Advances in The Design Optimization and Manufacturing Optimization of Bevel Gears-A Review

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***Abstract*— Exhaustive research supports new methods for designing and manufacturing bevel gears that are stronger and more cost-effective than ever before. Bevel gears were developed more than 70 years ago and are important gears that are still produced all over the world. There is widespread use of bevel gearing in industry and there are many special problems associated with this type of gearing[1]. An overview of recent advances in the research on bevel gear design optimisation and manufacturing optimisation is provided in this research study. Section II deals with design optimisation and Section III deals with manufacturing optimisation of bevel gears.**

Keywords—Hypoid gears;Spiral bevel gearsg;meta-heuristics; electrochemical honing

I. INTRODUCTION

Bevel and hypoid gears are commonly used in transmissions and drivelines for a wide range of industrial sectors. Although each sector has different requirements, there is an overall trend towards higher durability and lower noise, with development cost and time being two other factors that are very important to consider. With the bar being raised on the performance requirements of geared products, developing a high-efficiency design/development process has become increasingly challenging. The design of bevel and hypoid gears
is – unlike cylindrical gears – entirely dependent on the manufacturing process and thus so are their NVH and strength characteristics. This means that the design of hypoid and bevel gear tooth flanks, via the manufacturing machine settings, needs to be considered again within the context of the full system.

Spiral bevel gears have very complicated tooth flank form and mesh perpendicularly, it was very difficult to grasp a meshing condition. In the history of bevel gears, aspects from design to production control have been exclusively entrusted to the empirical method provided by cutting machine manufacturers (Gleason Corporation and Klingenberg GmbH) and are supported by intuition and experience of skilled engineers and operators[10]. To grow out of the empirical method implemented so far and to develop bevel gears that can secure high durability and reliability, equipment manufacturing companies developed the technology ranging from tooth flank form measurement of large bevel gears to tooth contact analysis that calculates a meshing condition.

II. DESIGN OPTIMISATION OF BEVEL GEARS

The design of any gearing system is a difficult, multifaceted and highly complicated process. When the system includes bevel gearing, the process is further complicated by the complex nature of the bevel gears themselves. In most cases, the design is based on an evaluation of the ratio required for the gear set, the overall envelope geometry, and the calculation of bending and contact stresses for the gear set to determine its load capacity. There are, however, a great many other parameters which must be addressed if the resultant gear system is to be truly optimum.
This section covers the developments in design optimization of bevel gears.

A. Kinematic Design and Analysis of Planetary Bevel-Gear Trains

One of the most common methods in analyzing speed ratios of planetary gear trains has been the tabulation method. For complex mechanisms where many gear trains are coupled together, this method becomes inconvenient. With bevel gears in the gear train, it fails to apply. Some textbooks also use formulas which apply only to gears with parallel axes of rotation. This fact is often not stated in machine design texts. These methods can become incorrectly used in the design and analysis of planetary bevel gear trains with nonparallel axes of rotation. With the use of computers and graphics, a convenient and reliable method can be derived. Freudenstein and Yang have derived the early graphical method for analyzing gear trains. C. P. Day,et al developed an algorithm [2] to extend the graphical method for analyzing coupled planetary bevel gear trains. A matrix formulation is used to include speeds of all gears rotating about their respective axes. Such formulation will aid designers and analysts in determining correct speedratios of all gears in a planetary gear train system.

B. Dynamic analysis of a gear pair

A single degree of freedom non-linear model is used for the dynamic analysis of a gear pair by H.Nevzat Özgüven, et al.[3] Two methods are suggested and a computer program is developed for calculating the dynamic mesh and tooth forces, dynamic factors based on stresses, and dynamic transmission error from measured or calculated loaded static transmission errors. The analysis includes the effects of variable mesh stiffness and mesh damping, gear errors (pitch, profile and runout errors), profile modifications and backlash. The accuracy of the method, which includes the time variation of both mesh stiffness and damping is demonstrated with numerical examples. In the second method, which is an approximate one, the time average of the mesh stiffness is used. However, the formulation used in the approximate analysis allows for the inclusion of the excitation effect of the variable mesh stiffness. It is concluded from the comparison of the results of the two methods that the displacement excitation resulting from a variable mesh stiffness is more important than the change in system natural frequency resulting from the mesh stiffness variation.

C. Modeling and load analysis of spiral bevel gears

A single degree According to different forms of gear power split transmission including parallel axes, star gear train and planetary gear train,a new type of spiral bevel gears power split system with cross axes transmission was proposed by GU Jian-gong, et al, and its structure and working state was explained[4].The transmission powers of every gear pair in the system were then calculated,and the power split situations were analyzed under conditions of all kinds of installation errors.

