permanently connected to a shaft or a hollow shaft, this gear-pair is called a permanent connection. The permanent connection is the path between different shafting systems within the same DOF. By contrast, the on-off state of the variable connection determines the different power flow, that is, shift sequences.

The graph theory model with the DOF as the basic unit is defined: edges represent variable connections between two degrees of freedom, which is called sub-path in the model; vertices represent mechanisms that belong to the same DOF, except for variable connections. Thus, the condition of gear formation is converted from the certain movement between the input shaft and output shaft to the certain path between the input DOF and the output DOF.

All of the PSTs like the one shown in Fig. 2a can be represented by the graph theory model shown in Fig. 2b. The scheme contains three independent sub-mechanisms when all the synchronizers are in the non-working state. Therefore, the graph theory model of the scheme contains three vertices (1, 2, and 3). The relationship between the variable connections of the scheme and the sub-paths of the graph theory model is shown in Tab. 1. The number of sub-paths in the graph theory model is $a = 1$, $b = 2$, and $c = 2$, respec-

tively. Then numbers a, b_1, b_2, c_1, c_2 are sequentially performed, where $(a_1, a_2, \cdots, a_n) \in a$, $(b_1, b_2, \cdots, b_n) \in b$, $(c_1, c_2, \cdots, c_n) \in c$. Sub-paths are used to represent the corresponding gear. For example, the corresponding ICE gear of the ICE path 1*b*3 is B and the corresponding EM gear of the EM path 2*a*1*b*3 is AB.



(a) Transmission schem (b) Graph theory model

Fig. 2 Transmission scheme and its graph theory model

Tab. 1 Relationship between the scheme and the model

DOF	Scheme	Graph theory model	
	Variable connections	Sub-path	Number
F_1, F_2	A	a	1
F_1, F_3	B_1, B_2	b (b_1, b_2)	2
F_2, F_3	C_1, C_2	c(c_1, c_2)	2

There are two types of power flow on the PST. One of them is that the input DOF (F_1 or F_2) is directly connected to the output DOF (F_3). With the ICE gear B_1 and EM gear C_1 as shown in Fig. 2a, the corresponding path of the graph theory model is 1*b*3 and 2*c*3. Another type is that the input DOF (F_1 or F_2) is connected to the output DOF (F_3) via the intermediate DOF (F_2 or F_1). With the EM gear AB_1 and ICE gear AC_1 as shown in Fig. 2a, the corresponding path of the graph theory model is 2*a*1*b*3 and 1*a*2*c*3. These paths form a connection between the two inputs, where both input shafts could provide power, so we define these paths as dual power paths and define the gears corresponding to the dual power paths as dual power gears.

As the dual power path goes through the two inputs at the same time, there is only one coupled path of the dual power path. For example, the dual power path of the ICE is $1a_1 2c_1 3$, its coupled EM path must be $2c_1 3$, otherwise, it will form a circuit. In order to provide torque support, the EM gear must keep the original gear still during the ICE gear shifts. Similarly, the ICE gear must keep the original gear still during the EM gear shifts. When one path is in dual power gear, the coupled path cannot shift.

1.2 Shift logic analysis

The PST has the following characteristics: each EM gear corresponds to three or four ICE gears because the operating range of EMs is usually two to four times longer than that of ICE; ratio steps progressively decrease from the low gears to the top gears.

The shift sequence of the EM gears and the ICE gears is shown in Fig. 3. There are at least n EM gears C including C_1, C_2, $\cdots$, C_n, and $n-1$ ICE gears B including B_1, B_2, $\cdots$, B_{n-1}. The other ICE gears can be B or AC.

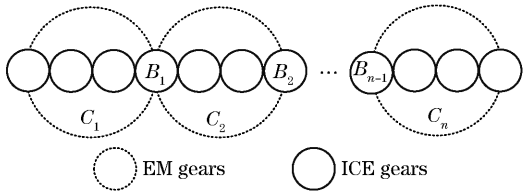


Fig. 3 Shift sequence of the EM gears and the ICE gears

When the number of sub-paths a is two, $2n_c$ ICE gears AC are formed at most, as shown in Fig. 4. Because A_1C_1 and A_2C_1 have the same variable connection c_1, the ratio step between A_1C_1 and A_2C_1 equals the ratio of sub-path a_1 divided by the ratio of sub-path a_2. Similarly, the ratio step between A_1C_i and A_2C_i equals the ratio of sub-path a_1 divided by the ratio of sub-path a_2. All of the ratio steps between A_1C_i and A_2C_i are the same. We can either delete some ICE gears AC or add some ICE gears such as B and AC to obtain progressively decreasing ratio steps.

