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Test Rig for Study of Efficiency and Power Flow in Coupled Planetary Gear Trains

V. M. Bhojawala*[1], B. Seth [2]

[1] Institute of Technology, Nirma University of science & Technology, Department of Mechanical Engineering, Ahmedabad-382481, India
[2] Indian Institute of Technology Bombay, Department of Mechanical Engineering, Mumbai-400076, India
* Corresponding Author Email: vipulmbhojawala@gmail.com

ABSTRACT

In a planetary gear drive, the power circulating within the system elements may vary significantly from that of input power to the system. This is because of the relative motion of the gear members, which has a considerable effect on the performance and efficiency of the systems. This paper describes the design and development of the coupled planetary gear train test rig. The test rig can be used for studying the efficiency and recirculation of power in coupled planetary gear trains (PGTs).

Keywords: Coupled planetary gear trains; Power-flow; Mechanical efficiency

1. INTRODUCTION

Applications using planetary gears have increased over a period of years because of the advantages related with planetary gears in comparison with ordinary gear trains. The aspects which characterise a planetary gear system are its compactness, co-axial arrangement of driving and driven shaft, large speed reduction possibilities, higher torque-to-weight ratio and decreased bearing loads. The Planetary gear systems are widely used in automobile final-drive units and automatic transmission.

Theoretically, the efficiency of PGTs can be calculated by assuming that the gear-mesh loss as the only power loss. Radzimovsky E.I. [1, 2] has given a simplified approach for determining power losses and efficiency of PGTs. Glower J.H. [3] has given formulas for the overall efficiency of different gear trains. Jensen P.W. [4] has given a simplified method to determine the transmission ratio and the efficiency of coupled planetary gear trains simultaneously. Pennestri E.and Freudenstein F. provided a method to calculate the efficiency of PGTs [5] and a review of formulas available to calculate the efficiency of PGTs [6]. White G. [7] has given method for identifying those arrangements that avoids internal circulation of power. Sanger D.J. [8] has provided a technique of power flow analysis through any single path of a general multi-path transmission system. The contributions discussed above are for theoretically calculating the efficiency of PGTs and power flow in coupled planetary gear trains.

Kasuba R. and Radzimovsky E.I. [9] developed a multipurpose testing machine for research studies in gearing with a compound planetary gear drive. The testing machine consists of compound planetary gear drive with the provision of changing the gears of the planetary gear drive to change the gear ratio. It has been used for determination of instantaneous gear tooth engagements loads, minimum film thickness and efficiency of compound planetary gear systems. The present test rig consists of two separate planetary gear trains with gears on the auxiliary splined shaft to change the configuration of coupled planetary gear train. It can be used for observing the efficiency and recirculation of power in coupled planetary gear train.

2. DESCRIPTION OF TEST RIG

The assembly drawing of the coupled planetary gear train test rig is shown in Fig.1. The design of the test rig is such that all the three shafts of basic elements (i.e. sun gear, ring gear and planet carrier respectively) of the two planetary gear trains have an accessible projection of shaft. These three shafts from each PGT have gears mounted on them and eight different configurations of the coupled planetary gear trains can be obtained by coupling different elements of the two PGTs using gears sliding on two splined auxiliary shafts. In this test rig, provision has been made for the alignment of input shaft, output shaft and the two splined auxiliary shafts with the help of a distance block which can be ground for proper alignment.

