Constructional design of the body shape of large gear wheels

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Abstract. The development of modern machines and means of production is characterized by ever-increasing performance parameters with decreasing equipment weight. When designing large gears, it is also necessary to consider the influence of the body shape of the gear wheel. The body shape of gear wheel must meet the basic requirements of stiffness and strength with the lightest possible construction of the gear wheel body. The work is focused on large gears, made with relief. Such gears can be forged, cast, or made by welding. The shape of the gear wheel body depends on several factors such as the size of the wheel, the material, the method of manufacture or use. The paper provides an overview of the body shapes used by large spur gears. These body shapes of spur gears will be the subject of further research, where suitability will be assessed based on stiffness of teeth and wheel weight.

1. Introduction
Wang in his work aimed at gear wheels volume reduction using Matlab simulation, achieved a total of 25.2% mass reduction and 11.42% power loss of the optimized transmission. The optimization was carried out from solid structure gear bodies to combination of web-type structure, with cross shape type structure and the biggest gear wheel was optimized to H-shape gear wheel structure [1]. Monkova et al. carried out a research about change of natural frequencies in gear wheel reduction. In this research the four gear wheels were made where, one had solid body and next three had ribbed body with same count of ribs but different rib width. Modal analysis proved that natural frequencies increase slowly at low natural modes than in high natural modes [2,3]. Heiselbetz et al. performed a weight optimization of a gear wheel taking into account manufacturing process and cyclic symmetry. Study performed a body optimization of a non-reduced gear wheel, where areas of the lowest stresses were cut out. The resulted shape then had to be modified for the easiest manufacturing. The final optimized gear wheel had its mass reduced by 25% of the whole gear wheel [4]. Xu Jin et al. work was to design a ball mill gear wheel. This wheel was designed for smaller radius than originally gear wheel. Yet the body shape of the mill gear wheel was designed to be light weighted using profiled web connected to outer gearing ring with holes in thicker width for connection to ball mill [5,6]. Sayama et al. in their work concluded a research of different types of gear wheel shapes on vibration. The designed and investigated shapes were weld structure, asymmetric welded gear, solid structure gear, and double web gear. The conclusions were that for a welded structure gear the vibration accelerations were smaller than the radial and axial ones, but larger for solid structure gear, smallest value of vibration acceleration were for the asymmetric welded gear, biggest acceleration vibrations had a double web gear [7,8]. Naveen et al. carried a research aimed at thin-walled structures of gear wheels. For the experiment there were designed three gears, one with thick symmetrical web, one with thin asymmetrical web and the last one was thin symmetrical web. The
result of the research was that with lowering a web and rim thickness the strength of the structure decreases [9]. Marunic performed an analysis of thin asymmetric thin rimmed gear. Conclusion of this research was that maxim stress is located at the rim and web joint. This stress is at maximum for the thinnest rim regarding the web thickness. But for the thicker rim, the maximum stress was increasing with thinner web [10,11]. Zhao et al. made a structural optimization of a double web herringbone gear. This gear was optimized by adding a material to the existed web structures and slightly tilt them. The volume of this gear increased by 5.3%, but maximal stress in the gear decreased by 11.9% [12].

2. Welded gear wheels
Gears of smaller dimensions can be made as welded in an easiest way possible. Such gear wheels have the shape of a disc. The extension of the hub is achieved by welding the ring to the disc, or by sliding the pipe hub into the hole of the disc (Figure 1).

3. Large welded gear wheels
Larger welded gear wheels rims are constructed from flat steel. The ends are welded with a butt weld, which must be located in the bottom land of two neighbouring teeth (Figure 2). The rim is connected to the hub either by one square plate and with the ribs (Figure 3) or by means of two square plates (Figure 4). The hub, plate and ribs are made from well-weldable steels. The rim is made of steel with better mechanical properties.
Figure 3. Welded gear with square plate and ribs.

Figure 4. Welded gear with square plates.

For larger wheels, it is common to use a circular plate, reinforced with ribs (Figure 5) or it can also be used without ribs (Figure 6). The hub can be made of cast steel and welded to the plate according to Figure 7.
The advantage of welded gears is the reduction of weight, the production of an expensive model is eliminated, the production time is shortened, and the price of the product is reduced. Welding is generally economically applicable to a smaller number of products. However, the final treatment must follow after complete welding process.
Figure 8. Welded gear wheel – dimensions.

Figure 8 shows an example of a welded gear wheel design. Dimensions can be designed according to empirical relations:

- **Hub diameter**
  \[ d_1 = 1.6 \cdot d_0 \] (1)
  \[ d'_1 = d_1 + 10 \text{mm} \] (2)

- **Inner rim diameter**
  \[ d_2 = d_h - 10 \cdot m \] (3)
  \[ d'_2 = d_1 - 10 \text{mm} \] (4)

- **Where** \( m \) is modulus
  \[ d_3 = 0.5 \cdot (d_2 + d_1) \] (5)

- **Holes pitch diameter**
  \[ s = 0.4 \cdot d_0 \] (6)

- **Plate thickness**
  \[ s = 0.8 \cdot s \] (7)

- **Rib thickness**
  \[ t_1 = 0.1 \cdot d_0 \] (8)

- **Weld dimensions**
  \[ t_2 = 0.02 \cdot d_0 \] (9)
4. Large forged gear wheels

Figure 9. Forged gear wheel – dimensions.