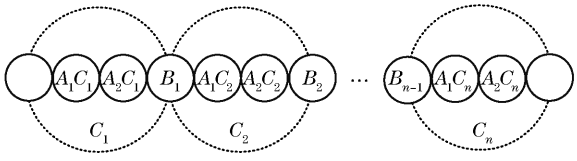


Fig. 4 Ratio steps between A_1C_i and A_2C_i

1.3 Optimization of shift sequences

In this paper, the PST, the shift sequences of which contain eight ICE gears and three EM gears, are taken as an example to study the opti-

mization of shift sequence. First, according to the number of ICE gears corresponding to the coupled EM gear, it can be divided into four types: 2–4–4, 3–3–4, 4–3–3, and 4–4–2. The first number, the second number, and the third number represent the number of ICE gears corresponding to the first, second, and third gears of the EM, respectively. By comparing the numbers of the sub-paths that the shift sequences contain, the following four shift sequences are obtained because they contain the smallest number of sub-paths, as shown in Fig. 5. These four shift sequences use only eight sub-paths to achieve eight ICE gears and three EM gears.

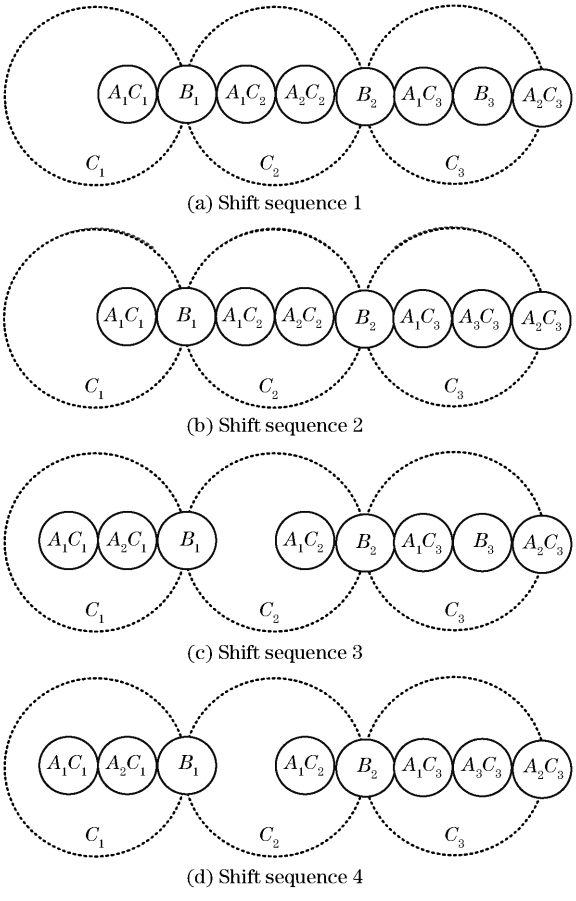


Fig. 5 Shift sequence for eight ICE gears and three EM gears

2 Synthesis of the Transmission Schemes

In order to avoid the scheme explosion caused by the exhaustion in the synthesis of the schemes, the concepts of the scheme of gear-pair and shaft and the basic configuration are defined in this paper. The scheme of gear-pair and shaft is defined as the scheme that ignores the arrangement of synchronizers. The basic configuration, defined as the scheme of gear-pair and shaft that ignores the number of variable connections with the same nature, contains at least one of each variable connection which is desired for the shift sequence studied above.

Through the method of simplifying the scheme into the scheme of gear-pair and shaft and then simplifying the scheme of gear-pair and shaft into the basic configuration, the number of components is greatly reduced and the structure is simpler. Therefore, this section firstly synthesizes the basic configuration according to the nature of the variable connections. Then based on the basic configuration, the scheme of gear-pair and shaft is synthesized according to the number of variable connections.

2.1 Define and analyze the basic configuration

The basic configuration consists of three parts: the shaft arrangement, the permanent connection, and the variable connection. There are two special characteristics of the PST discussed on this paper: the EM, the ICE, and the output shaft are arranged coaxially, as shown in Fig. 6; the schemes have two shaft systems containing shafts and hollow shafts.

