



## **AGMA Technical Paper**

# **Influence of Central Members Radial Support Stiffness on Load Sharing Characteristics of Compound Planetary Gearsets**

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

## **Abstract**

Abstract: In this study, a non-linear dynamics model of Ravigneaux compound planetary gearsets which adopts the intermediate floating component is set up based on concentration parameter. By considering the position errors and eccentric errors, the dynamic load sharing factors of the gearsets are calculated. The relationship between central members radial support stiffness and the dynamic load sharing factors is obtained and the influence of central members radial support stiffness on load sharing characteristic is analyzed. The research results show that central members radial support stiffness affects the gear pairs which are directly contacted to the central members, while the effect is rather small in the gear pairs which are not directly connected. Reducing the radial support stiffness of the central members helps improve the load sharing performance of the system.

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# Influence of Central Members Radial Support Stiffness on Load Sharing Characteristics of Compound Planetary Gearsets

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## Introduction

Planetary gearsets, a classification of epicyclic gears, have several advantages over fixed-center counter-shaft gear systems, including higher power density (transmitted power to gearsets volume ratio), compactness, ability to achieve multiple speed ratios through different power flow arrangements, and lower gear noise. In addition, axi-symmetric orientation of the planet gears in the gearsets creates negligible radial bearing forces and provides a self-centering capability. This relieves the requirement for bearing support. Based on the above advantages, planetary gearsets have been widely used in transportation, aerospace and energy development areas.

However, these advantages of planetary transmissions rely heavily on the assumption that each pinion carries an equal share of the total torque applied. In the production process, gear manufacturing and assembly variations, as well as design parameters may prevent such equal load sharing characteristics affecting the transmission performance.

The majority of published studies on dynamic load sharing focus on one-stage planetary arrangements. Hidaka, et al., [1-3] studied the planet load sharing of three-planet gearsets to show, both experimentally and theoretically, that perfect load sharing in a three-planet gearsets is achievable only if at least one central member (ring gear, sun gear, or carrier) is allowed to float. The same conclusion was confirmed by Muller [4]. Kahraman [5], in his 1994 paper, constructed a dynamic mathematical model of a planetary gear stage, which could be set to an arbitrary number of planets and corresponding possible gear sizes and tolerance variations, and fixity or not of the sun gear. In another paper [6], Kahraman considered load sharing of planetary gearsets again, both in a mathematical model and in experimental work, and showed reasonable agreement between his experimental results and mathematical model for a four-planet system. Ligata et al., [7] did further work along the lines of the paper of Kahraman [6] but added the numbers of planets and torque as parametric variables in their experimental study and obtained reasonable agreement with the theory. In Ligata's work, they demonstrated in an experiment that three-planet systems show excellent load sharing and that four-planet systems with the planets opposite each other show good load sharing between opposed planets, but not so good otherwise. They also mentioned, and one can see in the data plots, that for constant error and other variables, with the torque held constant, load sharing gets better for higher torques. Bodas and Kahraman [8] used a two-dimensional (2D) deformable-body model of a planetary gearsets and demonstrated theoretically that adding more planets makes the system more sensitive to certain gear and carrier manufacturing errors and assembly variations. They showed that different types of errors acting on each planet could be combined into a total planet error  $e_i$  representing the effective tangential (in the circumferential direction on the circle formed by planet centers) error of planet  $i$ . Singh [9-10] used a three-dimensional (3D) model of the same configuration to obtain similar conclusions. He showed that the directions of the pinhole position errors are important, with the errors in tangential direction having the most critical impact on planet load sharing. He concluded that increasing the number of planets in the system without appropriately tightening the pinhole position tolerances fails to deliver expected planet load reductions. His predictions clearly showed the maximum planet loads for an  $n$ -planet ( $n \geq 4$ ) system can become higher than the corresponding loads for a planetary gearsets with a smaller number of planets, unless the error magnitudes are appropriately controlled.

All of the models cited above only focus on one-stage planetary gearsets. The demand for fuel economy and more ratios for different speed and torque make vehicle automatic transmissions with compound planetary gearsets very desirable, while few scholars studied the load sharing characteristics of compound planetary gearsets.

In this study, a dynamics model of Ravigneaux compound planetary gearsets which adopts the intermediate floating component is set up based on concentration parameter. By considering the influence factors, including central member radial support stiffness, gear eccentric errors, gear position errors and backlash, the load sharing factors of the gearsets are calculated. The curves of the relationships between central members radial support stiffness and the load sharing factors of the

gearsets are obtained and the influence of central members radial support stiffness on load sharing characteristic is analyzed.