Empirical relations for designing the dimensions of forged gears according to head circle diameters $d_h \leq 500$ mm (Figure 9)

- **Shaft diameter**
  \[ d = 0.32 \cdot a \]

- **Hub diameter**
  \[ d_i = 1.6 \cdot d \]

- **Inner rim diameter**
  \[ d_2 = d_h - 10 \cdot m \]

- **Holes pitch diameter**
  \[ d_3 = 0.5 \cdot (d_2 + d_i) \]

- **Holes diameter**
  \[ d_4 = 0.25 \cdot (d_2 - d_i) \]

- **Plate thickness**
  \[ c = 0.32 \cdot b \]

- **Chamfer of the gearing**
  \[ n = 0.5 \cdot m \]

- **Radius**
  \[ r = 5 \text{ to } 10 \text{ mm} \]

Forged wheels require machining of the entire surface. For large series, the wheels are forged in dies. Examples of the design of die forging of gear wheels are on (Figure 10).
Figure 10. Die forged gear wheel.

An example of a cast iron or cast steel gear wheel design is shown in Figure 11. The main dimensions of the rim, arms and hub are determined.

Figure 11. Casted gear wheel.
5. Assembled gear wheels

Due to the savings in the usage of the quality material for gearing and the possibility of replacing the worn rim, it is advised to make them assembled. The rim is pressed onto the wheel body, most often from cast iron, which creates a whole gear wheel. The rim is often secured with bolts to secure its connection to the gear body. At Figure 12 is shown a gear wheel with a cast iron body and a steel rim. The following relations are empirically obtained for the calculation of the main dimensions, given $D_h = 500 – 2500$ mm, $b < 160$ mm

\[
\delta_r = \frac{a}{z_1 + z_2} \left[ 3 + 2 \cdot \frac{b}{a} + 0.01 \cdot \left( z_1 + z_2 \right) \cdot \left( \frac{z_1 \cdot z_2}{100} \right)^{1/3} \right]
\]  

(18)

Thickness of gear rim

\[
e = \left( 1 + 0.5 \cdot \frac{b}{a} \right) \cdot \delta_r
\]

(19)

Rim thickness

Where $a$ is center distance

Bolt diameter $d_0 = 0.5 \cdot \delta_r$  

(20)

Thickness of the side rib $g = 0.75 \cdot c$  

(21)

Rib width $h_i = 0.8 \cdot h$  

(22)

The shape of the arms is chosen:

If the ratio is $\frac{b}{\sqrt{e}} \leq 35$ , then the arms are chosen as a cross-shaped or as a t-shaped

If the ratio is $\frac{b}{\sqrt{e}} \geq 35$ then the arms are chosen as an I-shaped

Number of arm is chosen from the table 1 given the $X$ value:

Ratio for $X$ is $\frac{d_h}{m^{1/3}} \leq X$

| Value of $X$ | 299 | 399 | 799 | 1499 |
|-------------|-----|-----|-----|------|
| Number of arms | 4   | 5   | 6   | 8    |

Table 1. Number of arms to value X
6. Body shape of cast spur gears - case study

Spur gears with the following gearing parameters were examined: number of teeth \( z = 71 \), the normalized value of the modulus \( m_n = 7 \text{ mm} \), and a gear width of \( b = 150 \text{ mm} \). The load on the teeth of the spur involute gear has a continuous character. The value of width load was \( w = 100 \text{ N/mm} \). Tooth stiffness was determined on basis of tooth deformation. Maximum deformations were investigated when the load acted on the tooth addendum. Gear deformation is determined by using the finite element method. Figure 13 shows the investigated shapes of the bodies of large cast spur gears.
Figure 13. Variants of cast spur gears.

Figure 14 is a comparison of the effect of weight loss on gear stiffness for cast spur gears. Wheel B4 was chosen as a wheel with zero mass loss, because its weight was the largest of the proposed models. However, the B4 wheel weighed 50.5% less than a full solid-body gear wheel.

From Figure 14 it was determined that the gearing stiffness decreased with an increase in material loss. The exception was the B3 wheel due to its shape. Gear wheels B1 and B3 had the highest mass reduction, but their gear stiffnesses were smaller compared to wheels B2 and B4. The wheels B2 and B4 had almost the same amount of gear stiffness, but the wheel B2 had a greater mass reduction, which was more advantageous in terms of weight. Due to its having the highest gear stiffness and a relatively good weight, wheel B2 is the most advantageous.

7. Conclusion
Designs of large gear wheels are impacted by the requirements given to the constructors. One of these requirements is to design the gear wheel with enough stiffness of the gearing and reduce the overall mass of the gear wheel. Such reduction of the mass with retention of the stiffness means, that the only way is to change the gear geometry. Change in geometry of the gear wheel is mostly defined by experiments and thus the formulas are empirical.
Another possible requirement is a tendency to lower the machining expenses. This trend can be influenced by the gear wheel dimensions, manufacturing machines capabilities and number of gear wheels produced. As stated previously, the of stiffness of the gearing is considered as a must, therefore empirically gained knowledge of the minimum possible dimensions of the most critical parts or sections great tool to speed up a design process.

The body shapes of the spur gears described in the paper will be the subject of further research, where the suitability will be assessed on the basis of tooth stiffness and wheel weight.

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