D. Windage power loses from spiral bevel gears

In many aero-engines, the power to drive accessories is transmitted through high speed bevel gears in a chamber in the center of the engine. The windage power loss (WPL) associated with these gears makes a significant contribution to the overall heat generation within the chamber. Shrouding the gears provides an effective method of reducing this WPL and managing the flow of lubricating oil. Experimental and computational programs[5] are providing an improved understanding of shroud performance and design. A fully (360 deg) shrouded gear shows a big improvement over an unshrouded gear when running in air alone, but much of this benefit disappears as soon as a very small amount of oil is introduced under the shroud. This implies that the oil is recirculating under the shroud. Increasing the oil flow beyond this initial level increases the torque by the amount required to accelerate the oil mass flow up to the peripheral speed of the gear. Providing a full width slot in the shroud downstream of the oil jet allows the oil to escape without any recirculation and restores much of the benefit of the shroud. Further insight into the oil behavior is obtained from torque measurements and observations through a transparent shroud and with various slot configurations. The three main windage contributors, air alone, recirculation of oil under the shroud, and acceleration of the feed oil, are quantified and methods for achieving the optimum design are developed.

E. Optimisation of bevel gear pair by non-linear programming and meta-heuristics

For optimization of bevel gear pair design using a non-linear programming optimising software LINGO and meta-heuristics such as real coded genetic algorithm, ant colony optimisation and particle swarm optimisation algorithms, S.Arunachalam,et al. [6] developed a combined objective function which maximises the power, efficiency and minimises the overall weight and centre distance.

F. Optimisation design software for bevel gear based on Integer serial number encoding Genetic Algorithm

Bevel gear drive, characterized by changing direction, high coincidence and smooth transmission, etc., is widely used in the aerospace, automotive and large mechanical transmission system[7]. So its design quality not only affect its own transmission performance, size and weight but also have some impact on the machine's performance. In practical engineering design, involving many parameters, consuming much calculation time, prone to error, and repeated calculation, query and drawing are needed for series of product design, resulting in substantial duplication of effort. Liling Zhang,et al proposed optimization design software for bevel gear, in which automatic optimization design is realized. A mathematical model, programming of design data and realization of optimization design based on integer serial number encoding genetic algorithm, which effectively deals with continuous and discrete variable optimization problem and reduces the code length of the string to improve the encoding and decoding efficiency, no invalid solution or duplicate solutions, with improved encoding and decoding efficiency.

G. Local synthesis algorithm for spiral bevel gears

A method of application of local synthesis algorithm, tooth contact analysis, and stress analysis by application of finite element method, for spiral bevel gears,is proposed by Faydor L. Litvin,et al.[8]. The main goals are the improvement of the bearing contact, the achievement of a predesigned parabolic function of transmission errors, reduction of the magnitude of transmission errors as the precondition of reduction of noise and vibration, and avoidance of areas of severe contact stresses for the increase of the endurance of the gear drives. The proposed ideas have been proven by the manufacturing and test of prototypes of spiral bevel gear drives.

H. An optimised approach to straight bevel gear design

The optimal--or "rational"--design of gears can be a challenge due to the high number of variables, limitations, and interrelationships involved[9]. And also because, in each separate case, the objective functions, restrictions, and independent variables are generally different. Many of the specialists who have approached gear optimization by means of exhaustive search methods *[Dana (1969), Escanaverino (1984), and López (1993)]* first organized an evaluation of the objective function with reasonable design parameter values in place, and then compared and retained the most extreme results of the function in each step.

In this particular case a functional methodology is given, with the objective being to establish general principles and procedures for the rational calculation of gears, with an emphasis on straight bevel gears. The procedure utilized has as its starting point a mathematical model based on the ISO standards for gear load capacity and a system generated with interrelation between gear geometry and resistance. The ISO standards for the load capacity calculation of bevel gears (ISO 10300-1,2,3) was used to develop the relationships between the geometry and tooth resistance. Additionally, the procedure includes the verification of the gear's geometric qualities by means of "indicators" to establish restrictions in the field of possible solutions.

G. González Rey Rey proposed a computation program in Visual Basic 4.0, in which the rational parameters of the straight bevel geometry are obtained by means of an organized evaluation of the two objective functions that allows, in each step, to compare and to retain the extreme value in the functions (instantaneous optimum) and all values of each design parameter involved. The design parameters obtained by these means belong to the group of acceptable values and possible solutions in the design problem. In this case, the variable to maximize was the pinion torque applied in the gear transmission with restrictions of:

- Maximum load capacity to contact and bending stresses
- Transverse contact ratio greater than a minimum value
- No tooth interference occurrence
- Tooth top land thickness greater than a minimum value
- Outer tip diameter on gear no greater than a maximum value

I. Automation software for computer aided designing optimisation of bevel gearings

ION-FLORIN POPA,et al,[10] proposed a working methodology specific to engineering field, the scope representing the automatization of the entire conceptual cycle of a product. Thus, starting from pre-dimensioning computations of the product (using application software like: Turbo Pascal, C++, MathCad), a database or a data file is being created that is taken by a graphical application (AutoCAD, AutoLisp, Solid Works) which can automatically generate the design of product both in 2D and 3D. eventually, optimization is achieved by numerical simulation of the product behaviour under different specific strains. Depending on the results obtained, the cycle can be restarted, either by changing the input data and by changing the database that generates the size values of the respective product.

