SIMULATION DRIVEN IMPROVEMENT OF WORM GEARSET PERFORMANCE USING VIRTUAL PROTOTYPE

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Abstract. This study aims to present a contemporary approach for improvement of gearset output performance, based on virtual prototype. Powerful advantage of accessing gears parameters in detail at early stage of product development allows saving expenses and time to bring new product to the market by reducing the time for excessive physical prototyping and testing. Moreover, it is possible to quantify important parameters, that could not be measured directly by tests, and thus, to reach optimal design in cases of extreme loading.

Specific focus in this paper is set on a worm gearset, used for safety device in lifting equipment for nuclear power plants. The gear pair works as safety brake, using frictional parameters, typical for worm gearsets. The study is initiated after observed failures on physical prototype and the necessity of design improvement to meet requested performance. Some of the requirements are controversial and a balanced solution of the design parameters set is needed.

Virtual prototype is used to be explored using numerical techniques, especially Finite Element Method. Nonlinear model of contact behaviour is used to increase the accuracy of modeled physics task. An initial design is explored and analysed, which is used as a basis for subsequent improved design development. Both initial and optimal design are compared and analysed. Complete research illustrates a successive implementation of an approach, based on virtual prototyping, for specific gear design development. The main result is measured in saved time for physical prototyping and reaching an optimal solution.

Keywords: Wormset, Nonlinear, Contact, FEA, Virtual Prototype

1. Introduction

Gearsets have been and are subject of various researches as their design leads to a very effective method for transmitting power and rotary motion from the source to its application with or without change of speed or direction. Some empirical approaches are also standardized and are widely used in mechanical engineering. They are commonly based on the comparison of the maximum tooth-root stress with the permissible bending stress. Their determination depends on a number of different coefficients that allow for proper consideration of real working conditions (additional internal and external dynamic forces, contact area of engaging gears, gear material, surface roughness, etc.). Generally, empirics are applicable for conventional usage and could not give sufficient flexibility and accuracy in improving performance of designs that does not conform used standard values. Also, empirics do not give detailed overview of stressed geometry and thus, gives just an abstract view of possible actions for design improvement [1, 5].

Virtual engineering (VE) has emerged as a significant enabler for cost effective management of complex products over their lifecycle. Numerical simulation methods, used widely in VE, are currently well established in the product development processes. Simulation has its major advantage that the cost for a "numerical test" could be significantly lower than for an actual physical test, but the numerical simulation gives also a better understanding of the underlying physics and allows the user to check the influence of specific parameters changes and robustness. The numerical simulations are also very useful in design since they allow the influence of modifications and different parameters to be assessed. Applying virtual prototyping techniques for exploration of specific wormset design gives advantages to optimise the design and to improve its overall performance as to meet certain requirements [4].

This study aims to present an improvement of extremely high loaded worm gearset, used for safety device (brake) in lifting equipment for nuclear power plants. It uses frictional parameters, typical for worm gearsets, to prevent not allowed rotation in cases of damage. Examined gearing is used to hold a load that corresponds to applied torque of 76 kNm. The initial design is based on empirically evaluated geometry parameters and a physical prototype is produced for testing.

Preliminary experiments with an initial design physical prototype lead to failure as it is shown on figure 1. The damage has started by teeth breakage of worm after 44 tests done at gradually increased load from 50 kN·m up to 76 kN·m (maximal required work load).

Observed damages over tested sample requires a must-to-do improvement of design parameters as to avoid breakage, keeping existing interface dimensions of housings and other components same. As the design requirements are controversial, a balanced solution of wormset parameters is needed.

a) Damage over the worm

b) Damage over the worm gear

Figure 1. Failures of physically prototyped and tested sample of the initial wormset design

Identified damages over prototype needs a deep, detailed research, which is possible through applying VE technology. The assessment of all design parameters are performed through virtual prototype, which is explored by numerical techniques, especially Finite Element Method (FEM). Major bottleneck in this study is the nonlinear contact analysis of 3D model, which is required to obtain reliable results for bending and contact behaviour. An initial design is explored and analysed, which is used as a basis for subsequent improved design development [2, 6].

