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CRITICAL ANALYSIS OF DESIGN OF RAVIGNEAUX PLANETARY GEAR TRAINS

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Abstract:
Planetary gear trains have been applied for a long time in the automotive industry as an irreplaceable part of automatic gearboxes. This paper presents, based on existing research, the kinematic analysis and evaluation of Ravigneaux gear trains, effects of power flow analysis and power loss, evaluation of utility effects of energy utilization through analysis of efficiency. It also illustrates research topics that analyse technical challenges of understanding and predicting dynamics and vibrations of planetary gear trains in the process of design of their configuration, optimization of given gear trains in reference to set criteria and affirmation of validity of their constructions by prototyping and prototype testing on the test stand.

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1. INTRODUCTION

Ravigneaux gearset is a double planetary mechanism patented in France in 1949. This gear train consists of two central gears with outward-facing teeth and one central gear with inward-facing teeth, with two satellites in between connected by a carrier. It provides different revolution outputs and torques for various conditions of interconnected motion of elements. Ravigneaux gear train is used in various branches of industry, but it found the most intensive and wide-spread commercial application in automotive industry in production of automatic gearboxes, thanks to improvement of previously used gear trains, such as Simpson gear train [1]. Application of one carrier in case of this gear train causes it to be smaller, lighter and less expensive for production, because a carrier is most often the largest and the most expensive part of a planetary gear train.

This paper focuses on existing research and development of Ravigneaux gearset mechanism with special emphasis on the following aspects of influence: power flow and efficiency analysis, kinematic analysis, theory of graphs and nomographs (graphic display of multivariable functions), effects of vibrations, configuration design, gear train optimization and testing and prototyping.

This review paper may be a starting point that will lead the designer towards making good decisions in an early phase of design process so that eventual subsequent changes in design could be avoided in a later final phase of prototyping.

2. EFFECTS OF POWER FLOW AND EFFICIENCY ANALYSIS OF PLANETARY GEAR TRAINS

In case of planetary gear trains, efficiency is a parameter of evaluation of utility effect of energy utilization and it is one of the most important criteria for reliability assessment of built construction. Power losses in planetary gear trains originate from losses incurred by meshing of gears, from losses in bearings and losses incurred due to oil mixing and dispersion.

H. M. del Castillo [2] describes in his paper a systematic procedure for evaluation of efficiency of planetary gear trains. He shows that one may easily get an analytic expression for efficiency by use of a symbolic program for equation solving (*A symbolic mathematical computation program - SMCP*). There

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are several advantages of the proposed procedure in comparison with other methods proposed by various authors:

- Easy implementation on a computer and full automation,
- Requires only the information about structure of planetary gear circuits, i.e their number and composition,
- Provides not only efficiency but also torque acting upon circuit elements,
- Does not rely upon any analytic skill or knowledge of an engineer,
- Does not require performing all variants of expression for efficiency.

G. Del Pio and others [3] propose in their paper a method for kinematic analysis and power-flow analysis of bevel epicyclic gear trains of gyroscopic complexity. By virtue of new formulas derived in that paper, the methods based on graphic display of planetary gears have been expanded from spur gear trains to bevel gear trains. The famous *Villis* equation has been modified so as to maintain its validity for bevel gears.

Authors H. A. Hussen and others [4] have presented a new method of study for power loss and efficiency of planetary gear trains. Firstly, the paper describes the procedure for determination of consecutive value of angular velocity of any planetary gear train, on the grounds of which one may get consecutive values of relative angular velocities. Secondly, velocity sequence is used for determination of correct direction of torque for any three active members of planetary gear train. Thirdly, input and output links may be determined in movable reference carrier on the grounds of instructions about torque and relative velocity. Fourthly, the power that goes through any of the three active links of a planetary gear train is a result of a velocity and efficiency ratio of a gear pair from one equation. Fiftly, losses calculated in the rotating reference carrier are used for formulation of the total efficiency. The techniques of analysis that are presented here are general for majority of gear pairs where the factors to be studied are: power, power losses and efficiency.

After detailed verification of formulas originally proposed by Radžimovski, authors E. Pennestrı and P. P. Valentini [5] presented numerical equivalence of various approaches available for calculation of efficiency of epicyclic gears with two degrees of freedom. This analysis is based on the principle of virtual work and it enables interpretation of the Radžimovski formula as a specific case of general expression for calculation of efficiency of two units assembled in a parallel position. Also, it presents derivation of other six described methods and results for the example of problems that use all these methods. Despite obvious algebra differences in presented formulas, it has been presented that various approaches are equivalent in numerical sense.

