Analysis of gear reducer housing using the finite element method

I Zs Miklos, C C Miklos, C I Alic and S Rațiu
Politehnica University of Timisoara, Department of Engineering and Management, 5 Revolution Street, Hunedoara, 331128, Romania
E-mail: imre.miklos@upt.ro

Abstract. The housing is an important component in the construction of gear reducers, having the role of fixing the relative position of the shafts and toothed wheels. At the same time, the housing takes over, via the bearings, the shaft loads resulting when the toothed wheel is engaging another toothed mechanism (i.e. power transmission through belts or chains), and conveys them to the foundation on which it is anchored. In this regard, in order to ensure the most accurate gearing, a high stiffness of the housing is required. In this paper, we present the computer-aided 3D modelling of the housing (in cast version) of a single stage cylindrical gear reducer, using the Autodesk Inventor Professional software, on the principle of constructive sizing. For the housing resistance calculation, we carried out an analysis using the Autodesk Simulation Mechanical software to apply the finite element method, based on the actual loads, as well as a comparative study of the stress and strain distribution, for several tightening values of the retaining bolts that secure the cover and the foundation housing.

1. Introduction
The gear reducers are the most common mechanical systems used to change the motion input parameters, usually provided with an AC asynchronous electric motor for reducing the speed, at the same time with the increase of the output twisting moment, in accordance with its speed transmission ratio. The toothed wheel gear reducers have the advantage of a constant transmission ratio, they have a high yield and their maintenance is easy and cheap [1].

The fixed axle toothed wheel gear reducers may have one or more stages, being equipped with cylindrical gears (with parallel axes), conical gears (with concurrent axes), worm gears (with cross axes) or with a combination of conical toothed wheels and worm gears with toothed wheels, for obtaining high transmission ratios [1].

In practice, there are also gears with conventional cylindrical or conical toothed wheels with mobile axes, known as planetary or differential, which have the advantage of a high transmission ratio under a reduced gauge size [1].

Regardless of the construction type, the gear reducers with toothed wheels have housing.

The housing is an important part of the reducer, which has the role of ensuring the relative position of the shafts and, implicitly, of the toothed wheels. At the same time, the housing takes over, via the roller bearings, the loads of the shafts resulting from gearing, and conveys them to the foundation on which it is anchored. In this regard, in order to ensure the most accurate gearing, a high stiffness of the housing is required. For easy assembly of the shafts, toothed wheels and bearings, the housing is made of two pieces: the lower housing (housing body) and upper housing (housing cover) [2].
The housing can be manufactured in welded construction, using steel sheet, for the unique and small series products, or by casting, for the large series products; in this case, the conditions imposed by the casting technology and processing economy must be observed [2]:

- Achieving a wall thickness as uniform as possible by avoiding any clumps of material; to increase the strength and rigidity, it is recommended to use ribs;
- Ensuring a minimum thickness of the walls imposed by the casting technology and the nature of the housing material;
- Gradual passing from a slightly thicker wall to a thinner one, for reducing the residual stresses after casting;
- Ensuring sufficiently large radii and wall inclination (for easy release of the model out from the mould);
- Limiting the machined surfaces to the minimum necessary by making elevations (embossments) or dents (spotfaces) for the bearing surfaces of the nuts, bolts, covers, threaded plugs, etc.

In case of welded housings, it is necessary to observe some conditions related to the welding technology [2]:

- Using easily weldable materials;
- Ensuring accessibility for the execution of welding seams;
- Choosing constructive shapes suitable for welding automation;
- Making a symmetrical construction to reduce the internal stresses and not to deform the housing;
- The thickness of the walls must be smaller than at the cast housings, but not too small for preventing their burning during welding;
- Stiffening the housings with ribs;
- De-stressing the housings before machining.

The cover is fastened to the gear housing by means of threaded assemblies (bolts and nuts), and the housing is mounted on the foundation by means of anchor bolts. An important role in the housing resistance is played by the axial forces in the bolt stems, resulting from their tightening.

2. Housing modelling

2.1. Gear reducer designing

The gear reducer designing and, therefore, the 3D modelling of the housing, were carried out by using Autodesk Inventor Professional software.

The Autodesk Inventor products provides engineers and designers professional grade design and engineering solution for 3D mechanical design, simulation, visualization, and documentation. With Inventor software, engineers can integrate 2D and 3D data into a single design environment, creating a virtual representation of the final product that enables them to validate the form, fit, and function of the product before it is ever built. Autodesk Inventor includes powerful parametric, direct edit and freeform modelling tools as well as multi-CAD translation capabilities and industry standard DWG drawings. Inventor software helps you connect more effectively, reduce errors, and deliver great product designs faster [3].