2. Structural simulation of initial design

2.1. Virtual model and its properties

The existing initial design of high loaded worm gearset is modelled in detail and examined to obtain its characteristics of bending and local contact behaviour. Gearset model geometry is shown on figure 2 and consists of the worm, placed between worm gear and a support. The worm gear is presented as a segment, as the rest of the model has no influence over the gearing. Thus, two contact interfaces are presented – inside gearset and between the worm and its support.

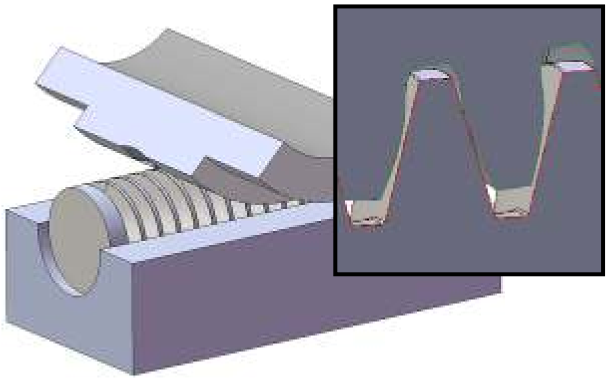


Figure 2. Examined geometry model and section view

Manufacturing technology allows using module value that does not correspond to the standard as well as worming diameter coefficient. These values are based on design geometry and transmitted power requirements. This is also a possibility for output parameters improvement through varying these values.

Major gearing parameters for this initial design are shown also in a separate table.

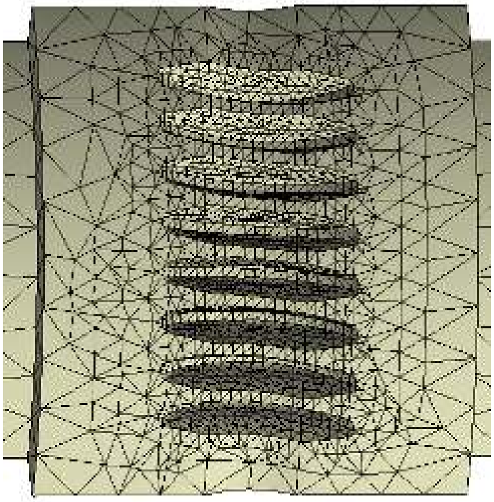
Table 1. Existing initial wormset design parameters

Type of Gearing	ZA
Number of teeth (z_w:z_{wg})	1:45
Pressure angle	15º
Module, m, mm	5.333
Helix angle, γ	4.5º
Center distance, a, mm	154
Worm diameter coefficient, q	12.712
Addendum, a*	1.453
Clearance, c*	0.29
Worm pitch diameter, d_w, mm	68
Worm gear pitch diameter, d_{wg}, mm	240

Used materials are three types of steel – S355 – for the support, 42CrMo4 – for the worm gear and 18CrNiMo6-7 for the worm. Common values for needed simulations properties (elasticity module, Poisson and friction coefficients) are used.

2.2. Simulation model

A 3D meshed structure is built, based on the above described geometry model, using the high order elements with midside nodes as for better shape description. Nonlinear contact elements are generated in common boundaries among structure components – worm/worm gear and worm/support. Meshed structure is shown on figure 3 by components as to present the density of the mesh (more than 1.5 million DOFs) that is needed for better surface stress evaluation.



a) Worm gear component model

b) Worm component model

Figure 3. Simulation model – components

The simulation 3D model is based on steady-state structural analyses, involving nonlinear contacts between the modelled bodies. Contact behaviour is described using frictional mathematical model and particularly – Augmented Lagrangian formulation (a penalty method with additional penetration control) [3, 7]. Usually, it is well applied for frictional contact pairs, as the pressure and frictional stresses are augmented during equilibrium iterations in such a way that the penetration is reduced gradually. The applied boundary conditions are shown in general on figure 4. They represent work loads applied as axial force (corresponds to 76 kNm transmitted torque) over the worm and transmitted by contact to the worm gear. Modelled gearset has contact ratio of 3.7 and two separate load cases are examined – with 3 and with 4 teeth in contact.