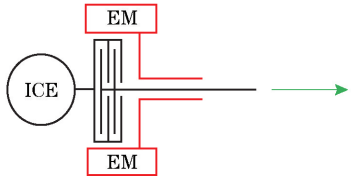


Fig. 6 Layout of the main shaft on the PST

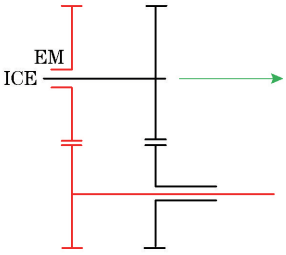
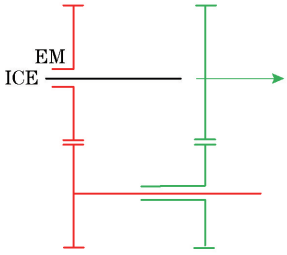
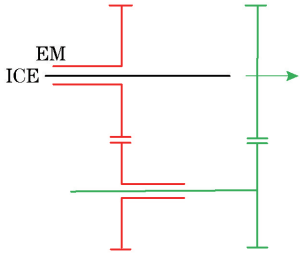
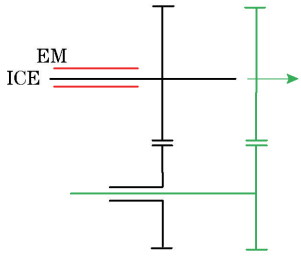
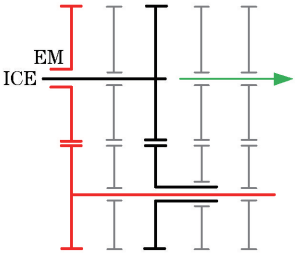
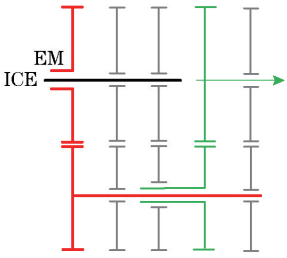
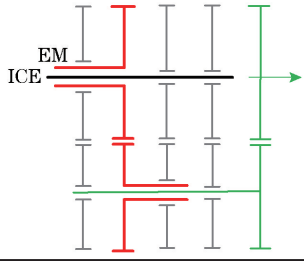
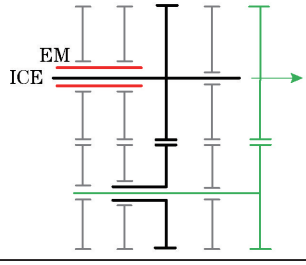
The variable connections in the basic configuration of the four-DOFs scheme are determined by the shift sequence. Different sub-paths in the different shift sequences result in different types of variable connections in the basic configuration.

For the PST with two shaft systems, the first shaft system comprises an ICE input shaft which belongs to the DOF F_1, an EM input shaft which belongs to the DOF F_2, and an output shaft which belongs to the DOF F_3. The second shaft system must fall within the three DOFs above, which

means that the shafts and the hollow shafts in the second shaft system must connect with the first shaft system via permanent connections.

There are four kinds of configurations and permanent connections, shown in row 1 Tab. 2. The variable connections are represented by the fine lines in the basic configuration. The four basic configurations are shown in row 2 of Tab. 2. If the synchronizer connects the shaft and the hollow shaft or shaft and shaft in the same shaft system, an additional variable connection will be formed. In the first shaft system, the ICE input shaft and the EM input shaft can form an additional variable connection a, and the ICE input shaft and the output shaft can form an additional variable connection b. Based on the different layout of the four basic configurations, it may form a, b or c, which are shown in row 3 of Tab. 2. In summary, all of the four basic configurations consist of five gear-pairs, including two permanent connections and three variable connections.

Tab. 2 Basic configuration of the PST with 2 shaft systems

a=2 b=1 c=0	a=1 b=1 c=1	a=1 b=1 c=1	a=1 b=2 c=0
			
			

2.2 Derivation of the scheme of gear-pair and shaft

The shift sequence 1 in the above section is taken as an example. The number of sub-paths a, b, and c are two, three, and three, respectively. The number of each variable connection that the basic configurations also need equals that the variable connections of shift sequence minus additional variable connections of the basic configurations. The scheme of gear-pair and shaft can be derived from the basic configurations, and the results are shown in Fig. 7.