In the study of [6] A. Kahraman and others there is a general formulation developed for kinematic analysis, search of kinematic configuration and power-flow analysis of planetary gears of automatic planetary gear trains. This tool may be used for definition and complete analysis of any assembly of automatic gearbox with one degree of freedom that consists of simple or complex sets of planetary gears. The formulation of power-flow analysis has been expanded so as to include losses as well.

J. Durand de Gevigney and others present an original analytical formulation for calculation of power loss due to tooth traction of inward-facing teeth of gears, including the effects of teeth profile modification [7]. In case of unmodified gears, results correspond well with classic formulae in professional literature, which further confirms the proposed approach. Bearing in mind two identical interior and exterior geometries of gears, when the velocity ratio is close to 0, efficiency of both gear set is similar, whereas for velocity ratio close to 1, internal gear set generates fewer losses than external one. It has been determined that the effect of modification of profiles upon loss of tooth traction in case of inward-facing teeth of gears is similar to the one of gears with outward-facing teeth and that significant improvements may be achieved by introducing the profile relief. As for individual gear pairs, it has been concluded that profile modifications may reduce significantly tooth traction losses (up to 30% in the given example), as indicated in Fig. 1.

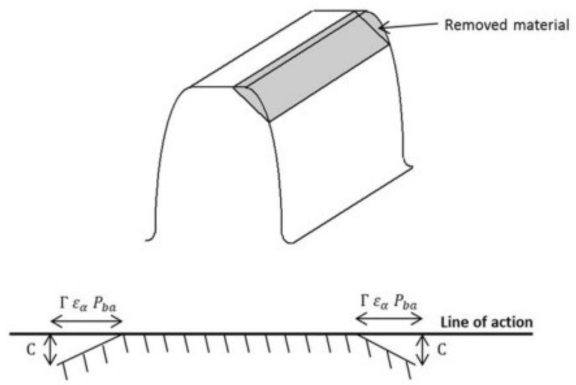

Fig. 1. 3D image and MAAG diagram of profile modification [7]

In urban conditions of car use, special attention must be paid to car needs for energy, quality of air and noise pollution of environment. It can be done in two ways: the first one is use of low emission hybrid vehicles, and the second one is use of improved efficiency transmission systems. A. H. Juber and others [8] analyzed in their paper the application of Ravigneaux hybrid transmission that could be applied in cars that are driven in urban environments most of the time. It is extremely efficient in low and mid gears, and less so in high gears. The Ravigneaux hybrid transmission is characterized by operative flexibility, compactness and simplicity. Efficiency of gear transmission system is essential for reduction of fuel consumption and environmental protection. It is proposed to use the method for calculation of hybrid transmission efficiency on the grounds of actual powers that run through it. The results indicate that it is very important to take into consideration efficiency of hybrid regimes when determining appropriate strategies of control.

3. KINEMATIC ANALYSIS OF PLANETARY GEAR TRAINS

Analysis and verification of Ravigneaux gear train play a very important role in application of planetary gear trains in automotive automatic gearboxes, thus the greatest number of analyzed papers is from that field.

In their paper, H. Chen and X. Chen [9] describe a geometric model for simultaneous representation of structure and kinematics of planetary gear train. The fact that the basic model unit, which is the smallest unit of planetary motion, ranges between graph theory and lever analogy, enables a more detailed visualization of kinematics, namely, velocities of all connections, which enables a better insight into effects of the basic circuit and their gear sizes upon the total velocity ratio of planetary gear train.

P. A. Simionescu describes in the scope of his paper [10] the general method for determination of assembly condition of epicyclic gears, regardless of the structure or type of gears. This method generates formulas that could be applied as functions to certain sums of numbers of teeth of epicyclic gears.

A detailed model and an analysis of gear sliding mechanism were described in the paper of S.Y.T. Lang [11]. Sub-assemblies of gear sets and carriers are too limited in a kinematic sense. Assuming that dimensions of gear set and carriers were designed so as for limitations to be met in identical way, it could be seen that the system has a surplus of consistent equations in kinematic and dynamic sense that could be separated during system analysis. The methodology is applied to systems of gears with flat evolvent profile, but it could be additionally expanded. The models developed as examples are for fixed, epicyclic and planetary gear trains.

I. Talpasanu and P. A. Simionescu presented a novel technique for kinematic analysis of bevel gears using the incidence matrices of an edge-oriented graph of the mechanism [12]. Kinematic equations are obtained in the form of a matrix using a cycle basis from a cycle matroid. These equations can be systematically generated and allow for an efficient computation of angular velocities of the gears and planet carriers of the mechanism without employing time derivative operations. As described in the paper, the method is applicable to bevel gear trains of any number of gears or degrees of freedom.

