Viability of Epicyclic Gear Transmission Layouts with Three Planetary Gear Trains

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Abstract—**Epicyclic gear train (EGT) synthesis deals with the enumeration of distinct EGT layouts with multiple planetary gear trains (PGTs) connected to each other through elements like permanent connections (or shafts), along with constraining elements like brakes and clutches, altogether works towards producing variety of speed ratios. Two aspects are important while synthesizing EGT layouts viz., identification of isomorphic (duplicate) layouts and identifying the viable (functionally realizable) layouts. The present work attempts to describe viability in EGT layout with 3 PGTs, 3 permanent connections, 2 clutches and 2 brakes. Python program is used to generate the viable layouts.**

Keywords—Epicyclic Gear Trains;Planetary Gear Trains; Speed ratios; viability.

I. INTRODUCTION

An Epicyclic gear transmission system (EGT) is sought when more than one speed ratio is required from a gear box. This necessitates usage of multiple planetary gear train (PGT). Synthesis of epicyclic gear transmission systems (EGTs) primarily involves the generation of various EGT layouts consisting of multiple planetary gear trains (PGTs) coupled together with constraining elements like permanent connections, clutches, and brakes, altogether designed to produce a variety of positive transmission ratios. These transmission ratios or speed ratios are possible by the constraining one or more elements of PGTs. i.e., engagement of one or more brakes or clutches during the transmission which enable the EGT to produce a different output speed proportional to the input speed. Thus, an EGT layout can be perceived of a structure consisting of all the elements mentioned above, represented in a meaningful way, from which the functionality can be derived., i.e. speed ratios can be realized.

A pair of gears can be represented by an equivalent four bar linkage [1] and Levai [2] proved that EGT system with two sun gears, one or more carriers and one arm can produce 34 unique layouts. Graph theory was introduced into structural synthesis of EGT by Freudenstein [3] and also, he established the correspondence between graphical representation and displacement equations of mechanisms [4]. Well defined rules for structural synthesis of compound differential mechanisms was given by Molian [5] who synthesized 35 mechanisms. Sanger [6] derived all possible mechanisms of Wilson gear box consisting up to 4 PGTs. But, a systematic methodology to enumerate all possible EGT layouts by incorporating control elements (brakes and clutches) was presented by Lloyd [7]. A PGT can be represented as a graph consisting of three vertices [8,9] as shown in figure 1, with each vertex representing each shaft (Sun or Arm or Annulus) of PGT. Usually, at the early stage of synthesis, the above elements are not distinguished, i.e., Sun, Arm or Annulus represented by three vertices in the graph are not differentiated.

During structural synthesis, since the three shafts of a PGT are considered indistinguishable from one another, and since all three are interconnected, a PGT can be represented as a complete graph of three vertices, Fig. 1(b) and hence the vertices 1,2,3 represents 'S', 'A' and 'R' which are identical in the synthesis point of view and thus, the edges connected through vertices 1-2, 2-3 and 1-3 represents the PGT with the elements connected to each other.
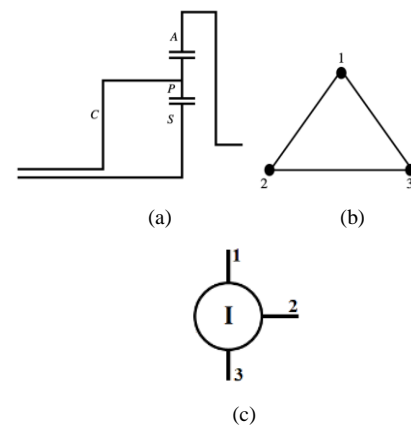

Fig. 1 A simple PGT and its graphical representations

II. VIABILITY OF AN EGT

Viability of an EGT is defined by Lloyd [7] which states that an epicyclic gear box is viable if all internal connections can be made coaxially. All EGT layouts synthesized according to the preceding steps need not in general comply with this requirement. However, using additional geared drives, one can make all the interconnections that the system requires. But this can only be done at the expense of its structural simplicity and the benefits of epicyclic gearing such as its compactness and hence lesser weight and so on. Also, it is proved that an epicyclic

mechanism is viable if a two-dimensional portrayal when lines are drawn representing the internal and external connections, the connecting lines do not cross each other, and only pass-through representations of gear sets if they are connected to the planet carriers.