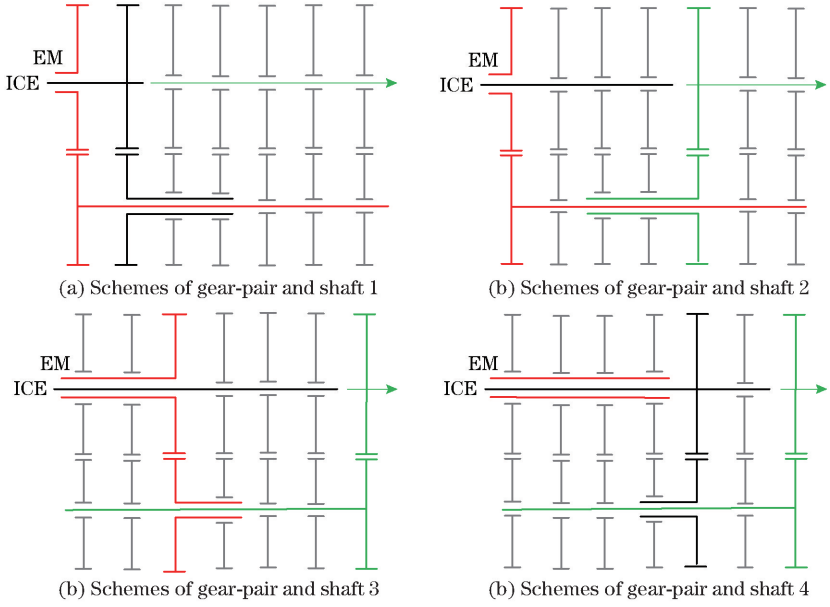
3 Multi-Parameter Optimization Design

3.1 Arrangement of synchronizers

In terms of evaluating the arrangement of synchronizers, this paper considers the following four principles: In order to achieve the function of power shifting, the two variable connection structures of the same synchronizer cannot be simultaneously combined in the overlapping of the adjacent gears; If a synchronizer arranged in the first shaft system is equivalent to that arranged in the second shaft system, the synchronizer should be placed in the first shaft system in order to facilitate the arrangement of the actuators; In general, the diameter of a synchronizer is greater than the center distance of the gearbox, so two synchronizers should not be arranged in the same position as the two shaft systems; Each synchronizer should better include three conditions: right engagement, left engagement and disengagement, and this design will help to reduce the number of

synchronizers.

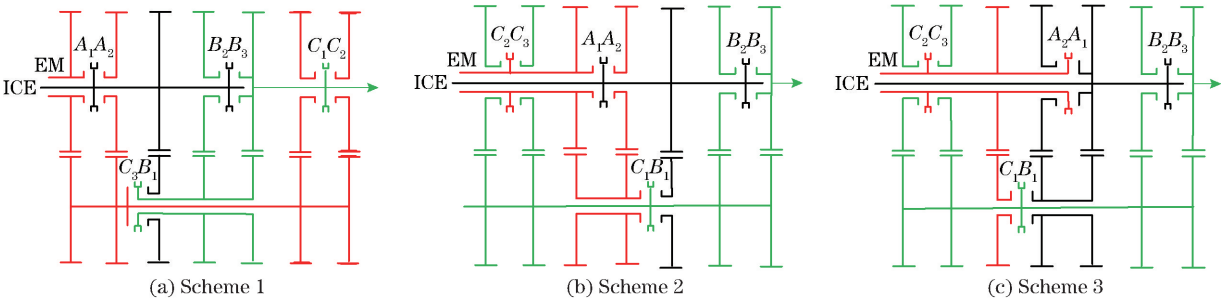
Finally, based on the schemes of gear-pair and shaft in the previous section, a total of three optimal PST schemes are obtained as shown in Fig. 8, in which scheme 1, scheme 2, and scheme 3 are derived from the scheme of gear-pair and shaft 2, the scheme of gear-pair and shaft 3, and the scheme of gear-pair and shaft 4, respectively. All the schemes include seven gear-pairs and four synchronizers.



(a) Schemes of gear-pair and shaft 1 (b) Schemes of gear-pair and shaft 2

(b) Schemes of gear-pair and shaft 3 (b) Schemes of gear-pair and shaft 4

Fig. 7 Schemes of gear-pair and shaft



(a) Scheme 1 (b) Scheme 2 (c) Scheme 3

Fig. 8 Optimal PST schemes

3.2 Gear ratios design

The ICE gear ratios play a key role in vehicle performance and the function of the EM gear ratios is to provide torque support to overcome the torque interruption during ICE gears shift. Therefore, the design of gear ratios is based on the requirements of ICE gear ratios. Since the actual gear ratios cannot be equal to the requirement gear ratios, the gear ratios design of the PST is contradictory and can be translated into the solution of over-determined nonlinear equations. The number of direct gears and the first gear ratio are given in this paper, based on the shift sequence and the demands for the vehicle. Progressively decreasing ratio steps from low gear to high gear are designed to fit the engine power curve for improved fuel economy[11]. Let R_1, R_2, R_3, and so on be the first, second, third, etc. gear ratios; then the ICE gear ratios can be formulated as

$$\begin{cases} R_2 = \dfrac{R_1}{1 + a^x} \\ R_3 = \dfrac{R_1}{(1 + a^x)(1 + ra^x)} \\ R_4 = \dfrac{R_1}{(1 + a^x)(1 + ra^x)(1 + r^2a^x)} \\ \vdots \\ R_n = \dfrac{R_1}{\prod\limits_{k=0}^{n-2}(1 + r^k a^x)} \end{cases} \quad (1)$$

where a^x equals the requirement of the ratio step between the first gear ratio and the second gear ratio. The value of r is solved based on the given first gear ratio, a^x and the position of direct gear.