Determination of basic kinematic and dynamic characteristics of complex planetary gear trains is a complex process for which there are several analytical, graphical and grapho-analytical methods developed. S. Muždeka [13] described in his paper the manner of determination of transmission ratio, loads and power flows for a planetary gear set with the sun and ring gear by lever analogy with the application of Wolfs structural symbol. The lever analogy is also defined for the planetary gear set with sun gears for which there is a structural symbol defined. The defined structural symbols are employed for definition of Ravigneaux gear structure. Application of structural schemes for an analysis of compound planetary gear trains is illustrated through analysis of certain planetary gearboxes` functional state. The possibility of analysis of blocked compound planetary gear train is defined too.

A detailed kinematic analysis of Ravigneaux gearset using the form of computation of number of revolutions for each given gear, independent from the axis around which they rotate, is described in the paper of author M. Novaković and others [14].

The study of [15] A. Kahraman and others defines kinematic analyses for computation of rotations velocity of gears and carriers, transmission ratio and search algorithm of kinematic configuration and formulation of power-flow analysis. A kinematic component computes velocities of rotation of gears and carriers. Given the type and number of planetary gear sets, the search algorithm determines all possible kinematic configurations and combinations of numbers of gears which result in the necessary set of transmission ratios, eliminating at the same time all kinematic surpluses and improper sequences of clutch.

Z. Levai [16] illustrates in his paper methods for kinematic analysis and determination of torques and forces of compound planetary gear trains with the sun and ring gear. The same author showed in his paper [17] that all types of planetary gears with all variants of connection could be derived from one common „ancestor“. These variants are derived by changing the diameter of certain gears: by changing the external (central or planet) gear one can get an internal gear and vice versa. The author says in his conclusion that there are two types of elementary planetary gears and 34 types of simple planetary gears, each of them with six variants of connection.

H. I. Hsieh and L.-W. Tsai presented a novel methodology for analysis of gear ratios of transmission mechanisms of epicyclic type [18]. Firstly, they explored kinematic characteristics related to various methods of work of basic units. Then, they showed that the total gear ratio of mechanisms of epicyclic gears can be expressed in function of their basic units. This method leads to automized deriving of gear ratio of epicyclic transmission mechanism without any need for symbolic software for manipulation.

The paper of D. Antonescu and others presents main kinematic schemes of planetary (cycloid) mechanisms with cylindrical gears used on the automotive automatic gearboxes with 3 + 1, 4 + 1 and 6 + 1 gears [19]. The structural-topological layout in the neutral position is achieved for each kinematic scheme. The gears are obtained by actuating the clutches and the brakes, which means joining two kinematic links using a clutch and locking one kinematic link using a brake. The structural formula of the specific kinematic chains is determined for each gear. The more gears we have the more comfortable is the car drive. The goal of this design is to get as many gears with simple structure of transmission as possible. This optimization has a great effect upon reduction of fuel consumption.

The novel method for kinematic analysis of parallel axial epicyclic gears is presented and named method of incidence and transmission, and it uses incidence matrices linked to an edge-oriented graph and linked to the mechanism and transmission joints (joints in contact with gear teeth) [20]. The paper of I. Talpasanu and others explains the novel technique for analysis of angular positions, speeds and accelerations of parallel axial epicyclic gears. On the grounds of the group of circuits, which makes the basis where the cycle matroid is derived from oriented graph of attached to mechanism, an independent group of kinematic equations may be generated with minimum number of variables. The proposed technique is very suitable for computer implementation and enables automatic generating of a kinematic equation of any epicyclic transmission with any number of gears and degrees of freedom.

A. A. Fogarasy and M. R. Smith present a novel method of kinematic analysis of epicyclic systems of gears which simplifies to a great extent the design process [21]. Various examples are used to illustrate the easiness of making and solving the relevant constraint equations. Further on, each invalid design proposal looks like a mathematical contradiction when trying to solve constraint equations. In addition to that, simplicity of constraint equations enables expedient and easy finding of alternative kinematic design.

The paper of authors E. L. Esmail and others [22] expands the previous methodology for the kinematic analysis of planet gears to determination of gear ratio of various industrial automatic gearboxes. One kinematic equation for determination of gear ratio is made regardless of complexity of the mechanism. The method reliability is determined by application of the main kinematic motion equation and comparison of results with three most frequently used industrial automatic gearboxes.

