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Letter to the editor

Comments on "Analysis of circulating power within hybrid electric vehicle transmissions", Mechanism and Machine Theory 64 (2013) 131–143, by A.K. Gupta, C.P. Ramanarayanan

1. Introduction

The study of power recirculation within planetary gear trains is very important for designing new hybrid transmissions with multi-path power flow. A major issue in this field is that of detecting possible power recirculation within the system elements. This phenomenon, which is a result of the relative motion of the gear members, is considered because power recirculation does not produce any useful output work. The problem of power recirculation has a significant effect on the performance and efficiency of hybrid transmissions.

Power recirculation in PGTs for hybrid electric vehicles is analyzed in [1–4]. Schulz [2] and Villeneuve [3] both discussed a specific power split transmission. Schulz derived the analytical conditions to avoid power recirculation within main components of the Dual-E planetary gear hybrid powertrain [2]. Villeneuve [3] investigated a power split transmission developed by Renault. Mattsson [4] discussed a method for determining suitable basic speed ratios for a general CVT and investigated several power split transmissions. However, published methods are still far from adapting simple algorithms for predicting power recirculation within multi-path planetary gear transmissions.

Gupta et al. [1] presented a method which utilizes the algebraic difference between the splitting power flow ratios x_1 and x_2 for determining the direction of the power flow in two-DOF planetary drives. This method is an extension to the method presented in Ref. [5] for analyzing power recirculation in one-DOF, two-stage planetary gear trains. The authors seem ambiguous about the key points of the method and include some fundamental errors in their analysis. The purpose of this paper is to demonstrate clearly a simple procedure to identify power recirculation in two-input one-output planetary gear trains.

In the beginning, it is necessary to make the following note; the numbering of members in the figures and the nomenclature adopted here are the same as that of [1]. The numbering of members in Figs. 2 and 4 of [1] is different. With reference to Eqs. (7) and (8) of [1], links 2 and 5 should be the gear carriers. In Fig. 4 (numerical example) the link numbering is different, with link 3 as gear carrier. To us, it is inevitable. It is appropriate to deal with the numerical example, regarding the numbering of members, separately from the numbering in the text.

However, there are three issues in [1] that we would like to bring to the readers' attention. **Firstly**, the statement in [1] that "Interconnections of two planetary units with two inputs and one output, or their inversions with a reversed direction of power flow can always be represented in the form of Fig. 2. (of Ref. [1])" is arguable.

Two planetary gear trains have four degrees of freedom and need three constraints to form a transmission assembly. These constraints appear as connections between rotating members (Fig. 1(a)) or grounded members, without rotation (Fig. 1(b)).

A different interconnection, Fig. 1(b), includes only one grounded member and two sets of coupled rotating members. Recently a hybrid scooter transmission was proposed (see Fig. 1 of Ref. [6], as an example). A motor-integrated parallel hybrid transmission was proposed in earlier literatures (see Fig. 1 of Ref. [7] in its second power mode, as another example).

Secondly, although the expressions derived for the power ratios are correct, Gupta et al. [1] presumed that: "two sources of power having the same power capacities are considered for derivation of the expressions and graphical representation of recirculating power within the system…" [1]. This is a **false premise**. In fact, this equality is never satisfied for different R's or ω's ; the two power sources are related to each other by the following equation:

$$\frac{P_1}{P_4} = -\frac{R_1(R_2 - 1)}{\alpha R_2(R_1 - 1)} \tag{1}$$

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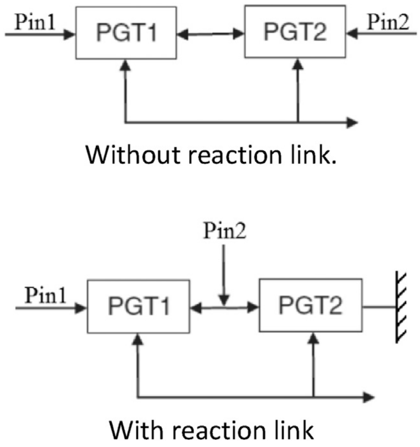

Fig. 1. Two planetary gear trains (parallel-connected) with and without reaction link.