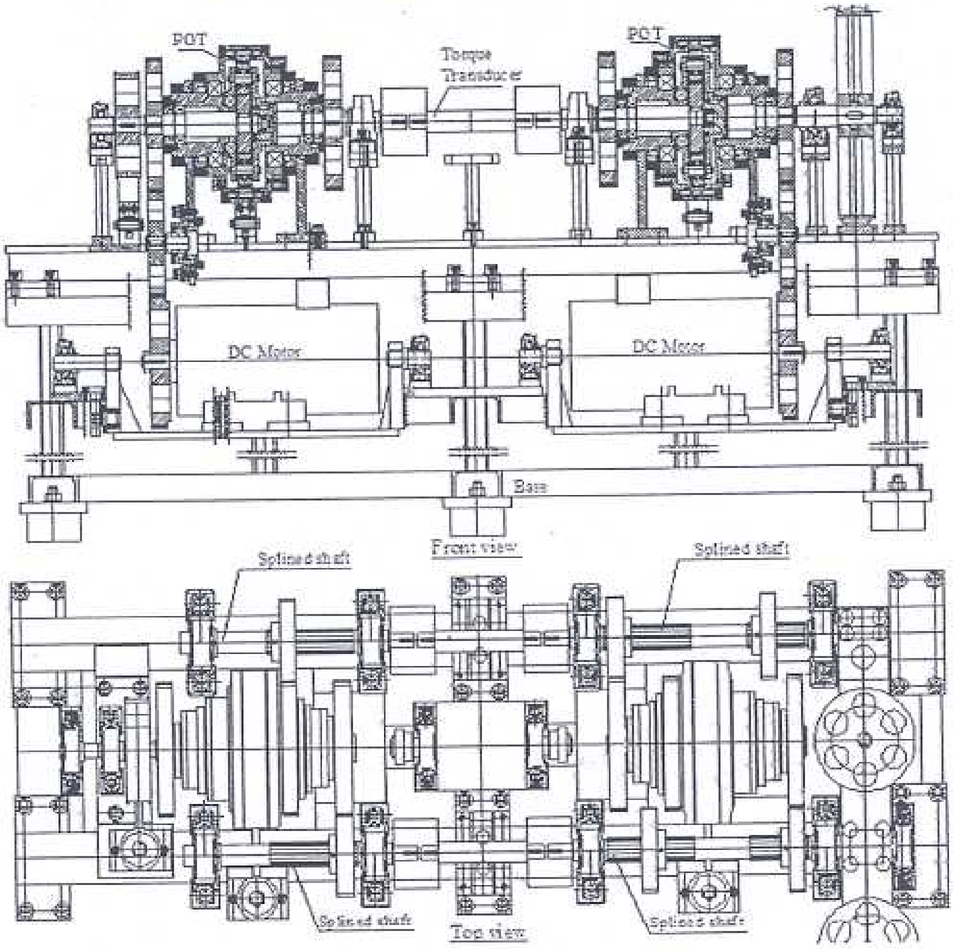


Fig. 1 Assembly of coupled planetary gear train test rig

In this test rig, the input can be given to either the sun gear of the first PGT or to the planet carrier of second PGT. Two separate DC motors are provided to drive the system. With the input to the sun gear of the first PGT and holding the ring gear of the second PGT using a band brake, it is possible to obtain four different coupled planetary gear train systems. Out of these four, two configurations correspond to systems having positive recirculation of power. The remaining two configurations correspond to systems having negative recirculation of power. Additional four configurations are obtained by making planet carrier of second PGT as the input and holding the sun gear of the first PGT using a band brake. All four configurations in this case correspond to power split systems.

The motors to drive the input to the transmission are mounted on platforms, which are free to rotate around the motor axes but are restrained from rotating by an instrumented link. When an input torque is applied, an equal and opposite reaction torque acts on the platform and corresponds to a proportional force sensed by the instrumented link. Thus, the force transducer in the link measures the input torque.

Rope brake dynamometer arrangement is provided to facilitate regulation and measurement of the output torque. Torque and speed can also be measured in the coupling between the two PGTs by using the inline torque sensors mounted on the splined-shafts. With these sensors it is possible to measure the power split ratio or the ratio of recirculated-power to the input power under steady state running conditions. Efficiency can be computed from the above measurements.

3. DESIGN OF PLANETARY GEAR TRAINS

In this test rig, eight configurations of coupled planetary gear systems are possible. For these configurations the forces acting on the gear tooth are calculated. It has been found that forces acting on the gear tooth are maximum in the configuration where sun gear is the input gear, ring gear of the first PGT is connected to sun gear of the second PGT, ring gear of the second PGT is hold and planet carriers of both the planetary gear trains are connected from where the output is taken. Based on this configuration the planetary gear train is designed which is shown in Fig. 2.