4. THEORY OF GRAPHS AND NOMOGRAPHS OF PLANETARY GEAR TRAINS

Although there are many automatic transmissions of epicyclic type, related methods of configuration design are still complex and subject to human errors. It is necessary to develop a simple methodology for systematic design of epicyclic gear trains of Ravigneaux type. Firstly, in order to determine design requirements, fundamentals and shifting of gears of four-gear and six-gear automatic transmissions of epicyclic type were illustrated. Secondly, a simple clutching-sequence method was proposed and illustrated on the grounds of kinematic nomographs of corresponding basic gear ratios. Further on, a planar-graph representation is presented to arrange the desired clutches for each possible clutching sequence into the epicyclic gear mechanism. Then, with the above methods, the systematic designs of epicyclic gear mechanisms are described for demonstrating feasibility of the proposed methodology in the paper of E. L. Esmail [23].

The same author, E. L. Esmail, uses in his paper [24] the nomographs and optimization techniques for synthesis of clutching sequence and number of gear teeth of Ravigneaux gear train. Fig.2 shows the novel Ravigneaux gear mechanism and Fig. 3, on the next page, illustrates its nomograph of clutching sequence. Then, the total gear ratios are derived and expressed in transmission ratios of all meshed gears.

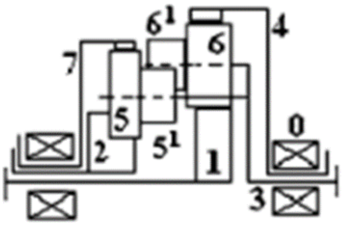

Fig. 2. New Ravigneaux gear train mechanism [24]

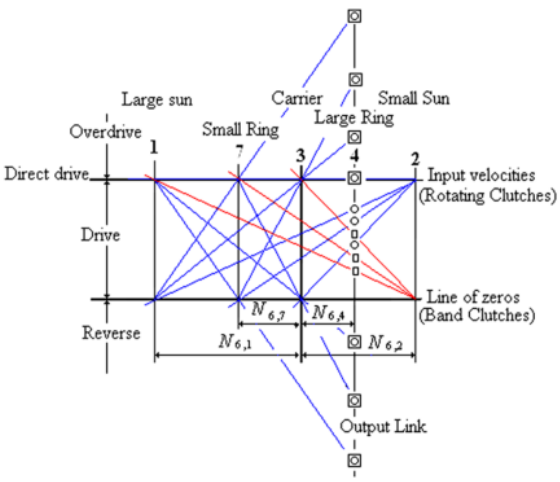

Fig. 3. Nomograph of clutching sequence for Ravigneaux gear train illustrated in Fig. 2 [24]

In their study [25], T. T. Ho and S. J. Hwang use the creative design methodology along with graph theory and analogue lever method for synthesis of feasible transmission systems for hybrid electric vehicles. The study proposes the total of 32 new hybrid gear trains, where each gear train consists of one Ravigneaux gear, one planetary gear, one input connection coming from the engine, one output connection to the end drive, two electromotors, two or three clutches and three brakes.

S. Y. T. Lang [26] developed a theoretical methodology of graphs for modeling gear train systems. This methodology is suitable also for kinematic and dynamic modelling and analysis. The modelled geared systems are currently limited to ideal non-deforming gears on a plain. The gear model is based on a determined model of rigid body and it uses rigid arms for modelling contact between the gears. Gear models enable taking into consideration the angle of pressure of involute gears for better dynamic representation.

Author E.L. Esmail contributes in his paper to development of a novel method for deriving the gear ratio of epicyclic gear mechanism [27]. Identification of basic gear train leads to automized making of kinematic nomographs in a systematic way. The main advantage of a nomograph is its simplicity. This is very useful in identification of the clutching sequence during phases of design of epicyclic gear mechanism.

The same author E.L. Esmail explains in his paper [28] that from such nomographs, the kinematic characteristics of an epicyclic gear mechanism can be expressed in terms of the gear ratio of its gear pairs. Angular velocities can be arranged in a discending sequence without using complicated artificial intelligence or algorithmic techniques.

In their paper, a group of authors H.-L. Xue and others [29] points out the significance of graph theory application that has been applied for a number of years in analysis and synthesis of gears and that is considered to be an efficient and systematic approach to modelling in the process of design of gear trains. All related algorithms can be applied in a suitable way into general computer programs, and use of computer programs enables quick analysis of performance of various configurations facilitating in that way optimization of design of simple and complex gear trains. As an illustration of application of this method, they used epicyclic gears with one degree of freedom and two-degree planetary gear trains.

H. Ding and C. Cai implemented a patent research so as to test the status of application of epicyclic gears used in automatic transmissions [30]. They researched 673 patents of automatic transmissions and got 274 various epicyclic gear trains which they presented in the corresponding two-color graphs and sorted out in 13 groups in accordance with the number of degrees of freedom. Structural characteristics are applied in order to discover if the received epicyclic gear trains could be used in automatic transmissions and to exclude configurations that do not correspond with requirements of automatic transmissions.