Autodesk Inventor is built for the continually evolving needs of the modern design and engineering professional.

Building on its breadth of modelling capabilities and powerful design automation tools, Autodesk Inventor 2018 marks the next step forward in professional-grade 3D mechanical engineering design. Interoperability enhancements enable distributed, multi-disciplinary teams to work together more efficiently with data from a variety of sources. The overall user experience is enhanced for more productivity and flexibility in response to direct feedback from customers around the world [3-4].

The computer-aided designing of the gear reducer was realised based on the specific input parameters, i.e. the transmitted power (P = 10 kW); input speed (n1 = 600 rot/min); transmission ratio (i = 2,50); inclination angle of the teeth (β = 10 degrees) and the required distance between axes (A = 180 mm).
The modelling and designing of the gear reducer components (gear, shafts, bearings, fasteners and seals, etc.) were carried out using the specific tools of the Design Module, their assembly being made by properly applying the assembly constraints. Figure 1 shows the 3D model of the gear reducer, in a simplified version, by omitting some elements such as: bearing covers, aperture cover, oil drain plug, retaining bolts, etc.

![Figure 1. The 3D model of the gear reducer](image)

2.2. Constructive sizing of the housing

When designing mechanical transmissions with toothed wheels, gear reducers, gearboxes, etc., the housing sizing is usually based on constructive relationships [5].

Thus, the thickness of the housing walls, the thickness and width of the foundation fastening shoes, cover retaining bolts and foundation retaining bolts are chosen either from tables or according to the gear size (generally given by its module) [5].

At the constructive designing of the housings, the shape and dimensions of the cooling ribs are at the discretion of the designer, without taking too much into account the strains, temperatures and their distribution in the housing walls [5].

The choice of the constructional shape of the gear housings is of particular importance, knowing that the connections, the holes for retaining bolts (in quite large number), etc., are stress concentration factors that must be also taken into account in designing [5], [6].

The anchoring of the housing and housing cover to the foundation was made using M8 bolt and nut assemblies and, respectively, M8 anchor bolts. In both cases, the threaded assemblies have been subjected to an initial tightening, which produced an axial force in the threaded rods, these ones being subjected to tensile stress.

Figure 2 shows the 3D model of the housing (with retaining bolts), obtained on the basis of the constructive sizing made by using the Autodesk Inventor Professional software.
3. Analysis of gear reducer housing using the finite element method

The finite element method is used for studying the state of stresses and strains of the resistance structures of high geometric complexity, for which the calculation is made easier if the whole is divided into simpler areas [7-9].

The finite element method is a mathematical method of numerical integration of partial differential equations put in variational form. This means that all the computational problems of the elastic structures will be reduced to a system of partial differential equations, which usually cannot be solved analytically. In this respect, the assessments of the stress states in the housing walls, i.e. the sizing and verification calculations based on classical methods are quite difficult to apply to complex housings [7-9].

With the development and spreading of numerical computers and computer-aided design software packages, the problems outlined above can be solved much easier, the MEF analysis of the 3D model being solved by means of dedicated software applications, or implemented in the computer-aided design software [7-9].

For this purpose, to apply the finite element method for carrying out the housing analysis, we used the Simulation Mechanical software, an integral part of Autodesk Inventor Professional software, thus eliminating the possible geometric errors that may occur when importing the 3D model of the housing.

Because the Simulation Mechanical software enables the modelling of bolt-nut assemblies as “threaded connections”, we considered a simplified 3D model of the housing for carrying out the analysis, by removing the real threaded connections (Figure 2). The simplified 3D model can be seen in Figure 3.

In order to carry out the housing analysis using the finite element method, we went through the following specific steps:
- Model digitization;
- Material selection (grey cast iron for housing and cover, concrete for foundation);
- Defining a surface contact for the 3D model elements;
- Establishing the boundary conditions, i.e. embedding on the lower surface of the foundation;
Figure 3. The simplified 3D model of the gear reducer housing

The modelling of “threaded connections” (Figure 4) was made by specifying the thread size (M8), the diameter of the bolt head and the nut, their holding surfaces, the internal surfaces of the bolt holes and the axial force in the bolt stem resulting from its initial tightening:

Figure 4. Modelling of the “threaded connections”

Load definition. In addition to the axial forces in the bolt stems caused by their initial tightening (defined as shown in Figure 4), we took into account the reactions in the holders of the two gear reducer shafts obtained by designing. The values of these reactions corresponding to the hinge-type holder (fixed) and plain holder (free), as two radial forces acting in the vertical plane (along the Y-axis) and in the horizontal plane (along the X-axis), and, respectively, as axial force, are shown in the Tables 1 and 2.
Table 1. Reactions in the 1\textsuperscript{st} shaft holders

| Index | Type | Reaction force | Axial Force (N) |
|-------|------|----------------|-----------------|
| 1     | Free | 29 N           | 1124 N          |
| 2     | Fixed| 1282 N         | 1972 N          | 546 N           |