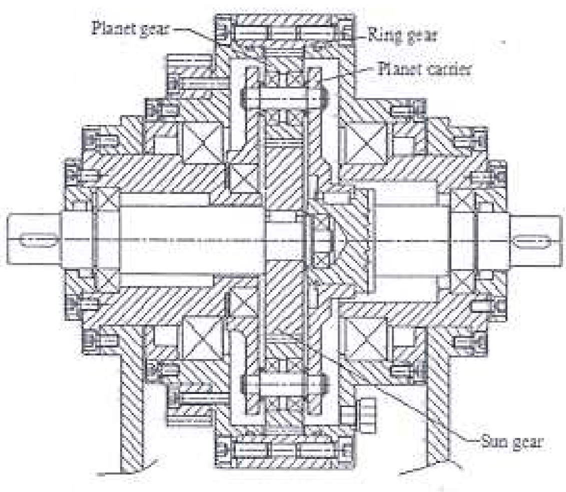


Fig. 2 Design of planetary gear train

4. POWER-FLOW IN COUPLED PLANETARY GEAR TRAINS

A simple PGT has two degree of freedom as there three independent shafts and hence constraint to one member gives single degree of freedom system. Two PGT_S have four degree of freedom and hence three constraints are required to have single degree of freedom system. These constraints can be applied by holding members or with coupling rotating members. Two PGT_S with three constrains as mentioned above is shown in Fig.3.

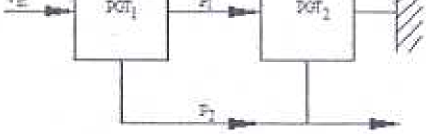


Fig. 3 Constraints with two PGT_S in parallel connection

The main difference between PGT and conventional gear train is the velocity of gear engagement. In case of conventional gear train, the axis of rotation is fixed. Therefore, the engagement velocity is equal to the pitch line velocity and power transmitted by the gears does not exceed the input power. In case of PGT, the velocity of engagement is not equal to the pitch line velocity because the planet gears rotate about their own axis as well as about the axis of central gears. Therefore, the power developed at gears may be different than that of the input power to the system.

In case of coupled planetary gear trains, there are three types of power flow systems: the power split system, the negative recirculation system and positive recirculation system. Types of power flow depend on the connection between PGT units. Kinematic and power-flow analysis gives following results for two PGTs in parallel connection as shown in Fig.3.

$$R_{O/I} = (R_1 R_2)/(R_1 + R_2 - 1) \quad (1)$$

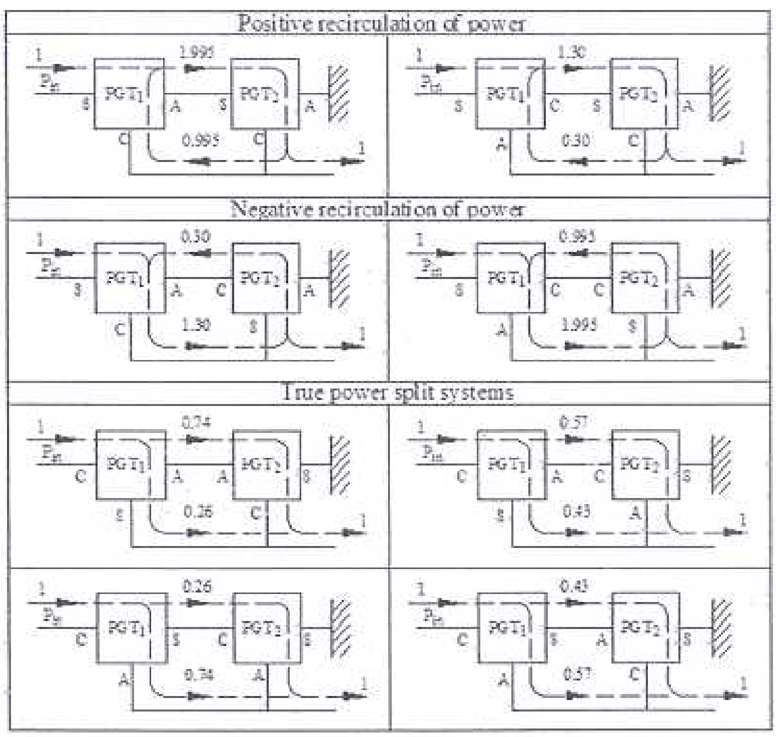
$$P_1/P_{in} = (R_2 - 1)/(R_1 + R_2 - 1) \quad (2)$$

Where,

$R_{o/i}$ = output/input speed ratio
P_{in} = input power, P_1 = power carried in path1, P_2 = power carried in path2
R_1 = output/input speed ratio for PGT1 when member P_1 is stationary
R_2 = output/input speed ratio for PGT2 when third member is stationary

It is possible to develop eight different coupled planetary gear trains in output coupled arrangement with the present test rig. Power flow diagram of eight coupled planetary gear trains is shown in Table 1. Where input is from the left, output is to the right and A, C and S represents ring gear, carrier and sun gear of PGTs.