Thirdly, considering the circulation of power, Gupta et al. [1] concluded that the circulation of power depends upon the algebraic difference of the power ratios x_1 and x_2 according to the following three conditions, stated in Eq. (26) Ref. [1]:

$$\left.\begin{array}{ll} x_1 - x_2 < 0 & \text{or} \\ x_1 - x_2 > 0 & \text{or} \\ x_1 - x_2 = 0 & \end{array}\right\} \tag{2}$$

A total of nine possible cases of power flow in combination with the individual limits of x_1 and x_2 were analyzed and illustrated in Table 4 [1]. However, we disagree with the authors of ref. [1] on their conclusion. The basic error of these equations is that the input power ratio isn't properly applied. The possibility of power recirculation in the system is completely independent on the difference of the power ratios x_1 and x_2. Therefore, the proposed constraints upon $(x_1 - x_2)$, are redundant and analytically worthless. The supporting arguments are detailed below.

First, we will show that, the two inputs for any planetary gear train are completely coupled. The recirculating power-flow analysis within the system is typically carried out by considering no power losses. For the system shown in Fig. 1, the input power ratio depends on R_1, R_2 and α.

1.1. Input power ratio

For the entire PGT, torque and power flow equations can be written for the case when there is no power losses as

$$T_1 + T_4 + T_o = 0 \tag{3}$$

$$T_1\omega_1 + T_4\omega_4 + T_o\omega_o = 0 \tag{4}$$

The input power ratio $\frac{P_1}{P_4}$ can be written as;

$$\frac{P_1}{P_4} = -\frac{R}{\alpha} \tag{5}$$

where $R = (\omega_4 - \omega_o)/(\omega_1 - \omega_o)$, $\alpha = \omega_4/\omega_1$ and $\omega_3 = \omega_6 = \omega_o$.

The overall speed ratios r_1 and r_2 can be written as

$$r_1 = \frac{\omega_3}{\omega_1} = \frac{R_1(1 - R_2) - \alpha R_2(1 - R_1)}{(R_1 - R_2)} \tag{6}$$

$$r_2 = \frac{\omega_6}{\omega_4} = \frac{R_1(1 - R_2) - \alpha R_2(1 - R_1)}{\alpha(R_1 - R_2)} \tag{7}$$

The overall speed ratio R between member 4 and member 1 relative to the output member o, is obtained by eliminating ω_3 and ω_6 from Eqs. (6), and (7). On simplifying, the overall speed ratio R, can be expressed in concise form as

$$R = \frac{R_1(R_2 - 1)}{R_2(R_1 - 1)} \tag{8}$$

Substituting R from Eq. (8) into Eq. (5) and simplifying, the input power ratio can be written as:

$$\frac{P_1}{P_4} = -\frac{R_1(R_2 - 1)}{\alpha R_2(R_1 - 1)} \tag{9}$$

1.2. Analysis of circulating power

The expressions derived for the power ratios x_1, x_2, y_1 and y_2 are as following

$$x_1 = \frac{P_2}{P_1} = \frac{(1-R_1)(R_1-\alpha R_2)}{R_1(R_1-R_2)} \tag{10}$$

$$x_2 = \frac{P_5}{P_4} = \frac{(1-R_2)(R_1-\alpha R_2)}{\alpha R_2(R_1-R_2)} \tag{11}$$

$$y_1 = \frac{P_3}{P_1} = \frac{R_1(1-R_2)-\alpha R_2(1-R_1)}{R_1(R_1-R_2)} \tag{12}$$

$$y_2 = \frac{P_6}{P_4} = \frac{R_1(1-R_2)-\alpha R_2(1-R_1)}{\alpha R_2(R_1-R_2)} \tag{13}$$

It is understood that the circulation of power depends on the direction of power flow which in turn, depends upon the sign of the power ratio. The sign of power split ratio represents the direction of power delivery [8].

