COMPUTER AIDED DESIGN OF CYLINDRICAL AND BEVEL MODULAR GEAR SIZE RANGES

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Abstract: *Size ranges of gears provide a rationalization of design and production procedures. For the manufacturer, they have the following advantages: the design work can be done once and the production of selected sizes can be repeated - hence it becomes more cost-effective. This implies further following advantages for the user: competitive and high quality products, short delivery times and an easy availability of spare parts. Modular products also often involve size ranges. In this paper, a computer system for design of cylindrical and bevel gear size ranges is presented. The computer system was written in Object Pascal language using Delhi Enterprise 6.0 programming environment.*

1. INTRODUCTION

A size range (parametric series of products) is a collection of technical products e.g. machines, machine sets or subsets as well as individual parts which fulfill approximately the same function and have the same technical design (constructional solution, form). Moreover the sizes of particular items of the size range change in a stepwise manner according to special rules and additionally manufacturing procedures are as similar as possible. In the most frequent case, initially a chosen one item from a size range is fully designed. Its design is called a basic one. Derived designs for the consecutive items (elements) of the size range are worked out based on special rules i.e. most frequently - changes consist in assuming main dimensions of a design from a series of dimensions given by formulas, tables or charts, additionally a geometrical similarity is preserved. Such size ranges are called dimensionally similar or dimensional ones. As an example, one can consider gears e.g. cylindrical two-stage gears which differ generally in distances between shafts axis, sizes of geared wheels and shafts and in consequence load capacities. Sometimes, for one stepwise series of items, slightly different types of machines can be considered but the series of dimensions is achieved. Such size range is called type-dimensional one e.g. ship propulsion motors. In case of low power, four-stroke engines are used. However, for high and medium powers – two-stroke engines (because they have smaller overall dimensions) or gas turbines are applied. There are also mixed size ranges which can be divided in single-type and geometrically similar or different-type ones. An application of the method of parametric size ranges is advised for design of machines which are manufactured in long production series, when the range of items is comparatively broad e.g. combustion or electrical engines, gears, pumps, compressors, machining tools etc. Production of dimensionally similar machines (e.g. size range of gears) has several advantages i.e.: necessity of single performance of general constructional tasks connected simultaneously with many similar size range items, usage of the same materials and repeatedly manufacturing of particular batches of production. Due to this, higher quality of the product can be achieved – simultaneously - spending less financial resources as well as obtaining an output in shorter time. A disadvantage of this approach is a restricted choice of a size of a machine or machine sets what can result in non-optimal service conditions of the machine. Additionally, the utter items of a size range, especially in the case of a broad range, are relatively less rationally designed in comparison to other machines designed deliberately for this application. Therefore the comparison of dimensions, total weight and service indicators of afore mentioned machines gives better results for the latter one [4].

Versatile applications of computers for design of size ranges yield not only the greatest but also not fully exploited possibilities to accelerate and improve the work of gear designers. The following particular areas of applications can be considered:

1) complex computer programs written in Borland Delphi – used for calculations of strength of gears which can replace the most frequently used programs (in design offices) written in e.g. MathCAD,

2) graphical systems allowing for automation of drawing of basic machine parts (AutoCAD, LogoCAD and others),

3) usage of data bases containing standards, numbers of technical drawings, lists of documentation (technical specifications), lists of spare parts, list of standard parts or parts produced according to catalogues (e.g. bearings, seals, screws, bolts etc.),

4) expert systems aided a design process, allowing for performance of calculations - which suggest the solution to a designer or even solving some partial tasks fully and individually.

In the present paper, an attempt to modern design methodology of size ranges of gears is presented. Own computer system has been prepared. The system incorporates the essential rules which allow for proper design of gears, especially it allows for taking into consideration the following aspects of gear design:

- universal area of usage,
- type-diversification,
- unification,
- standardization.

The goal of the present work has been a preparation of a computer program supporting a routine of a design of modular-segment size ranges of gears. The program should allow for design of combinations of two-, three- and up to (theoretically) six-stage gears. The following types of gears are considered: cylindrical-cylindrical, bevel-cylindrical, cylindrical-bevel, bevel-cylindrical-cylindrical, cylindrical-bevel-cylindrical, cylindrical-cylindrical-cylindrical etc. Moreover, the program uses the modules i.e. data about the afore designed pairs of geared wheels. This program is more universal in comparison to the existed ones because it allows for rapid design of classical as well as modular-segment size range of gears.

An idea of the program is to support a work of an inexperienced designer because it contains a knowledge data base in a form of tables, recommendations, relations, versatile graphical relationships, ultimate values of particular parameters (e.g. ultimate strengths) etc.

Such a program has to posses a reasoning module. A knowledge data base equipped in a reasoning module makes it possible to support the decisions of a user – wanting to solve difficult subproblems (partial problems of gear design). An advanced version of such a program could fully solve a subproblem without further action of dialog with the user. In case of a design of a size range of gears containing up to thirty gear items of stepwise increasing strength parameters and load capacities – it is necessary to work out a special database. The database is used to gather the knowledge i.e. data about gear structure, geometry, kinamatics, dynamics, strength and load capacity etc. The general algorithm of design of a modular size range of cylindrical-bevel gears can be described in the following steps:

1) determination of a layout a size range,
2) initial (design) calculations for:
   a) cylindrical stages,
   b) bevel stages,
3) creations of particular items (designs) of the size range using the prepared modules,
4) verification calculations,
5) drawing of technical documentation.