5. EFFECT OF VIBRATION TO PLANETARY GEAR TRAINS

The research implemented in this field has intensified over the last two decades. A wide spectrum of researched topics indicates technical challenges related to understanding and predicting dynamics and vibrations of planetary gears.

The paper of Z. Liu and others proposes a phenomenological model of vibration signal of epicyclic gear train which considers uneven distribution of load among planetary gears [31]. This model assumes that angular motion of a planetary gear simulates manufacturing or assembly errors in transmissions and computes various ratios of load distribution among planetary gears. Then, sprectral structures of vibration signals of epicyclic gear trains under uneven load distribution are derived from the phenomenological model.

In their article, authors C. G. Cooley and R. G. Parker [32] summarize the articles published in journals on dynamics and vibrations of planetary and epicyclic gears. The research in this field includes, among other topics, also mathematical models, vibration mode properties, dynamic response predictions including nonlinearities and time-varying mesh stiffness fluctuations, the effects of elastic compliance, and gyroscopic effects. Practical aspects are also included, for example, planet load sharing, planet phasing, tooth surface modifications, and characteristics of measured vibration response. Experiments conducted on planetary gears, although rare, demonstrate that some phenomena, such as vibrations of elastic gears, could happen. Measurements of planetary gears have interesting spectrums, which include frequency measurements of side range. The study analizes various manufacturing errors in planetary gears and how these errors affect dynamics of planetary gears.

In their paper [33] authors Y. Liu and others study vibration mechanisms of the central gear which is positioned so as to float inside planetary gear train and introduce a variable pressure angle, time-variable overlap ratio and time-variable meshing phase so as to research effects of these dynamic parameters upon response of system vibrations under various working conditions. Fig. 4 illustrates an example of dynamic model.

This floating set may be subjected to a change of pressure angle, overlap ratio and meshing phase and when gear faults occur, the variation will be enlarged. In order to study the influence of dynamic parameters on the vibration response of planetary gearboxes under different operating conditions, there is a novel model demonstrated with grouped parameters which contains time-variable pressure angle, time-variable overlapping and establishing of time-variable meshing phase.

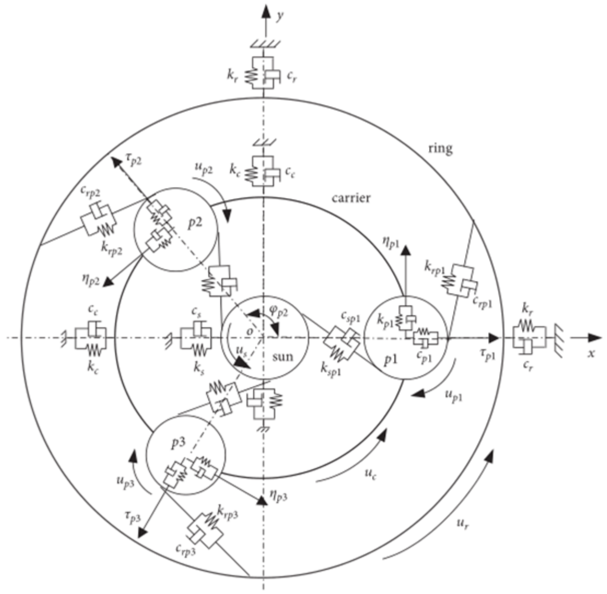

Fig. 4. Dynamic model with three satellites positioned at equal angles [33]

In their paper, authors J. Zhang and H. Guo [34], as well as J. Zhang and others, in their paper [35], analyzed a hybrid electrical vehicle equipped with composite Ravigneaux gear train which encounters a whining noise during acceleration in EV driving mode. For the purpose of analyzing vibro-acoustic sources, there is a vibration model established with grouped parameters of 5 degrees of freedom for dynamic system of planetary gear train, as well as measured noise pressures derived from transmission on the test bench for processing and recognition of data. It has been discovered that the main cause of vibrations of hybrid transmission are non-linear behavior of vibrations of planetary gears. Strong vibro-acousic noises become less intense after application of modifications of micro-geometry on planetary gear trains.

In his article [36], F. Pfeiffer refers once again to the important role of Ravigneaux planetary gear train used in systems of automatic power transmission. These gear trains have a complex mesh structure and they are a source of parameter-excited vibrations in the interior of an automatic transmission. In order to model the dynamics of such a gear correctly, the dynamics of the complete transmission and, additionally, at least the approximate dynamics of the complete driveline system, must be considered. This article sets up a model on the grounds of theory of multi-body systems which covers for the above mentioned aspects and enables simulations, for the purpose of study and then reduction of vibrations.