Table 1 power flow diagram for coupled planetary gear trains



From equation (2), three types of power flow can be determined. As shown in the Fig.1, the two aligned planetary gear trains are coupled using two splined shafts on either sides of the common axis of the PGT_S. Torque, speed and power can be measured in the coupling between the two PGTs by using the inline torque sensors mounted on the splined-shafts. These experimental results can be compared with theoretical results obtained from equation (2). Out of the eight systems two systems have positive recirculation of power; two systems have negative recirculation of power and the remaining are split power systems. A positive recirculation of power corresponds to $(P_1/P_{in}) > 0$ while a negative recirculation of power corresponds to $(P_1/P_{in}) > 0$.

5. EFFICIENCY OF COUPLED PLANETARY GEAR TRAINS

Fig.4 shows a schematic of coupled planetary gear train, where sun gear is the input gear, ring gear of the first PGT is connected to sun gear of the second PGT, ring gear of the second PGT is hold and planet carriers of both the planetary gear trains are connected from where the output is taken.

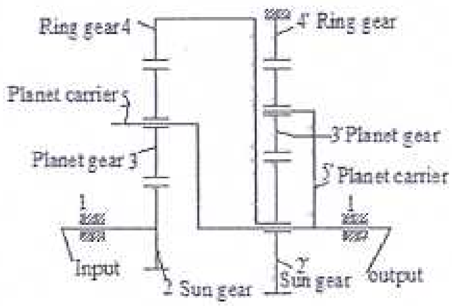


Fig.4 Schematic of coupled planetary gear train

Simple planetary gear train has three main elements two central gears (sun gear and ring gear) and one arm. The ratios of torque acting on them are given in Table 2 when power flows from central gear to ring gear and ring gear to central gear.

Table 2 Ratios of torque acting on main elements of simple planetary gear trains

(a) Power flows from central gear to ring gear	(b) Power flows from ring gear to central gear
$T_4/T_2 = h\eta$	$T_4/T_2 = \eta/h$
$T_4/T_5 = -h\eta/(h\eta + 1)$	$T_4/T_5 = -h/(h + \eta)$
$T_2/T_5 = -1/(h\eta + 1)$	$T_2/T_5 = -\eta/(h + \eta)$

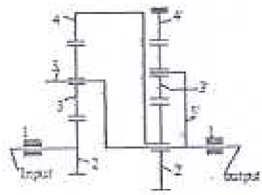
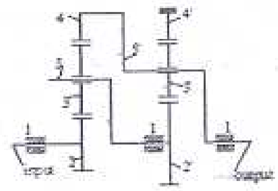
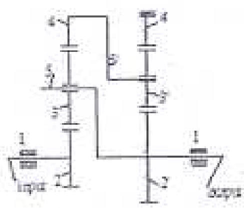
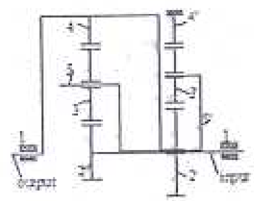
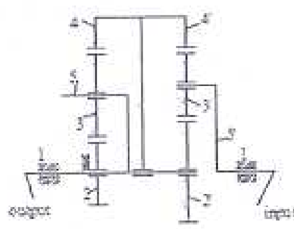
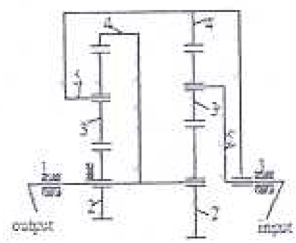
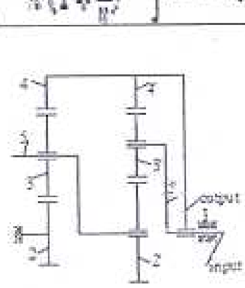
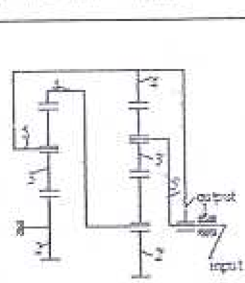
Where, T_2, T_4 and T_5 are the torque acting on the sun gear, ring gear and planet carrier respectively. h is the ration between the radii of ring gear and sun gear. η is the efficiency of simple planetary gear train considering planet carrier as stationary. From Table 2 the following equations can be developed when applied to the above coupled planetary gear train.

