Critical Review of Design of Planetary Gears and Gear Box

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Abstract
There is a great need for efficient and compact gear boxes in automotive and industrial applications to improve upon their power density while reducing their dynamic vibration and noise deliveries. It is accepted that planetary gear transmissions have several advantages in comparison to conventional transmissions, such as a high power density due to the power division using several planet gears. This paper presents a literature review on design of planetary gear and gear box.

Keywords- Gears, Planetary Gears, Optimisation, Load rating

Introduction
Gear Box is mechanical mechanism which houses a number of gears in pairs of combination to give required speed reduction or increase depending on the requirement at the specified power input. There are various types of gearboxes depending on the type of gear used.

I. Helical Gear Box: Helical gears are used to get reduction. Input and output shafts are inline.
II. Worm Gear Box: Worm-wheel is used for transmission of power for given reduction. The input shaft and output shafts are at right angle to each other.
III. Bevel Gear Box: Bevel gears are used for transmission of power where input & output shafts are at inclinations.
IV. Heli-worm Gear Box: To get higher reduction a combination of helical and worm is used. Input and output shafts are at right angle to each other.
V. Heli-bevel Gear Box: Input and output shaft are at inclined to each other.
VI. Planetary Gear Box: To get high reduction in compact size, planetary gear systems are preferred.

A Planetary or Epicyclical gearing systems are employed to achieve high reduction ratio in a small and power dense package. Planetary Gear Trains are extensively used for the transmission and are the most critical component in a mechanical power transmission system. They play a very vital role in all the industrial areas, any failure in the gear train leads to a total system failure [7] thus a through approach in design of planetary gear train to get the best performance is very necessary.

The advantages of planetary gear trains are higher torque capacity, lower weight, small size and improved efficiency of the planetary design. As the weigh is 60%, and half the size of a conventional gear box, it is very likely to have a misconception that it is not as strong [8]

Literature Review
A review on the literature was carried out in order to have a detailed knowhow of developments in the field of planetary gear gearboxes and the use of various techniques for compact design of planetary gear boxes. The detailed literature review is as below.
Tristan M. Ericson et. al. [1] presented a study on modal testing experiments performed on a
stationary spur planetary gear through a range of applied torques. The independent vibrations of each gear component were measured by accelerometers mounted directly to the gear bodies near the meshing teeth. Natural frequencies were compared to the predictions of an analytical lumped-parameter model.

Shyi-Jeng Tsai et al. [2] reported a study on Gear meshing analysis of planetary gear sets with a floating sun gear. A stiffness model was prepared as shown in fig. 1.

Fig. 1: Stiffness Model of a planetary gear [2]

The influence of the design parameters, such as the tooth numbers, backlash, and assembly/manufacturing errors of the gear sets were analysed. The amount of the backlash does not affect the shape of the movable area, but a small backlash of the gear set will reduce the area. The analysis offers insight into the extreme error conditions for the assembly of the sun gear at the ideal centre of the planetary gear set. The results are useful for designers to select suitable tolerance classes for the backlash and the components of gear sets.

Dr. Alexander Kapelevich [3] reported analysis and design of epicyclic gear arrangements that provide extremely high gear ratios. This arrangement is shown in fig. 2.

Fig. 2: Differential Planetary Gear arrangement [3]

Fig. 2a & b present differential-planetary arrangements with compound planet gears. Fig. 2a shows that sun gear engages with a portion of the planet gear that is in mesh with the stationary ring gear whereas Fig. 2b shows that sun gear engages with a portion of the planet gear that is in mesh with the rotating ring gear.

The efficiency of these types of planetary gear arrangements was in opposite proportion to gear ratio, and was much lower than for conventional, two-stage, epicyclic gear arrangements. One potential area of application is in different positioning systems that need very low-output RPM and typically do not require high-output torque.

D.R. Salgado et al. [4] presented a study on analysis of the transmission ratio and efficiency ranges of the four-, five-, and six-link planetary gear trains. The planetary Gear Trains were enumerated in the form of links and ratios, efficiencies were determined.

Bernad et al. [5] presented a study on light weight design of planetary gears transmission.