The final scope of the paper is to present a way of reducing the time from the conceptual phase to the starting-up phase of a product on the market, interfering within the designing-checking-optimization area by automatization the specific activities, using computation techniques.

J. Dynamic simulation of spiral bevel gear

Spiral bevel gears are one of basic mechanical units to transmit motion between concurrent axes. The transmission has quite a few merits, such as the big overlap ratio, the high loading capacity, the high transmitting efficiency, the stability and the small noises, and they are widely used in automotive vehicle, planes, machine tools and all kinds of machines[12]. Mechanical properties of spiral bevel gear have significant influence on the whole mechanical structure and play an important role in the system optimization, strength check, fault diagnosis and fault prediction, and gear tooth meshing-dynamic load is an important issue in the gear research field. JIHUI LIANG ,et.al developed three-dimensional models of spiral bevel gears created by SOLIDWORKS and then converted to ADAMS by means of data exchange interface between SOLIDWORKS and ADAMS. By the contact algorithm theory of multi-body dynamics and ADAMS, the dynamic simulation of the spiral bevel gears mesh is specified. The curves of angular speed, torque and meshing force on the spiral bevel gears are obtained by simulation calculation, which provide references to research on dynamic characteristics of gear driving device.

K. Fatigue stress calculations of straight bevel gears

To reduce the transmission errors, the straight bevel gears need be high precision manufactured. Due to a many complex factor such as the large range of bearing vibration amplitudes, gearing manufacture tolerances, gearing contact deformations, gear bending deflections, shafts bending deflections and torsion deformations, bearing clearances, is difficult to avoid the gearing teeth impact and load concentration[13]. The straight bevel gear teeth contact is given by an elongated ellipse, the gear overall dimensions depending by the teeth contact length. Is absolutely needed that the contact patch to cover the entire teeth length for full load gearing. But, this is impossible because of the teeth manufacturing errors and also gearing assembling errors. The paper presents a new straight bevel gear system for large dimension photo voltaic (PV) platforms. The PV tracking movement's errors depending by straight bevel gearing errors and also by the tracking elements deflections. The design accuracy of straight bevel gear is influencing the load transmission, the size and gear weight and also the system performances. The paper analyses the influence of the geometry of straight bevel gears on the combined geometry factor for the pinion and also the wheel of a straight bevel gear from a tracking system transmission, for static load.

III. MANUFACTURING OPTIMISATION OF BEVEL GEARS

The manufacturing of bevel gear is often difficult because of unpredictable tool wear during the gear cutting process. This results in undesired additional manufacturing costs due to unexpected production stops for tool changes. Because of its complexity, it is not entirely possible to analyse the bevel gear cutting process sufficiently. This section elaborates the developments on the manufacturing optimization of bevel gear production process.

A. Kinematical optimisation of spiral bevel gears

Zhang-Hua Fong et al., [14] proposed kinematical optimization and sensitivity analysis of circular-cut spiral bevel gears. Based on the Gleason spiral bevel gear generator and EPG test machine, a mathematical model is proposed to simulate the tooth contact conditions of the spiral bevel gear set.

B. Electrochemical honing (ECH) of bevel gears

Electrochemical honing (ECH) is emerging as a potential gear finishing technique in which achieved surface finish and material removal are significantly influenced by the processing time. J. P. Misra,et.al, conducted experimental investigation[15] to explore the influence of processing time on process performance parameters: surface quality of gear teeth profile, tribological performance of the teeth surface and process capability and thus, to estimate the optimum processing time by graphical analysis.

C. Computer-aided manufacturing of spiral bevel and hypoid gears

Chung-Yunn Lin, et al proposed a mathematical model of an ideal spiral bevel and hypoid gear-tooth surfaces based on the Gleason hypoid gear generator mechanism[16]. Using the proposed mathematical model, the tooth surface sensitivity matrix to the variations in machine–tool settings is investigated. Surface deviations of a real cut pinion and gear with respect to the theoretical tooth surfaces are also investigated. An optimization procedure for finding corrective machine–tool settings is then proposed to minimize surface deviations of real cut pinion and gear-tooth surfaces.