For the particular system discussed in [1], the directions of power flow in members 2 and 5 are always the same, thus it makes no sense to calculate the difference between the two power ratios x_1 and x_2.

Here, we will show that when link 2 is an input link, link 5 will be an output one and vice versa.

From Eq. (10)

$$P_2 = \frac{(1-R_1)(R_1-\alpha R_2)}{R_1(R_1-R_2)} P_1 \tag{14}$$

Substituting P_4 from Eq. (9) into Eq. (14) and simplifying, gives

$$P_2 = \frac{(R_1-\alpha R_2)}{(R_1-R_2)} \frac{(R_2-1)}{\alpha R_2} P_4 \tag{15}$$

From Eq. (10)

$$P_5 = \frac{(1-R_2)(R_1-\alpha R_2)}{\alpha R_2(R_1-R_2)} P_4 \tag{16}$$

From Eqs. (15) and (16), it is clear that

$$P_2 = -P_5 \tag{17}$$

The direction of power flow depends also upon the sign of the power flowing through the member. A positive power indicates that the power flows into the member and a negative power indicates that the flow is from the member.

Since members 2 and 5 are rigidly connected to form a common link, then Eq. (17) implies that P_2 and P_5 are the input power to and the output power from the same link, or vice versa, and their sum equals zero for all cases.

The direction of power flow through the common link 2 and 5, can be found from either Eq. (10) or Eq. (11). There are two power flow directions; either the power flows from link 2 to link 5 or it flows in the opposite direction. Fig. 2 shows the two types of power flow for a two-input one-output PGT.

With type I power flow, link 6 must be an output link, while link 3 may be either an input or an output link. When the sign of the power ratio $y_1(=P_3/P_1)$ is negative, link 3 becomes an output link. With type II power flow, link 3 must be an output link, while link 6 may be either an input or an output link. When the sign of the power ratio $y_2(=P_6/P_4)$ is negative, link 6 becomes an output link.

The direction of power flow in members 3 and 6 plays an important role in detecting the power flow pattern in two inputs and one output system.

For no power recirculation the only condition that must be satisfied is:

$$y_1\left(=\frac{P_3}{P_1}\right) < 0 \quad \text{and} \quad y_2\left(=\frac{P_6}{P_4}\right) < 0 \quad \text{for all values of } x_1 \text{ and } x_2$$

The possibility of power recirculation in the system is completely independent on the power ratios x_1, x_2 or their difference; (x_1-x_2). Therefore, the proposed constraints upon x_1, x_2 and (x_1-x_2) [1], are redundant and analytically worthless.

Simply, for no power recirculation

$$\frac{y_1}{y_2} = \frac{\alpha R_2}{R_1} > 0 \tag{18}$$

For power recirculation

$$\frac{y_1}{y_2} = \frac{\alpha R_2}{R_1} < 0 \tag{19}$$

Therefore, Power flowing in the connected members of the output shaft, determines whether the input powers divide between internal paths or recirculate within the system.

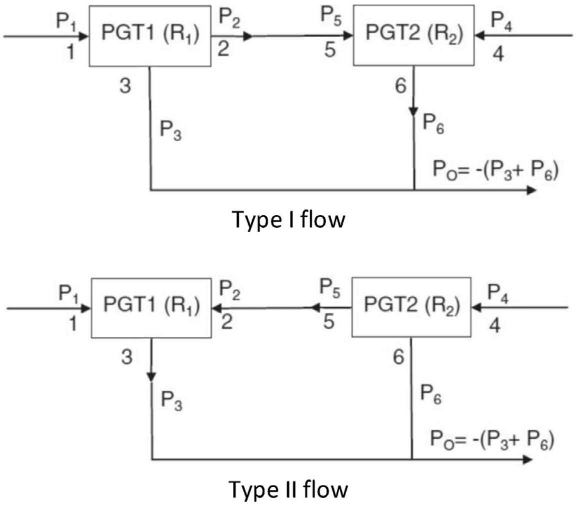

Fig. 2. Types of power flow for a two input one output PGT.