2. DETERMINATION OF A LAYOUT OF A SIZE RANGE

Determination of a layout (structure) of a size range can be performed in the following manner:
1) Making a list of the basic parameters which a designed gear has to achieve – a customer gives the requirements for an output moment M_{2k} [N m], a rotational speed on an output of the gear n_{2k} [rev/min] and an application coefficient K_A, which is determined by a character of changes of moments on shafts of a motor and a machine. Moreover, the customer can issue demands on the overall dimensions and the total mass of the gear and consequently (what is mutually interconnected) on the costs of the gear.

2) Determination of a number of stages of the gear – assuming a maximal ratio for bevel geared wheels 4,5 (5 for cylindrical ones) and rotational speed of a motor n_1, total ratio is equal to:

$$u_c = \frac{n_1}{n_{2k}},$$

then, the number of stages k of the gear (for bevel geared wheels) can be calculated using the following formula:

$$4{,}5^k \geq u_c$$

and

$$k \geq \frac{\lg u_c}{\lg 4{,}5}.$$

3) Choice of a layout (functional structure) of the gear – it has to be determined whether the input and output shafts are placed parallely or their longitudinal axis create a particular angle. This decision results in the layout detailed solutions i.e. which partial gears will create a final complex gear.

4) Calculation of ratios for particular stages: (total ratio u_c is divided into the ratios for the particular stages $u_{1/2/3/4/5/6}$, taking into account the maximal allowable ratios for different types of geared wheels i.e. for cylindrical geared wheels u_{max} =5,6 and for bevel geared wheels u_{max} =5, respectively. Then, the obtained values of ratios $u_{1/2/3/4/5/6}$ are normalized to

so called normal values u_{nom}, according to the assumed rules.

5) Calculation of input moments and rotational speeds for the gear particular stages – these values are calculated upon the following formulas (where the designation was applied: k –number of stages, x – description of a considered stage):

$$M_{(2x-k)} = \frac{M_{2k}}{\prod_{i=x}^{k} u_i},$$

where: M_{2k} – output moment for the complex gear, u_i – ratios for the particular stages.
Then, input rotational speeds for the particular stages are calculated as follows:

$$n_{(2x-k)} = \frac{n_1}{\prod_{i=1}^{x-1} u_i},$$

whereas the input rotational speed for the first gear n_1 are equal to the rotational speed of the motor.
6) Transfer of data to the adequate computer program modules – final routine in which the above data are written (saved) in the data base. Based upon these data the detailed engineer calculations can be performed for the chosen gear pairs (cylindrical or bevel, respectively) and stages. The verification calculations are performed. In case when several solutions have been obtained – then the calculations can be done for several items from the size range.

3. ALGORITHM OF GEARS DESIGN

3.1. Initial calculation of cylindrical gears

After establishing the structure of the particular items of the size range and a choice of a motor – the basic parameters of the geared wheels for the particular stages can be determined. Aiming for this task, the initial (design) calculations are performed – calculating the gear module and the pitch diameter.
The normal module is calculated based on the formula:

$$m_{n\,obl} \geq \sqrt[3]{\frac{2 \cdot M_1}{z_1^2 \cdot \psi_b} \cdot \frac{Y_{FS} \cdot Y_\varepsilon \cdot Y_\beta \cdot K_v \cdot K_{F\beta} \cdot K_{F\alpha}}{\sigma_{FP}} \cdot \cos^2\beta},$$

where: the needed parameters have to be initially chosen [3].
The pitch diameter is calculated using the formula:

$$d_{1obl} \geq \sqrt[3]{\frac{2 \cdot M_1 \cdot (u+1)(Z_E \cdot Z_H \cdot Z_\varepsilon \cdot Z_B)^2 \cdot K_v \cdot K_{H\alpha} \cdot K_{H\beta}}{\psi_b \cdot u \cdot \sigma_{HP}^2}}.$$

In this case also the needed parameters have to be initially chosen [3].
The calculated value d_{1obl} of the pitch diameter has to fulfill the following condition:

$$d_{1obl} \leq \frac{m_n \cdot z_1}{\cos\beta}$$

In the case if the above condition does not hold then the expert system coupled with the program (for design of modular size ranges of gears) issues the following suggestions (tips, solutions) for a designer:
- change (increase) of pinion teeth number z_1,
- change (increase) of normal module m_n,
- change (increase) of tooth deflection β.

The first action is strongly suggested because it is the easiest one to apply. It has to be checked whether the teeth numbers z_1 and z_2 have the greatest common divisor. If they are undivided then life and silent-running feature increase. Then, based on the initially chosen values of z_1 and z_2, the real ratio u_r is checked. It has to enclose within the limits of the tolerance of the nominal ratio u_{nom}.