The seventh gear of the shift sequence 1 is the direct transmission, setting the first gear ratio to 6.5 and the seventh gear ratio to 1.00. All ratios are calculated through the solution of over-determined equations, and the results are shown in Tab. 3.

Tab. 3 Design gear ratios for the ICE

R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
6.50	3.82	2.51	1.81	1.41	1.16	1.00	0.89

By taking the minimization of the infinity norm and Euclidean norm of each gear ratio as the optimization objective, the solution of these equations can be transformed into optimization problems of several variables shown as

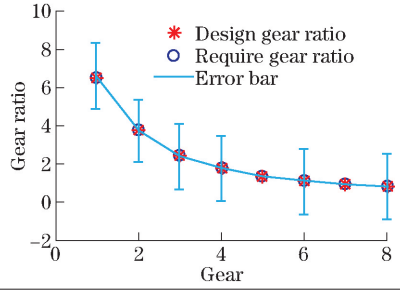
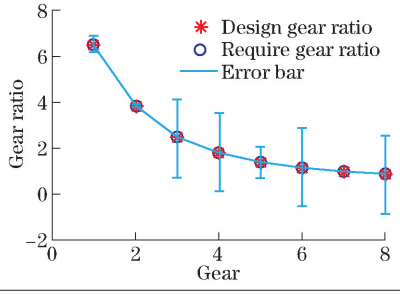
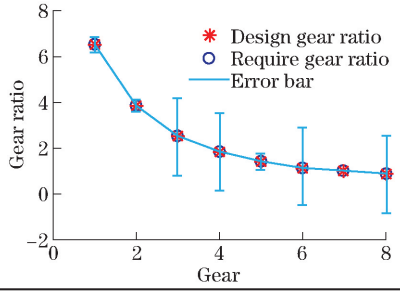
$$\min(\max\{|f(i)-R_i|/R_i\})_{0.5} \tag{2}$$

$$\min\left(\sum_1^i((f(i)-R_i)/R_i)^2\right) \tag{3}$$

where $f(i)$ is the design ratio and R_i is the required ratio.

According to engineering experience, the result of the gear ratio design is considered reasonable when all of the gear-pair ratios are between 0.3 and 3 and the infinity norm is less than 5%. All gear ratio designs of the PST with eight ICE gears and three EM gears based on shift sequence 1 are listed out in Tab. 4. From Tab. 4, it can be concluded that all gear-pair ratios are within a reasonable range except the sixth gear-pair of scheme 1, which is 0.14. All the infinity norms of these schemes are less than 5% Therefore, the gear ratios designs of scheme 2 and scheme 3 are reasonable.

Tab. 4 Gear ratio designs

Scheme	Gear-pair ratio	ICE gear ratio	EM gear ratio	Design error of gear ratios	Infinity and Euclidean norm
1	0.94 0.70 2.99 1.12 0.79 0.14 0.38	6.71 3.78 2.47 1.84 1.42 1.19 1.00 0.89	6.71 2.47 1.19		1.69 4.12
2	0.82 0.39 2.16 1.61 1.26 0.47 0.33	6.55 3.82 2.48 1.85 1.42 1.18 1.00 0.88	6.55 2.48 1.18		1.69 3.46
3	0.84 0.40 2.21 1.30 1.75 0.64 0.46	6.47 3.80 2.46 1.83 1.39 1.17 1.00 0.87	4.80 1.83 0.87		1.68 3.42

4 Conclusion

In this study, a novel and efficient methodology different from the total enumeration design is presented to design PSTs. The key points of the methodology are the graph theory model of the PST and the basic configurations. According to the analysis of the relationship between DOFs on the graph theory model, it is found that different variable connections have different characteristics on shift sequences. Therefore, the possible shift sequences can be synthesized based on these characteristics. Basic configurations, defined as the basis from which the schemes of gear-pair and shaft are derived, are obtained for the two shaft systems' PSTs. The scheme of gear-pair and shaft can be derived by adding variable connections to the basic configurations, according to the shift sequences. Furthermore, the design concept can also be applied to other fixed gear transmissions, such as AMTs and dual clutch transmissions, which will be studied in the future.

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