$$T_{in} = T_2 \quad (3)$$

$$T_{out} = T_5 + T'_5 \quad (4)$$

$$T_2/T_5 = (-1)/(h\eta + 1) \quad (6)$$

Table 3 Schematic of coupled planetary gear trains with equations for efficiency

1.  $\eta_p = \dfrac{1 - hh'\eta\eta'}{1 - hh'}$	2.  $\eta_p = \dfrac{h'\eta' + hh'\eta\eta' + 1}{h' + hh' + 1}$
3.  $\eta_p = \left[\dfrac{hh'\eta + h' + \eta'}{h' + \eta'}\right]\left[\dfrac{h' + 1}{hh' + h' + 1}\right]$	4.  $\eta_p = \left[\dfrac{\eta' - \eta hh'}{h' + \eta'}\right]\left[\dfrac{h' + 1}{1 - hh'}\right]$
5.  $\eta_p = \left[\dfrac{h'\eta + h(h' + \eta')}{h'(1 + \frac{h}{\eta'})}\right]\left[\dfrac{h'(1 + h)}{h' + h(h' + 1)}\right]$	6.  $\eta_p = \left[\dfrac{(h'\eta' + 1) + hh'\eta'}{(h'\eta' + 1)(h + \eta)}\right]\left[\dfrac{(h' + 1)(h + 1)}{1 + h' + hh'}\right]$
7.  $\eta_p = \left[\dfrac{hh'\eta\eta' + h\eta + h'\eta'}{(h'\eta' + 1)(h\eta + 1)}\right]\left[\dfrac{(h + 1)(h' + 1)}{h + h' + hh'}\right]$	8.  $\eta_p = \left[\dfrac{hh'\eta + h' + \eta'}{h'(1 + h\eta)}\right]\left[\dfrac{h'(1 + h)}{hh' + h' + 1}\right]$

$$T_{2'}/T_{3'} = (-1)/(h'\eta' + 1) \tag{7}$$

$$T_4/T_2 = h\eta \tag{8}$$

As ring gear 4 and sun gear 2' are connected,

$$T_4 = -T_{2'} \tag{9}$$

Substituting the equations (6), (7), (8) & (9) into equation (4)

$$T_{out} = (hh'\eta\eta' \quad 1)T_2 \tag{10}$$

From equation (3) and (10)

$$T_{out}/T_{in} = hh'\eta\eta' - 1 \tag{11}$$

Let, $\eta = \eta' = 1$

$$R_{i/o} = -T_{out}/T_{in} = 1 - hh' \tag{12}$$

Equation (12) is the input/output speed ratio ($R_{i/o}$) for coupled planetary gear trains shown in Fig.4.

$$\eta_p = -(T_{out}\,\omega_{out})/(T_{in}\,\omega_{in}) = (1 - hh'\eta\eta')/(1 - hh') \tag{13}$$

Equation (13) is the overall efficiency (η_p) for coupled planetary gear trains shown in Fig.4. Similarly, equations for overall efficiency has been derived for all eight configuration of coupled planetary gear trains and are given in Table 3. As discussed previously, Efficiency can be computed from the measurements in this test rig. These experimental results can be compared with theoretical results obtained from efficiency equation of coupled planetary gear trains as shown in Table 3.

6. CONCLUSIONS

The design and development of coupled planetary gear train test rig is explained with the scope of experimentation. The test rig is under fabrication. The test rig can be used for studying the efficiency and recirculation of power in coupled planetary gear trains (PGTs).

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