An exemplary algorithm of choice of values of parameters z_1 and z_2 is as follows:

- **if** z_1 **and** z_2 (have a common divisor) **then** $z_1 = z_1 + 1$ **and** repeated checking whether they have a common divisor,
- **if** z_1 **and** z_2 (still have a common divisor) **then** ($z_1 = z_1 + 1$ and $z_2 = z_2 + 1$) **and** repeated checking whether they have a common divisor,
- **if** z_1 **and** z_2 (still have a common divisor) **then** ($z_1 = z_1 + 2$ **and** $z_2 = z_2 + 1$) **and** repeated checking whether they have a common divisor,
- **if** z_1 **and** z_2 (still have a common divisor) **then** ($z_1 = z_1 + 2$ **and** $z_2 = z_2 + 2$) **and** repeated checking whether they have a common divisor,
- **if** z_1 **and** z_2 (still have a common divisor) **then** ($z_1 = z_1 + 1$ and $z_2 = z_2 - 1$) **and** repeated checking whether they have a common divisor,
- **if** z_1 **and** z_2 (still have a common divisor) **then** ($z_1 = z_1 + 1$ **and** $z_2 = z_2 - 2$) and repeated checking whether they have a common divisor.

Another important geometrical condition which is checked – using the support via the knowledge data base – is a condition on the distance between shaft axes [3].

If the above formulated conditions are fulfilled the calculations aiming for a determination of the geometrical parameters of geared wheels are performed. Finally, the checking of fatigue strengths of cylindrical wheels – according to the polish standard PN-ISO 6336 – is executed.

3.1. Calculation of bevel gears

There is the following scope of the calculations of bevel gears:
- initial (design) calculations,

- verification of fulfillment of geometrical conditions,
- calculations of geometry of geared wheels,
- calculations for checking the fatigue strength of the geared wheels teeth.

During the initial calculations, the average pitch diameter of bevel pinion is determined using the formula:

$$d_{m1} \geq \sqrt[3]{2M_{H1}\, K_v\, K_{H\beta}\, K_{H\alpha}\, \frac{\sqrt{u^2+1}}{u} \left(\frac{S_{H\min}\, Z_{M-B}\, Z_H\, Z_E\, Z_{LS}\, Z_\beta\, Z_K}{\sigma_{H\lim}\, Z_{NT}\, Z_X\, Z_L\, Z_R\, Z_v\, Z_W} \right)^2}$$

where the needed parameters have to be initially chosen [3].
Additionally, the average normal gear module is calculated based on the following formula:

$$m_{mn} \geq \frac{2 \cdot M_1}{d_{m1} \cdot b} \cdot \frac{S_{F\min}}{\sigma_{F\lim}} \cdot \frac{Y_{Fa} \cdot Y_{Sa} \cdot Y_\varepsilon \cdot Y_K \cdot Y_{LS} \cdot K_A \cdot K_v \cdot K_{F\beta} \cdot K_{F\alpha}}{Y_{ST} \cdot Y_{NT} \cdot Y_{\delta relT} \cdot Y_{RrelT} \cdot Y_X}$$

where the needed parameters have to be also initially chosen [3].
As opposed to the case referring to the cylindrical gears, here only one geometrical condition has to be fulfilled. It is a relationship enclosing number of tooth of the bevel geared pinion and wheel:

$$d_{m1obl} \leq \frac{m_{mn} \cdot z_1}{\cos \beta_m},$$

whereas the real ratio of a bevel geared pair (bevel stage) is equal to:

$$u_1 = \frac{z_2}{z_1}.$$

A process of a choice of the tooth numbers z_1 and z_2 is performed according to the similar algorithm like for the cylindrical wheels.
The calculations checking the fatigue strength of the bevel gears (supported by the expert system) are performed according to the international standard ISO 10300.

4. PROGRAM DESCRIPTION

The computer program was written using the Object Pascal language, in the Delphi Enterprise 6.0 environment. During the operation of the program installation on the particular computer hard disc, the following directories are installed:

- directory Data Base,
- directory Knowledge Base,
- directory Size Ranges of cylindrical and bevel gears as well as of their combinations.

The above mentioned directories enclose the adequate files, respectively. Therefore the directory Size Ranges encloses the modules with description of procedures in programming language Pascal, the main file of the program, graphic files, files of graphical resources (object-oriented technical drawings) as well as other files which arise after a compilation.

5. Conclusions

The worked out computer program and the whole package of the related programs is suitable for design of different combinations of size ranges of cylindrical as well as cylindrical-bevel gears. It can be also used for design of single gears of different types: cylindrical, bevel and cylindrical-bevel ones. The exceptional feature of the system is a linkage with the created data bases. The pairs of geared wheels can be chosen from the data base. Moreover, these pairs have the demanded capacities and ratios – therefore they can be used for creation of modules in the designed size range of gears. The knowledge base allows for an automatic check of the compulsory conditions. The base even suggests the proper ranges of values of important parameters of gears of every considered type. The designer obtained also some tips about particular procedures which has to be applied within the actual phase of the design process.

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