6. EFFECTS OF CONFIGURATION DESIGN UPON PLANETARY GEAR TRAIN

Challenges faced by engineers and researches in the process of design of planetary gear train configuration provided a good foundation for application of Ravigneaux epicyclic gears in automotive automatic transmissions.

Authors W. M. Hwang and Y.-L. Huang presented the synthesis procedure for discovering feasible clutch layout for the given clutching sequence of planetary gears and proposed a systematic methodology for layout of clutching sequence for automotive automatic transmissions [37]. Firstly, they presented the method for constructing coded sketches for planetary gear train. In the coded sketch, all coaxial links, except for the output link, are arranged in the certain sequence called a sequence of coaxial links. In conclusion, there were two rules of identification for identification of invalid clutching sequences in a logical way. Rule number 1 indicated the way to arrange a band clutch without passage interference. As per rule 2, invalid clutching sequences, which lead to infeasible clutch layouts, may be encountered in an early phase of configuration design. On the grounds of proposed coded sketches and rules, the synthesis procedure was presented so as to search step by step for all usable coded clutch layouts from the given clutching sequence.

The paper [38], presented by G. Kouroussis and others, illustrates an efficient formulation for automatic transmission modelling for evaluation of vehicle performance in an early phase of a power train design. The corresponding equations of motion are obtained with the help of the virtual power principle, involving all rotating parts of the gearbox. This formulation offers a powertrain / vehicle dynamic model developed for the sake of simplicity (rigid interconnected bodies with kinematic constraints), and sufficiently efficient to simulate continuously the gear shifts. The developed model reveals itself as a valuable tool for simulating the implementation of different control laws governing the gear shifts.

Application of epicyclic gears enables big carrying capacity and compactness of power gears. Author A. Kapelevich focused in his paper [39] on analysis and design of epicyclic gear trains which enable extremely high transmission ratios. Transmission ratios of over hundred thousand to one could be used for special two-degree planetary gear trains. The paper presents an analysis of such unusual layouts of gear and defines their main parameters, constraints and transmission ratio maximization approaches. The paper also describes numerical examples, existing designs and possibilities of their potential application.

The system of epicyclic gears may provide only two gears of transmission ratios in automatic transmissions used in automotive industry. Ravigneaux gears are a modified version of epicyclic gears with two sets of planetary gears and central gears with exterior or interior teeth enabling them to provide four gears (ratios). Authors E. Moulick and others considered the analysis of design and optimization of Ravigneaux gears in their paper [40]. They compared the Simpson gear train with the Ravigneaux gear train, and conducted a simulation with both gear trains in *MATLAB* (*Simulink*), keeping all other vehicle parameters such as transmission ratios, engine and vehicle parameters, and compared the results gained. They compared these results with percentage change in the velocity ratio and determined that the results were within 10% of the calculated value.

In their paper [41] authors E. L. Esmail and others present a methodology for design of two-ring Ravigneaux-type epicyclic gears that are applied in automatic transmission for automobiles. This paper is a partial attempt at attaining the maximum possible velocity ratios for any given epicyclic gear train. The result of this paper indicates that the nine-link Ravigneaux-type gear mechanisms with two degrees of freedom could attain eight forward speeds at most. It is a great breakthrough in design of eight-speed automatic transmissions by use of Ravigneaux gear mechanisms with nine links. This structural design has realized a reduced length of automatic transmission, while having minimum number of gears. The methodology may be applied to any transmission mechanism depending on its kinematics and geometric constraints.

In his study [42] X. Song presents the main structure of automatic transmission design. According to the structure of characteristics of gear planetary mechanism, different combinations of transmission actuator get the movement rule and working principle of each gear position, and calculate the specific parameters of each row of planetary gear mechanism. The central gear of planetary gear mechanism is the sun wheel, and satellites should be positioned symmetrically between the sun wheel gear ring, as indicated in Fig. 5.

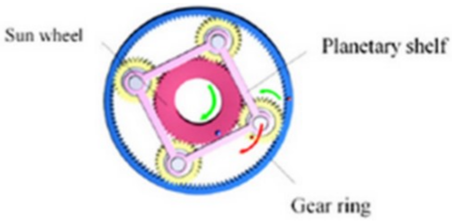

Fig. 5. *Schematic diagram of the planetary gear structure [42]*

Authors Y. F. Chen and others present in their paper [43] development of a new design of vehicle components and a new torque vectoring differential. Over the last years, this technology has attracted attention because of its potential to improve vehicle performance and safety of driving. Firstly, the principles of design of current torque vectoring were analyzed and and their systematic configurations were transferred from schematic diagrams. Secondly, a new design of torque vectoring, consisting of the Ravigneaux transmission and two brakes, was presented while discussing feasibility of the new configuration. On the grounds of conducted analysis, it has been determined that a new design of torque vector with the Ravigneaux transmission has a good potential for this function. The vehicle dynamics could also be improved by way of a system aimed at meeting driving requirements such as stability and turnability, whereas better safety and driving performance are considered to be feasible by way of the new Ravigneaux transmission and new design of torque vectoring to be applied to vehicles.