Fig. 3: PGT concepts [5]
A higher number of applied planet gears results in a higher mesh load factor, according to AGMA 6123-B06, as well as an increasing difficulty in assembling the planets according to Looman with low numbers of teeth. Thus the number of teeth for the central gears was increased in order to compensate for the advantage of a better power division for higher numbers of applied planets. Difference in the centre distances of two gear pairs was offset by applying addendum modifications for transmission concepts with high gear ratios. In that case the addendum modifications cannot be applied in the best way to reduce the tooth-load factors, or, in other words, to increase efficiency. One possibility in order to achieve equal centre distances would be to use different normal modules for each transmission stage. The addendum modifications can then be chosen so that the tooth-load factor of each gear pair reaches a minimum.

Cheon-Jae Bahk et al. [6] presented a nonlinear dynamic model of a planetary gear with tooth profile modification (TPM). Combined use of the optimum sun–planet and ring–planet mesh TPM, which were determined by minimizing response when applied individually, was expected to further reduce the dynamic response. The minimal dynamic response was achieved at a much different combination of sun–planet and ring–planet mesh TPM. Different TPMs required to minimize gear vibration depending on the amount of mesh stiffness fluctuation and the mesh phase. Different TPM minimizes the vibration at different vibration modes. Syed Ibrahim Dilawer et. al. [7] presented study on optimal design of the gear train with the load analysis carried out in the gear trains by varying the module (3, 4, 5, 6) for all the gears for three different power levels 10 HP, 15 HP and 20HP. Module is the ratio of the pitch circle diameter (in millimetres) to the number of teeth. It is denoted by \( m \), where \( m = \frac{D}{T} \) & \( D= \) Pitch Circle Diameter, \( T= \) Number of Teeth. The recommended series of modules in Indian Standard are 1, 1.25, 1.5, 2, 2.5, 3, 4, 5, 6, 8, 10, 12, 16, 20, 25, 32, 40 and 50. The modules 1.125, 1.375, 1.75, 2.25, 2.75, 3.5, 4.5, 5.5, 7, 9, 11, 14, 18, 22, 28, 36 and 45 are of second choice. Following four systems of gear teeth are commonly used in practice. 14 ½° Composite systems, 14 ½° Full depth involute systems, 20° Full depth involute systems and 20° Stub involute systems. The tooth profile of the 20° full depth involute system may be cut by hobs. The increase of the pressure angle from 14 ½° to 20° results in a stronger tooth, because the tooth acting as a beam is wider at the base. The materials used for gears depend upon the service factor and strength like wear or noise conditions etc, and they come in metallic and non-metallic form. For industrial purposes metallic gears are used, commercially can be obtained in steel, cast iron and bronze. Cast iron is widely used because of its excellent wearing properties, in which Cast Iron with UTS 480 Mpa, Elongation 6-16% was selected considering its long service life, high wear resistance, low production cost, high stability and surface finish [7].

The tooth load of the Wear tooth load (Ww) for all the gears in the gear train was higher than the Dynamic tooth load (Wd), and the Dynamic Tooth load (Wd) was less than Static tooth load (Ws) for all gears in system. As this condition has to be true for safety against tooth failure, hence design was safe.

Nenad Marjanovic et. al. [8] in their study of practical approach to the optimization of gear trains...
with spur gears used gear train optimization for concepts of gear trains with spur gears, selection of materials, selection of optimal gear trains and selection of optimal position for shaft axes of gears trains with spur gears. Reasons for optimizations are gears carry highest load and need large number of parameters for complete description. The volume of the gear train with spur gears was reduced by 22.5%. Software GTO accomplishes needed results in a very short time.

Jelena Stefanović et. al. [9] presented method of optimization of planetary gears by formulation of objective functions taking optimization variables as no. of teeth, no of planets, gear modules, face width and objective function as mass, Volume, efficiency, manufacturing costs.

Juraj Jablonick et. al. [10] prepared a 3D model for differential planetary gear & presented analytical solutions based on the fundamental strength and kinematics relations valid for simple planetary gear.