D. Hot forging process design of magnesium alloy AZ31B bevel gear

Magnesium alloys have relatively low workability at room temperatures due to hexagonal crystal structure. In general, the forging process of magnesium alloys is considered to be very difficult because of the poor flowability and the sensitivity to the temperature and strain rate. Taken spur bevel gear as an example, the hot forging process of the complicated shape parts of magnesium alloy AZ31B was investigated by Juan Liu, et. Al.[17] by means of finite element (FE) simulations combined with experiments. After the two-stage hot forming process (preforming operation without gear shape and finish forging operation) was determined, the influence of various shapes of preform dies on the hot forging process was discussed by the commercial finite element analysis software Marc, and the optimum preform die shape was obtained. According to the numerical simulation results, the hot forging experiments of magnesium alloy AZ31B spur bevel gear were successfully conducted. By comparison between experimental load–stroke curves and the calculated ones, it shows that the calculated results are consistent with the experimental ones.

E. Vectorial tolerance allocation of bevel gear

The purpose of functional tolerancing process is to define the geometrical specifications (tolerances) of parts ensuring functional requirements. An important distinction in tolerance process is that engineers are more commonly faced with the problem of tolerance synthesis rather than tolerance analysis. In tolerance analysis the parts tolerances are all known and the resulting geometrical requirement respect is calculated. In tolerance synthesis, on the other hand, the geometrical requirement is known from design requirements, whereas the magnitudes of the parts tolerances to meet these requirements are unknown. In this paper, we focus on the gear tolerances, and we propose an approach based statistical analysis for tolerance analysis and genetic algorithm for tolerance synthesis. Usually, statistical tolerance analysis uses a relationship between parts deviations and functional characteristics. In the case of tolerance analysis of gears, thus relationship is not available in analytic form, the determination of a functional characteristic (kinematic error,…) involves a numerical simulation. Therefore the Monte Carlo simulation, as the simplest and effectual method, is introduced into the frame. Moreover, to optimize the tolerance cost, genetic algorithm is improved. Indeed, this optimization problem is so complex that for traditional optimization algorithms it may be difficult or impossible to solve it because the objective function is not available in analytic form. For the evaluation of the fitness of each individual based on Monte Carlo simulation, the number of samples is the key of precision. By a large number of samples, the precision can be improved, but the computational cost will be increased. In order to reduce the computational cost of this optimization based on Monte Carlo simulation and genetic algorithms, the strategy is to adopt different precision of fitness; different numbers of samples during the optimization procedure are introduced into the algorithms[18].

F. Optimal design of variable helix angle bevel gear

The traditional copying process method of cutting bevel gear produces large error, which leads to allocate load unequally and short the life of gear. However, Variable helix angle bevel gear (VHABG) is a new kind of gear based on numerical control technology. It is a new way to cut large size bevel gear accurately with traditional milling machine. But the volume of the gear is large, cost is high. The above problem limited the application of the gear. Li Tiejun ,et.al [19] analyzed variable helix angle bevel gear and established its optional mathematics model is. The optimal solution of the gear is found with genetic algorithms. Compared with the traditional optimal methods, the result shows that applying genetic algorithms to solving the optimization problems with many restraints and many types of variants is feasible, and the method is of importance to the application of the gear.

G. Pinion machine settings for bevel gears

In some cases, some of the pinion machine settings' values calculated by local synthesis method may be too large for machine-tool and beyond the adjustive ranges. A new approach 1 for design of spiral bevel gears based on local synthesis method is proposed. One of pinion machine settings, work offset, can be assigned in advance, and this gives more freedom for designing pinion tooth surface. In order to get a predesigned parabolic function of transmission errors with limited magnitude of maximal transmission errors, the contact path with the shape of straight line, genetic algorithm is used[20]. In this process, tooth contact analysis (TCA) is embedded to constitute the design route,so that the overall control of engagement quality is realized.

IV. CONCLUSIONS

It is necessary to undertake a heavy and long development process before reaching a gearbox design that satisfies all the economic, technical and security requirements. Gear design has long been a "black art." The gear shop's modern alchemists often have to solve problems with a combination of knowledge, experience and luck. In many cases, trial and error are the only effective way to design gears. While years of experience have produced standard gearsets that work well for most situations, today's requirements for quieter, more accurate and more durable gears often force manufacturers to look for alternative designs. The challenges of today's very demanding bevel gear transmissions are: silence, precision, repeatability of movements, high-speed and erratic loading. The esoteric nature of bevel gear design requires many software package to be developed to calculate equations, perform stress and materials analyses, produce computerized design and manufacturing optimization. Research over the years has contributed to the diffusion and development of new customer applications: from modern anthropomorphic robots to the most sophisticated vehicles, to ever faster and more accurate printing machines.

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