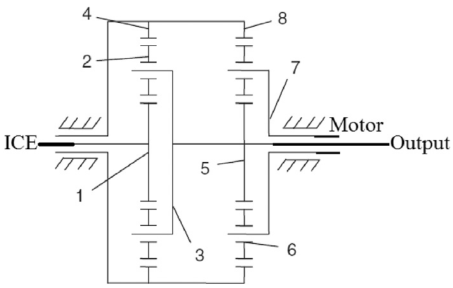

Fig. 3. Coupled planetary gear train as hybrid transmission.

1.3. Application example

After analyzing the power flow circulation through the links of the coupled planetary gear drive, shown in Fig. 3, Gupta et al. [1] stated that "Since there is a power re-circulation and if small amount of the input powers passes through the ring gears, this makes it more efficient."

However, this statement is only partially true because this train shows no signs of power recirculation for the described operating conditions. The supporting arguments are detailed below.

For the example PGT shown in Fig. 3, the values of R_1 and R_2 can be expressed in terms of number of teeth on the sun and ring gears as [9]:

$$0 < R_1 = \frac{Z_1}{Z_1 + Z_4} < 1 \tag{20}$$

and

$$R_2 = \frac{Z_5 + Z_8}{Z_5} > 1 \tag{21}$$

Eq. (10) can be written for the coupled PGT shown in Fig. 3 as following:

$$x_1 = \frac{P_4}{P_1} = \frac{(1 - R_1)(R_1 - \alpha R_2)}{R_1(R_1 - R_2)} \tag{22}$$

There are two cases:

1. $x_1 < 0$

For this case, since $P_1 > 0$, then $P_4 < 0$ and link 4 is an output link in PGT1. The input velocity ratio α $(= \omega_7/\omega_1)$ can be deduced from the inequality $\frac{(1-R_1)(R_1-\alpha R_2)}{R_1(R_1-R_2)} < 0$ as:

$$\alpha < \frac{R_1}{R_2} \tag{23}$$

2. $x_1 > 0$

Similarly, when $x_1 > 0$ and since $P_1 > 0$, then $P_4 > 0$ and link 4 is an input link in PGT1. The ratio α can be deduced as:

$$\alpha > \frac{R_1}{R_2} \tag{24}$$

It is apparent that the power, in coupled ring gears 4 and 8, is flowing from gear 4 to gear 8 when $\alpha < R_1/R_2$, or in the reversed direction when $\alpha > R_1/R_2$. So increasing α may change the direction of the power flow in the coupled ring gears 4 and 8 but has no effect on power recirculation.

For no power recirculation, the only condition that must be satisfied is the one given in Eq. (18). From Eq. (9), the input velocity ratio α for this configuration is:

$$\alpha = \frac{R_1(R_2 - 1)}{R_2(1 - R_1)} \frac{P_7}{P_1} \tag{25}$$

Substituting the value of α in Eq. (18) and simplifying, we get:

$$\frac{y_1}{y_2} = \frac{R_1(R_2 - 1)}{R_2(1 - R_1)} \frac{P_7}{P_1} \tag{26}$$

Since P_1, P_7, R_1, R_2, $(R_2 - 1)$, and $(1 - R_1)$ are all positive quantities, then $y_1/y_2 > 0$ and for the described operating conditions, there is no power recirculation.

2. Conclusions

It has been shown that the power split ratios in a multiple-path transmission system may be expressed in terms of input velocity ratio and velocity ratios (which can be determined relatively easily). The method of applying the result to evaluate the power carried by the parts of a specific system has been demonstrated by means of an example. A simple procedure to identify power recirculation in two-input one-output planetary gear trains has been demonstrated clearly. With this new procedure it is only necessary to compare power flow ratios to identify power recirculation. The necessary and sufficient operating conditions for power recirculation in two-input transmissions, are proven rigorously.

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