Consider the schematic and graph representation of 3-epicyclic, 6-speed system as shown in Figure 2 (a), which depicts the permanent connections as well as the port elements and disposition of clutches. Since all the port elements [8] are to be connected to the exterior, it is necessary to ensure that the graph Figure 2 (b) is planar, and all the port vertices lie on the boundary of one face or one region of graph.
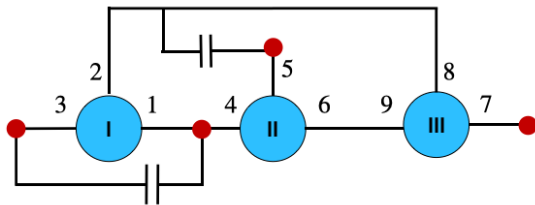
(a) Schematic of EGT with three PGTs, three permanent connections, two clutches and 4 port elements
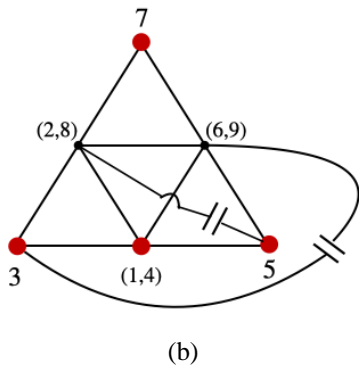

(b)

Fig. 2 Graphical representation of EGT with three PGTs, three permanent connections, two clutches and 4 port elements

III. METHODOLOGY

As the first step, the following operations are performed.

1. The edges of the graph that pass through the clutches are ignored for the time being. Thus, the edge between vertices 2(8) and 5, and between 3 and 6(9) in figure 2 (b) are ignored.

2. An additional vertex V is introduced in the graph (Figure 2(b).

3. An edge is introduced between vertex V and every port vertex.

Planarity of the latter graph (Figure 3) is to be ensured before proceeding further.
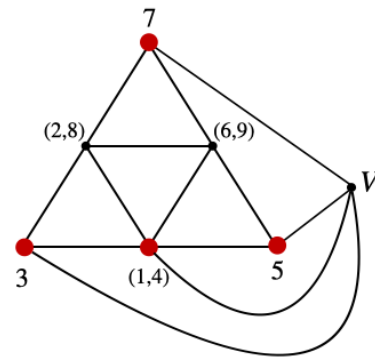

Fig. 3 Ensuring all port vertices lie on one region

In the second step, connections via those clutches which were ignored in the first step are introduced. Here, again the planarity of the graph is to be preserved. From figure 2 (b) such a connection is not possible without destroying the planarity of the graph. The following demonstrates a way to convert the above nonplanar graph (with clutches in place) into a planar graph.

In the figure 3, let element 5 be the planet carrier. Then, owing to the definition of viability of epicyclic mechanisms, one may choose either of the following options. In the first option, an additional vertex 5* and two edges (shown as broken lines for convenience) is introduced as illustrated in figure 4 (a). The vertices 5 and 5* are then treated as equivalents. Thus, a connection between vertices 2 and 5 is considered equivalent to that between elements 2 and 5*. In the second option, the edge between vertices 4 and 6, which is diagonally opposite to vertex 5 is removed to permit a direct connection between the vertices 2 and 5. Figure 4 (b) illustrates this option. It is important to observe that the vertex 5 was mirrored across the edge (4,6) because, 4,5 and 6 are elements of same PGT. For the same reason, edge (4,6) was removed from the graph in the second option. In terms of interconnections existing between the shafts of EGT system, the two options simply mean that the element 5 is a planet carrier and that the connection between the elements 2 and 5 can be achieved only by passing through the planet gear.

The connection between vertex 3 and vertex 6 is also shown in the figure 4 (a) and 4 (b). It may be seen that the shifting of vertex 3 across the edge (1,2), followed by the connection of 3* (not shown in figure) to vertex 6 leads to a nonplanar graph. Similar observation can be made from the graph shown in 4 (b), when the edge (1,2) is removed from the graph and vertex 3 is connected to vertex 6. Figure 4 (a) shows that the shifting of vertex 9 (or 6) across the edge (7,8) leads to a planar graph. Also, removal of edge (7,8) permits the connection between the vertices 3 and 6 while the planar structure of the resulting graph is ensured.
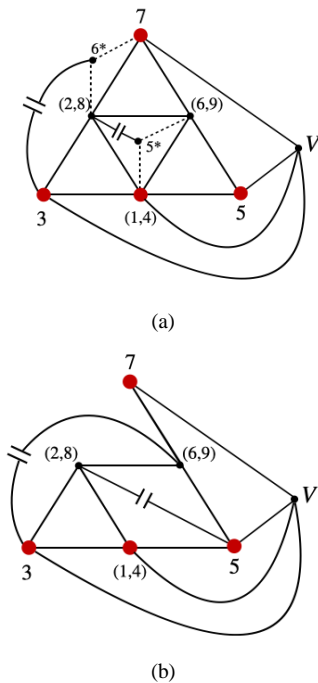
(a)

(b)

Fig. 4 Viable EGT layouts having N=3, L=3, B=2 and C=2

The consequence of the above assumptions is that, certain elements of the layout are planet carriers has been the reduction in the number of distinct variants. Or alternatively, there is a reduction in the number of ways in which the three shafts of a PGT unit in the EGT system can be assigned as that of the sun gear or the annulus or the planet carrier. In figure 6.21, for example, elements 4,6,7 and 8 can take the role of sun gear and annulus only since the elements 5 and 9 are always planet carriers. In other words, only 'two' permutations are possible in PGTs 2 and 3. In PGT-1 on the other hand, all 'six' permutations can be had. Thus, the total number of viable variants for the layout shown in figure 4 is found to be 24 (6 x 2 x 2).