7. OPTIMIZATION OF RAVIGNEAUX PLANETARY GEAR TRAIN

Optimization of a planetary gear train in reference with criteria of transmission ratio, efficiency, stressing, noise, weight, expenses and delay is an imperative goal of success of any design relative to this type of mechanism. Each of these criteria could be simulated by mathematically unified models and optimized by use of corresponding computer programs.

All gears differ among themselves in terms of position of input, output, reactions, various links and number of ring gears and teeth on each set. Despite of that, it was possible to define a new unified formulation for kinematic ratio, for efficiency and torque calculation. Analytical study for conception becomes possible by solving an “inverse equation”, as authors R. Mathis and Y. Remond illustrated in their paper [44]. Synthesis of the number of teeth of planetary gears of an automatic gearbox used in automobiles is formulated as a limited problem of optimization that is solved by evaluation of distribution algorithm.

In their paper [45], authors S. Miladinović and others presented optimization of Ravigneaux planetary gear through analysis of safety degree with change of material, module and gear width. On the grounds of *Taguchi method* and *ANOVA analysis,* it has been concluded that a module with 89.86% of gear width has the greatest effect upon safety whereas a module with 3.85% of gear width has the least effect upon safety. The difference in mass between Ravigneaux set of planetary gears with maximum and minimum degree of safety amounts to 4.921 kg, which makes around 28% of complete mass.

Ravigneaux planetary gears attain significant contacts on teeth face and transmit great torque distributing load evenly among several ring gears which results in reduction of safety coefficient for teeth face durability. In their paper [46], S. Miladinović and others dealt with optimization of input variable parameters: materials of gears, gear widths and gear modules for minimum value of safety coefficient necessary for durability of teeth face of the first sun and ring gear pair in the Ravigneaux set of planetary gears (Fig. 6). They presented the estimated range of safety coefficient for durability of teeth face for all combinations of input variables and their levels and determined that the data resulting from those tests were close to the estimated range of results.

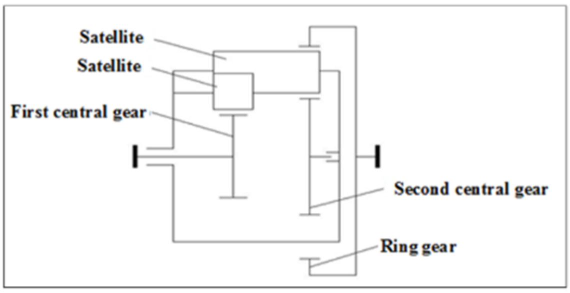

Fig. 6. A schematic representation of Ravigneaux planetary gear set [46]

The paper of authors A. Grkić and others presents the process modelling of gear shifting in planetary gear shifter by use of a computer in *Matlab/Simulink* environment [47]. The indicated results show that application of contemporary methods and techniques in design of complex gear trains, such as planetary gear train, enables quick assessment of possible solutions and their optimization. It is possible in this way to conduct a high-quality analysis of transitory process during gear shifting, as well as to have the possibility of analysis of construction parameters of gear train upon the process of gear shifting. By use of computers in the modelling of gear shifting process it is possible to generate various variants of virtual models of gear trains with relevant data on its characteristics which provides support to designers in making decisions in iterative process of design, i.e. in making adequate decisions in initial phases of design.

8. TESTING AND PROTOTYPING OF RAVIGNEAUX PLANETARY GEAR TRAIN

The technological flow in development of planetary gear trains starting from the concept, design and model is reaffirmed by production of its first prototype physical model. Nowadays, production of a prototype, as an important part of product development, includes various activities from forming, optimization and conducting of computer simulations (virtual prototype) to building a tangible, functional part (physical prototype).

Author G. Achtenova describes in his article [48] a concept of modular test stand for testing gear pairs with fixed mechanical axes of automobile transmissions, as well as testing of separate planetary sets of automatic transmissions. It is possible to make a direct link in a modular stand with a closed power circuit between two identical planetary sets, which will be assembled face to face and connected to electro-motor without any flange or clutch, axis or gear. This variant is especially interesting because:

1) it is rarely described in professional literature and

2) this topology enables major simplification in terms of testing standard gears.

The test stand is cheap, simple, and easy to operate, with great potential for future measurement and it is displayed in Fig. 7.