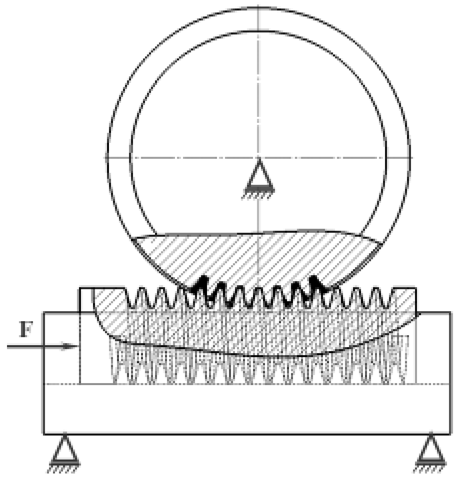
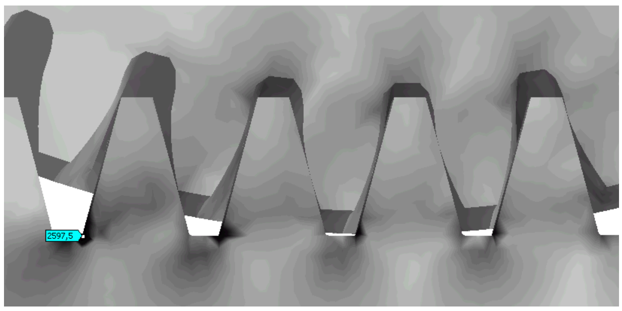


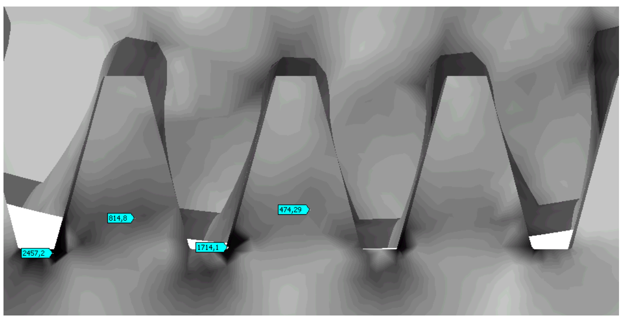
Figure 4. Applied boundary conditions

2.3. Simulation results

Major parameter for design evaluation and future comparison is the equivalent von Mises (second deviatoric stress invariant based) stress yield criterion, suitable for metals. Two measures are tracked – stresses on the contact surfaces (contact stress) and internal (bending) stresses. Equivalent stress distributions and maximal values in characteristic zones are presented in detail – on the sample section view on figure 5.



a) Four teeth in contact



b) Three teeth in contact

Figure 5. Sample equivalent stress distributions for initial design load cases

Obtained results show varying max surface (contact) stresses in interval 1700÷2600 MPa and bending stresses over 800 MPa that definitively will cause breakage (as it is observed over prototyped sample). It could be resumed that major source for failure is the relatively high teeth which leads to bending and damage. Next step is to develop a modified new geometry in direction of decreasing tooth height as to avoid failure.

3. Improved design simulation

A detailed geometry of the improved design have been developed in 3D with next design parameters changed as shown underlined in table 2 below.

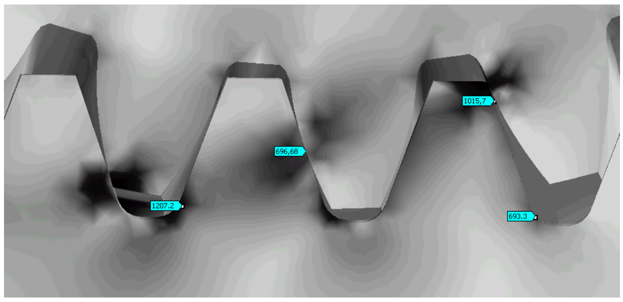
Table 2. Improved wormset design parameters

Type of Gearing	ZA
Number of teeth (z_w:z_{wg})	1:30
Pressure angle	20º
Module, m, mm	8
Helix angle, γ	6.8º
Center distance, a, mm	154
Worm diameter coefficient, q	8.365
Addendum, a*	1
Clearance, c*	0.2
Worm pitch diameter, d_w, mm	68
Worm gear pitch diameter, d_{wg}, mm	240