## Dynamic models

Ravigneaux compound planetary gear transmissions are based on a simple planetary gear train with a clever combination, whose structure is more complex than a simple planetary gear train. The Ravigneaux compound planetary gear system studied in the paper is illustrated in Figure 1. A long planet  $b$  connects two planes of double-planet gearsets  $s_1$ - $a$ - $b$ - $r$  and  $s_2$ - $b$ - $r$ . Here  $s_1$  and  $s_2$  are the sun gears,  $r$  is the ring gear, and  $a$  is the short gear. All planets,  $a$  and  $b$ , are supported by a single carrier  $c$ . The compound arrangements shown in Figure 1 have four central members,  $s_1$ ,  $s_2$ ,  $r$  and  $c$  that can be used as input, output or reaction members. At any given power flow condition, only three of these four members will have assignments. Therefore, by applying different clutching arrangements, the input, output and reaction members can be selected in different ways from the four central members of the gearsets. This way, it is possible to obtain permutation  $P(4, 3) = 24$  distinct power flow configurations. With such inherent ratio flexibility, it is feasible to achieve up to five desirable forward and at least one reverse gear ration using the same compound gearsets under different clutching schemes. This allows significant reductions in transmission size and weight making compound planetary units very desirable for such applications.

The dynamic model of this system employs a number of simplifying assumptions.

1. Each gear body is assumed to be rigid and the flexibilities of the gear teeth at each gear mesh interface are modelled by a spring having periodically time-varying stiffness acting along the gear line of action. This mesh stiffness is subject to a clearance element representing gear backlash.
2. Each central member was assumed to move in the torsional  $\theta$  direction and radial  $x, y$  direction, while planets  $a, b$  were assumed to move in the torsional  $\theta$  direction only.
3. As the damping mechanisms at the gear meshes and bearings of a planetary gearsets are not easy to model, viscous gear mesh damping elements are introduced representing energy dissipation of the system.

In Figure 2, the central members  $s_1$ ,  $s_2$ ,  $r$  and  $c$ , which are mounted on linear elastic bearings with the stiffnesses  $k_{s1}$ ,  $k_{s2}$ ,  $k_r$ ,  $k_c$ , are constrained by torsional linear springs of stiffness magnitude  $k_{s1t}$ ,  $k_{s2t}$ ,  $k_{rt}$ ,  $k_{ct}$ . The magnitudes of torsional stiffness constrains can be chosen accordingly to simulate different power flow arrangements with different fixed central members. Each gear body  $l$  ( $l = s_1, s_2, r, c, a_n$  and  $b_n$ ) is modelled as a rigid disk with a polar mass moment of inertia  $I_l$ , radius  $r_l$  and torsional displacement  $\theta_l$ . Here  $\theta_l$  is the vibrational component of the displacement defined from the nominal rotation of the gear. External torques  $T_l$  ( $l = s_1, s_2, r$  and  $c$ ) are applied to the central members to represent input, output and reaction torque values. The carrier inertia,  $I_{ce}$ , is defined in equation 1.

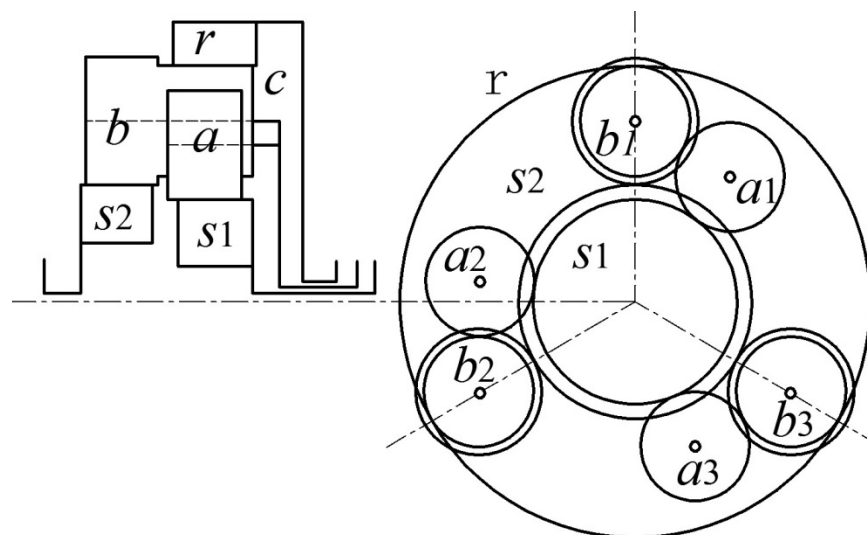


Figure 1. Ravigneaux compound planetary gearsets arrangements considered in this study