Example: 2 – When one of the shaft serve as planet carrier.

Consider an EGT with three PGTs (N=3), three permanent connections(L=3), two clutches (C=2) and four port elements (P = 4) as shown in fig. 5
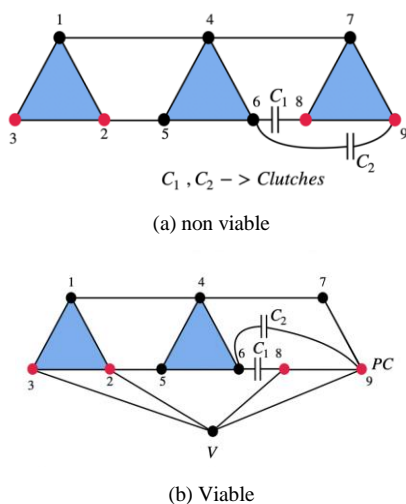

(a) non viable

(b) Viable

Fig. 5 A non-viable and Viable EGT Layout

In the above fig. 5a, the three triangles show three PGTs, (1,4), (1,7) and (2,5) are permanent connections, the vertices marked as "red" represents port elements. One clutch is connected in between shaft-6 and shaft-8. Another clutch is located in between shaft-6 and shaft-9 of PGT-2 and PGT-3 respectively. As explained earlier, all the port elements should be accessible from outside the graph, for the EGT to be planar. In fig. 5, shaft- 8 which is a port element is not accessible. Therefore, out of the shafts {4,9,8}, at least one of these shafts i.e., either shaft 4 or shaft 9 or shaft 8 must serve as planet carrier in order the EGT to be viable as shown in fig. 6. Let us say, shaft – 9 serves as planet carrier.

To make viable, the edge opposite to the node-9, which is a planet carrier i.e., (edge 7-8) is dissolved and all the port elements are connected to an external vertex 'V' as shown in figure 5b.

Example: 3 – When a pair of shafts serve as planet carrier

Let us take the EGT layout as shown in fig. 6 (a).

The connections from the port element to an external vertex V as discussed earlier, is intersecting and hence the resultant EGT is a non – planar and thus it forms a non-viable EGT layout. To make this viable, one of the pair of shafts {[2, 7], [1, 4], [6, 9], [4, 7]} must be made as the planet carrier so that the resultant EGT layout will be viable as shown in figure 6 (b). Here, all the ports can be connected to exterior vertex, and thus the planarity is retained, which means that the EGT layout is a viable layout.
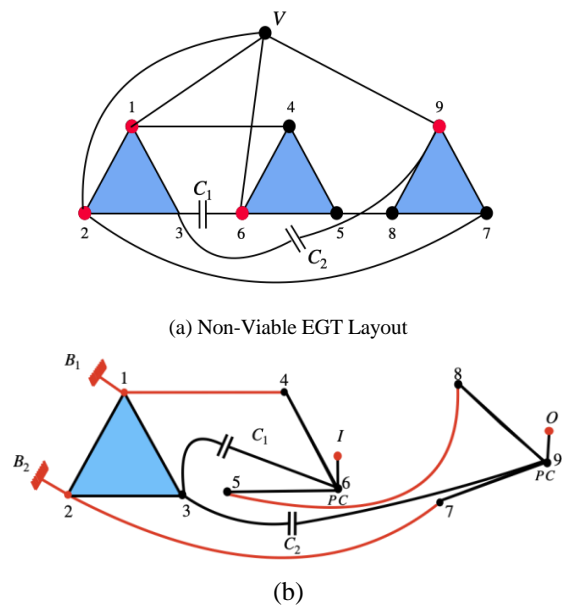

(a) Non-Viable EGT Layout

(b)

Fig. 6 Viable EGT layout with shafts (6,9) as planet carriers

IV. CONCLUSION

Viable aspects of an EGT with three PGTs, three permanent connections, two clutches and four port elements is explained. It is understood that viability forms an important step during the synthesis of EGT layouts. A python program is developed to enumerate all the viable EGT layouts in the category. The total number of viable EGT layouts are found to be 34.

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