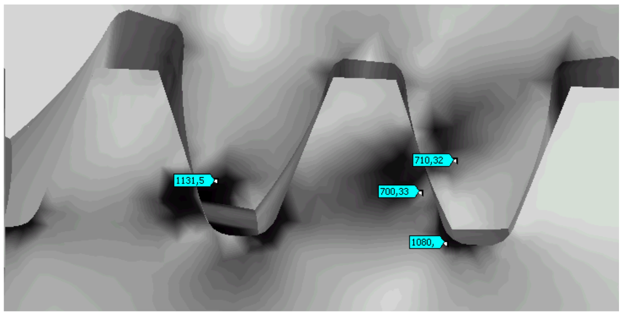
Gear ratio is changed, which is unimportant as the device acts as brake and does not change motion parameters. Other parameters are also changed, keeping two values – for the centre distance and for the outer worm gear diameter – both fixed because of existing moulds and equipment for the casted components. Final design parameters results could be summarized as decreased tooth height and increased tooth thickness, but decreased number of contacting pairs.

New set of two analyses (for both variants of contacting teeth) are performed, using same material properties and boundary conditions. Similar simulation model is built, again using a segment of the worm gear, worm itself and opposite support.

The results are presented again in general on figure 6 below. Newly calculated design shows lower stress values, compared to the original initial one, as the maximal contact stresses reach 1200 MPa, which is allowable compared against material limit. Bending stresses does not exceed the value of 710 MPa, which is lower, but close to material limit. These decreased (compared to original design) stresses are due to the thickened teeth by the increased module and pressure angle.



a) Three teeth in contact



b) Two teeth in contact

Figure 6. Sample equivalent stress distributions for improved design load cases

4. Improvement results analysis

Final review of the achieved results is performed through a comparison over obtained results for the initial existing design versus the improved one. This comparison is conducted again using equivalent stresses as parameter – surface (contact) values and bending values. These parameters are shown separately for the worm and for the worm gear as to show more detailed obtained results. Graphically, it is depicted on figure 7 below.

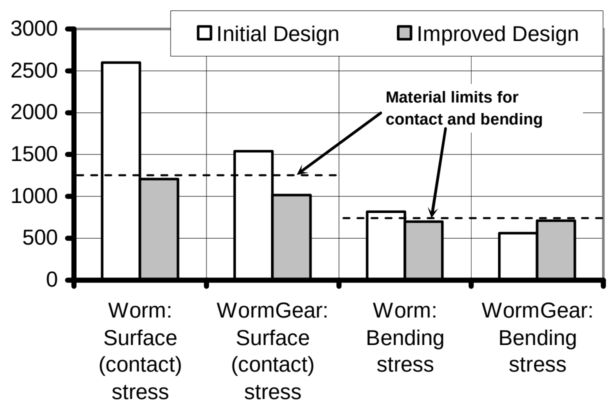


Figure 7. Output parameters comparison between initial existing and improved designs

Two major achievements are outlined:

- Redistributed and equalized stresses between both components in gearing pair – worm and worm gear – for the improved design;
- Maximal stress values decreased to reach values less than required material limits.

It is important to note once again that this improvement is achieved without modifying any existing complex casted parts. This decreases the overall cost of modification.

5. Conclusions

A successive implementation of an approach, based on virtual prototyping, for specific gear design development is demonstrated through the presented paper. The work is connected to an industrial project, where issues during physical prototype testing are emerged. Performed improvement is a good demonstration of one of the features of VE approach – the ability to research in detail reasons and cause for certain failure.

Another point is the possibility for multiple design variants assessment without producing time and resource consuming physical prototypes. In fact, the reported in this article improved design is a consequence of a set of tested through virtual simulations variants. Virtual prototyping approach results directly in an effective solution, that is reached relatively fast in time if compared to traditional approach that involves physical testing. Additional gain is the understanding of the nature of failure and directions for improvement, which is obtained through virtual prototype assessment.

Proposed approach is conductive to the designer as to evaluate design at various stage of PDP, to compare and to find optimal solution among concurrent designs, on a very cheap price (time) – i.e. speed up product development and decrease its cost. Its applicability is proven for the examined gearset. It is a family member of several safety devices for crane equipment, used in special applications as power plants. Thus, future work in the direction of design improvement would include revision and optimisation of existing already in production ones.

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