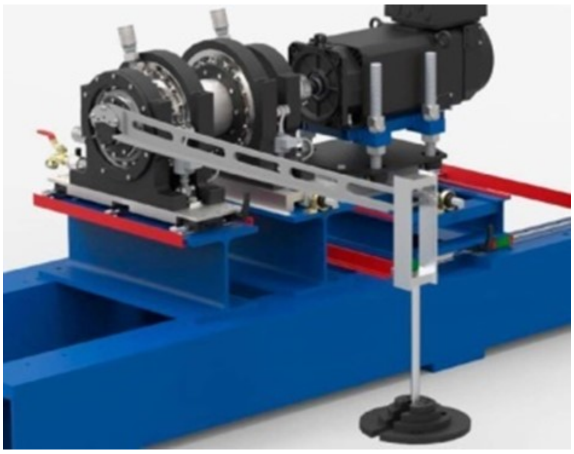

Fig. 7. Visualization of assembled test stand [48]

Rapid prototyping is considered to be a progressive group of technologies, which made possible especially over the last few years the production of components with special accuracy. This technology was introduced for the first time by company *3D Systems* in 1987. The major quantity of over 2/3 of all installed machines in the world is located in the US. In Europe, the Great Britain and Italy are the main countries that dominate in using devices for rapid prototyping. Article [49] written by authors J. Sedlak and others describes prototyping of models of a planetary mechanism by applaying additive method of rapid prototyping using a *3D* printer called *uPrint*. The first part of article includes theoretical analysis of the main principle and kinematic parameters of the model of planetary mechanism. The second part begins with experimental analysis of calculation of planetary assembly and continues with description of production process of all individual parts of mechanism and with description of the final completion of the planetary mechanism prototype. Fig. 8 illustrates what the model looks like after completed assembly of planetary mechanism.

Fig. 8. Final assembly of planetary mechanism model [49]

9. CONCLUSION

The main idea of this paper was to indicate the great importance of application of Ravigneaux planetary gear train as an integral part of automatic transmissions and their application in the automotive industry. It includes an overview of papers written on application of Ravigneaux planetary gear train, as an integral part of automatic transmissions in automobiles, which illustrate their complexity and the following conclusions are made:

- The paper determines that effects of modifications of teeth profiles upon loss of traction in case of ring gears are similar to gears with outward-facing teeth and significant improvement can be made by introduction of profile relief. As for individual gear pairs, it was determined that profile modifications could significantly reduce tooth traction losses (as much as up to 30% in the given example);
- Application of Ravigneaux hybrid transmission in the automobiles driven most of the time in urban environments leads to high efficiency at low and medium velocities, and to less efficiency at very high velocities. The Ravigneaux hybrid transmission is characterized with operative flexibility, compactness, and simplicity. Efficiency of gear train system is of key importance for reduction of fuel consumption and environmental protection;
- Determination of basic kinematic and dynamic characteristics of compound planetary gear trains is a complex process for which there are several analytical, graphical and graphoanalytical methods developed. The method of structural analysis proved to be especially useful in analysis of compound multi-sequence gear trains;
- The more gears we have the more comfortable is the car drive. The purpose of design is to get as many gears with a simpler transmission structure as possible. This optimization has a significant influence upon reduction of fuel consumption;
- A hybrid electrical vehicle equipped with composite Ravigneaux planetary gear train and featuring high-level noise during acceleration in EV driving regime was analysed. It has been discovered that non-linear behavior of vibrations of planetary gear teeth is the main cause for vibrations of hybrid transmission. High-level vibro-acoustic noise is mitigated after application of modifications of micro-geometry upon planetary gear trains;
- On the grounds of conducted analyses, it has been determined that a new design of torque vector with Ravigneaux gearbox has a good potential for this function. The vehicle dynamics could also be improved with a system meeting driving requirements such as stability and turnability, and better safety and drive performances are considered to be feasible by way of new Ravigneaux gearbox and new design of torque vector to be applied in vehicles;
- Optimization of Ravigneaux planetary gears through analysis of safety coefficient with change of materials, modules and width of gears by use of *Taguchi method* and *ANOVA analysis* brought about the conclusion that the module with 89.86% has the greatest effect upon safety coefficient, whereas the gear width of 3.85% has the least effect upon safety coefficient. The difference in mass between Ravigneaux set of planetary gears with maximum and minimum degree of safety amounts to 4.921 kg, which makes around 28% of complete mass.

In future references, the following studies will focus on detailed kinematic analysis of the concrete construction of the Ravigneaux gear train, power flow analysis and determination of its efficiency by way of analytical methods and experimentally on the test stand.

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