Fig.6: Kinematics scheme of differential Planetary gear [10]

Fig.7: Power ratio differential planetary gear [10]

Derived force and kinematics relations express the basic functional dependence between the value of the input torque and the output torque and also dependencies between the main and secondary gear ratio. The analytical solution of the differential planetary gear was prepared, computer model of the transmission system and then the prototype gear to validate the calculated data.

Wen-Hsiang Hsieh et. al [11] presented the design procedure for Cam-controlled planetary gear trains. New designs were obtained through the process of the creative mechanism design approach, and 3 new designs synthesized from graph have been obtained. The feasibility of the new designs was verified by conducting kinematics simulation & concluded that the new designs can produce a more wide range of non-uniform output motion than the existing design, and better alternatives for driving a variable speed input mechanism.

Dr. Ing. T. Schulze et. al. [12] presented report on load distribution in planetary gears using MDESIGN software. The uniform load distribution on gear flank gives better life.

Fig.8.a : Bad load distribution on flank [12]

Fig.8.b : Good load distribution on flank [12]

The load measures in tooth contact were caused by distribution of load on tooth pairs. The calculation method of load distribution was based on using deformation influence numbers. The deformation coefficients $a_{ik}$ of influence coefficients method are the basic of load distribution. The influence
coefficients $a_{ik}$ are the absolute values of deformation in section $i$, which are the result of the force in section $k$, in relation to the single force in section $k$. It applies that $a_{ik} = a_{ki}$. The solver algorithm using influence coefficients was the most effective way to calculate the load distribution. The quality of load distribution depends on the numbers of normal planes and accuracy of influence numbers.

$$Y_1 = F_1 \alpha_{11} + F_2 \alpha_{12}$$

And $\alpha_{11} = Y_{E1} / F_E$ & $\alpha_{12} = Y_{E2} / F_E$ (1)

Where, $\alpha_{11}$, $\alpha_{12}$ are influence coefficient at position 1 because of force at position 1 & 2.

$Y_{E1}$, $Y_{E2}$ are deformation at position 1 because of unit force at position 1 & 2.

The general way to use flank modifications was described by the following 3 steps:

A. Load depending deformations should be influenced by design arrangements in such a way that they are reduced or maybe compensated.

B. The residual linear variable part of contact line deviation depending on load, thermic and centrifugal force has to be compensated by helical flank modification.

C. The contact line deviation, which balances around expected value 0, caused by measurement deviation of gears, deviation of gear wobbling and other raisings of load on the face side has to be reduced by an additional lead crowning.
C. The advantages of planetary gear trains are higher torque capacity, lower weight, small size and improved efficiency.

D. Planetary Gear Box weighs 60%, and half the size of a conventional gear box. \(^7\)

E. In design of planetary gear box, iterative considerations need to be given for composite arrangement to have minimum number of components, higher transmission efficiency, and higher load carrying capacity.

F. High reductions ratios are possible in single stage differential planetary gear arrangement but will work for low torque applications only like positioning systems in robotics, aerospace \[^3\].

G. Multicriteria Mathematical modelling methods can be applied to planetary gears and it determines a set of pareto optimal solution for various objective functions.

Identified Research Gap
Based on the finding of the literature review, following research gap is identified.

1. Very few researchers have reported the study on design of two stage planetary gear box. However the high reduction ratio i.e. 78:1 was not designed in two stage planetary gear box.

2. High reduction in single stage differential planetary gears arrangement works only for low torque application and has low efficiency \[^3\].

Hence authors have taken the research work on design of two stage planetary gear box.

Conclusion
From this critical review of research on design of planetary gears and gearbox, we can conclude the following:

1. The design parameters like Number of teeth, module, number of planets, face widths, tooth profile modification, material are very important in deciding the load capacity in bending and wear, life and cost of gears.

2. Finite Element analysis, MDESIGN, Load distribution Program (LDP) are important methods used for load analysis of planetary Gears.

3. Gear Train Optimizer, MDESIGN are software used for gear design and optimisation.

4. Optimisation of various objective functions like volume, mass, efficiency and production cost can be modelled by using Multicriteria Mathematical modelling and a set of pareto optimal solution can be obtained.

5. Load distribution on gear teeth can be calculated by using deformation influence coefficient and matrix method.

6. Deformation of tooth flank due to load can be reduced or compensated by tooth flank modification.

References