Table 2. Reactions in the 2\textsuperscript{nd} shaft holders

| Index | Type | Reaction Force | Axial Force (N) |
|-------|------|----------------|-----------------|
| 1     | Free | 1987 N         | -1923 N         |
| 2     | Fixed| 1151 N         | 661 N           | -546 N          |

These loads are defined by selecting the Bearing Load option in the symmetry axes of the bearings, as shown in the Figure 5 for the radial force in horizontal plane (along the X-axis) and, respectively, as shown in the Figure 6 for the radial force in vertical plane (along the Y-axis) and axial force.

Figure 5. Defining the radial load in horizontal plane (X-axis)

Figure 6. Defining the radial load in vertical plane (Y-axis) and axial load (Z-axis)

The 3D model of the housing, prepared for conducting the analysis according to the steps described above, can be seen in Figure 7.
The housing analysis using the finite element method was carried out for three distinct values of the initial tightening forces for the retaining bolts of the housing cover (F1) and, respectively, for the retaining bolts for anchoring the housing on the foundation (F2), according to Table 3.

**Table 3. Values of the tightening forces for the three variants of analysis**

| Variant | F₁ (N) | F₂ (N) |
|---------|--------|--------|
| Variant 1 | 600    | 800    |
| Variant 2 | 1200   | 1500   |
| Variant 3 | 2500   | 3000   |

After performing the analyses, the results are displayed and interpreted, i.e. the nodal displacements and von Mises stress state, using the geometric model elements as shown in the Figures 8-9 for the 1st variant, Figures 10-11 for the 2nd variant, and Figures 12-13 for the 3rd variant of analysis.

It was found that, for the three variants of analysis, the stresses had maximum values (29, 31, 41 MPa) in the area of the holes made for retaining bolts, but below the permissible limits afferent to the materials used, the displacements being also small, i.e. amounting some hundredths of mm.

In the 3rd variant of analysis, the stress state in the threaded assembly elements is shown in Figure 14, where it can be seen that the mostly stressed bolts are the retaining bolts of the housing cover, next to the roller bearings, the stress value being also below the permissible limit (56 MPa).
4. Conclusions
By applying the finite element method to analyse a gear reducer housing, we studied the influence of the retaining bolts tightening force magnitude on the stress state and nodal displacements of the housing, for the specified input parameters. It has been found that, by increasing successively the tightening forces, the nodal displacements had a very low decrease (approx. 0.001 mm), while the equivalent stress (von Mises) had a significant increase, but within the allowable stress limits of the materials from which the component elements are made.

The maximum stresses in the housing and the housing cover occur in the bolted connection areas, but in the remaining areas these stresses do not exceed 10 MPa.

The stresses in the bolted connections are also within acceptable limits.

References
[1] Crudu I, Ştefănescu I, Paşcuru D and Palaghian L 1981 Atlas Reductoare cu roţi dinţate, Editura Didactică şi Pedagogică, Bucureşti, România
[2] Muşat M and Stoica G 2003 Transmisii Meccanice cu reductoare într-o treaptă (Îndrumar de proiectare), Editura Printech, Bucureşti, România
[3] ***www.autodesk.com
[4] Dolga L, Revencu M, Maci C A and Giuchici M 2004 Parametric and feature based modelling with applications in Catia and Inventor, Editura Politehnica, Timișoara, România
[5] Miklos I Z, Cioată V G and Miklos I 2002 Modelarea carcasei unui reductor cu ajutorul programului Mechanical Desktop, Simpozionul naţional cu participare internaţională Proiectarea Asistată de Calculator, Prasic’02, Vol. III, Braşov, România, Noiembrie 7-8, pp 245-248
[6] Davis M, Mohammed Y S, Elmustafa A A, Martin P F and Ritinski C 2009 Designing for Static and Dynamic Loading of a Gear Reducer Housing with FEA, American Gear Manufacturers Association, Technical Resources

[7] Spyrokos C Ch 1994 Finite element modeling in engineering practice, Morgantown, W. Va. West Virginia University Press

[8] Cioată V G and Kiss I 2017 Dynamic analysis and parametric optimisation of the connecting rod using Autodesk Inventor, Machine Design 9(1) 29-34

[9] Cioată V G 2008 Determining the machining error due to workpiece--fixture system deformation using the finite element method, Annals of DAAAM & Proceedings of the 19th International DAAAM Symposium, Trnava, Slovakia, October 22-25, pp 253-255