Reduction of Gearing Pressure Pulsations and Noise Level in Gear Pumps using Non-standard Gearings and FEA Analysis

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Abstract: In industry all over the world there is a need to make gear pumps (which are included in many industry units and machines) more silent and without unnecessary noise and pulsations they producing. Main part of the gear pump noise is caused by meshing gearing while rotating in the pump (causing fluid transport) in discontinuous run and causing pressure pulsations. This article reveals approaches leading to lower noise level using transformation of gears such as asymmetric gearing or continuous contact gearing, which both providing different tension scatter and reduce level of tension in stressed areas of the tooth. In this article are also mentioned some of the tools which can analyze gear noise using FEA and analyze pulsations in numerical models.

Keywords: asymmetric gearing; continuous contact gearing; mechanical analysis; gear meshing; silent gear pump.

1 Introduction

Gear pumps [1] use rotating gearing with two same gears to transport working fluid in gear space from the inlet to the outlet. So the work is not continuous which results into pressure pulsations between co-occupying teeth. These pulsations are the main source of noise radiating from the gear pump. Reducing pulsations with standard solutions such as increase of number of teeth, bigger pressure angel or helical gears does not have satisfying results because of the limitations of standard involute gears.

Asymmetric gears provide possibility to gain number of teeth and pressure angle to the satisfying level without losing its load capacity. There is also a possibility to use non-involute gearing, such as continuous contact gearing which provides very different tension in the tooth and nearly zero pulsations.

New development experiments for verification of the design modifications can be expensive and take a lot of time. There are programs such as EgeMATor or HYGESim which can simulate these experiments and help with further optimalizations. Gear noise can be also analyzed with FEA. Tension results can be transformed thanks to the Euler-Lagrange analysis to have noise level results.

2 Standard solutions

Standard solutions to prevent from pulsations and noise are increase of teeth on each gear, increase the value of a pressure angle and using helical gear. Unfortunately, it is not enough for desired noise reduction. It is possible to see how big the decrease of noise level is when standard solution is used in [2], where a modification for a wheel loader was made.

The article reveals a difference where gear pump (originally with nine-teeth gearing) was transformed to gear pump with twelve-teeth gearing. According to the measurement original level of noise was 87.6 dB. After an increase of number of teeth, new value was demonstrably lower by 1.7 dB to the value of 85.9 dB. Decrease of level of meshing pressure was also proven. For twelve-teeth gearing was value lower by 30%.

Interesting solution came from Jihostroj Velešín company called T3T [3]. Design of a gearing can be seen in Fig. 1. Gear width was divided into tree parts, where axis of each tooth is shifted by 30°. Thanks to this

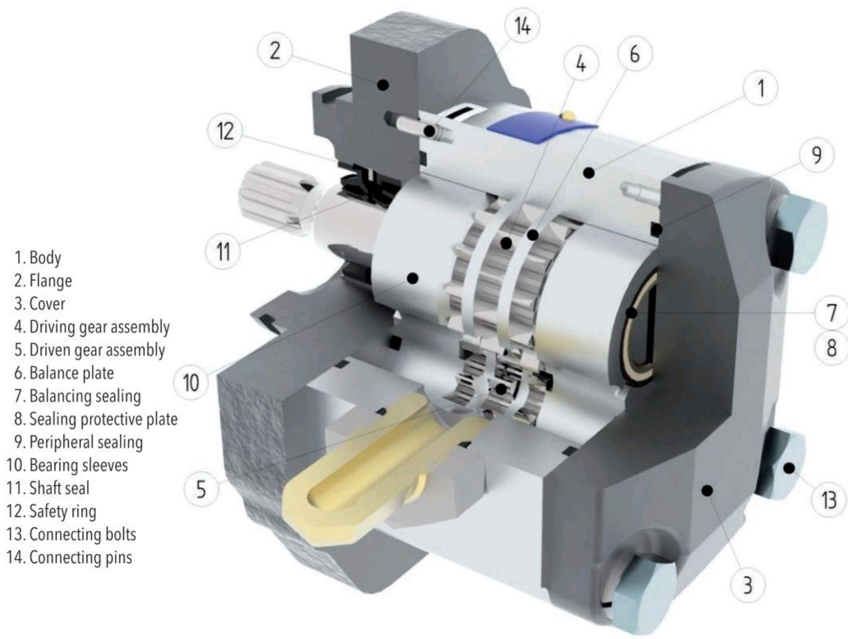

Fig. 1: Gear Pump Jihostroj T3T – lower pulsations [3].

the output flow goes more smoothly from the pump – exactly one third after another compared to the standard gearing. So, the pressure pulsations are partly eliminated. They have higher frequency but on the other hand much lower amplitude.

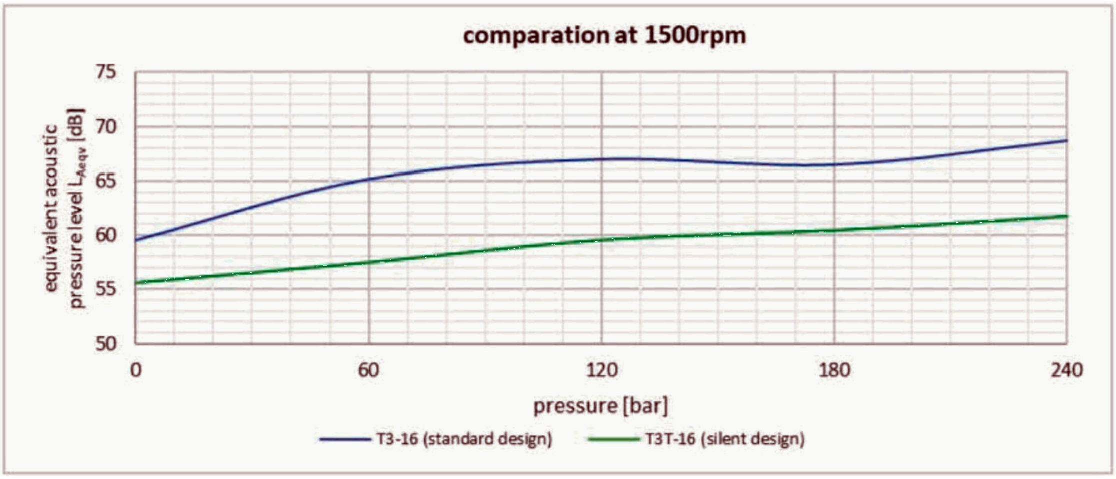

Fig. 2: Gear pump T3T noise reduction [3].

The result is noise reduction. In Fig. 2. there can be seen course of acoustic pressure in dB and output pressure from the pump, where there is clearly demonstrated a noise reduction roughly by 7 dB.

3 Asymmetric gearing

Increase of number of teeth on the gear leads to thinner teeth and so to the decrease of load capacity of each tooth. Asymmetric gearing is normally used to increase load capacity in applications where greater torque is needed (so a higher load capacity in dedendum of each tooth is provided). The main idea of using asymmetric gearing in gear pumps is to remain on the same level of load capacity (as it is on standard pump gearings) while increasing a number of teeth [4]. So, when number of teeth is increased, width of tooth dedendum is decreased. This decrease needs to be compensated to stay on the same level of load capacity per tooth. One of the solutions is asymmetric gearing which has different pressure angle on the working (meshing) side and cost side of the tooth.

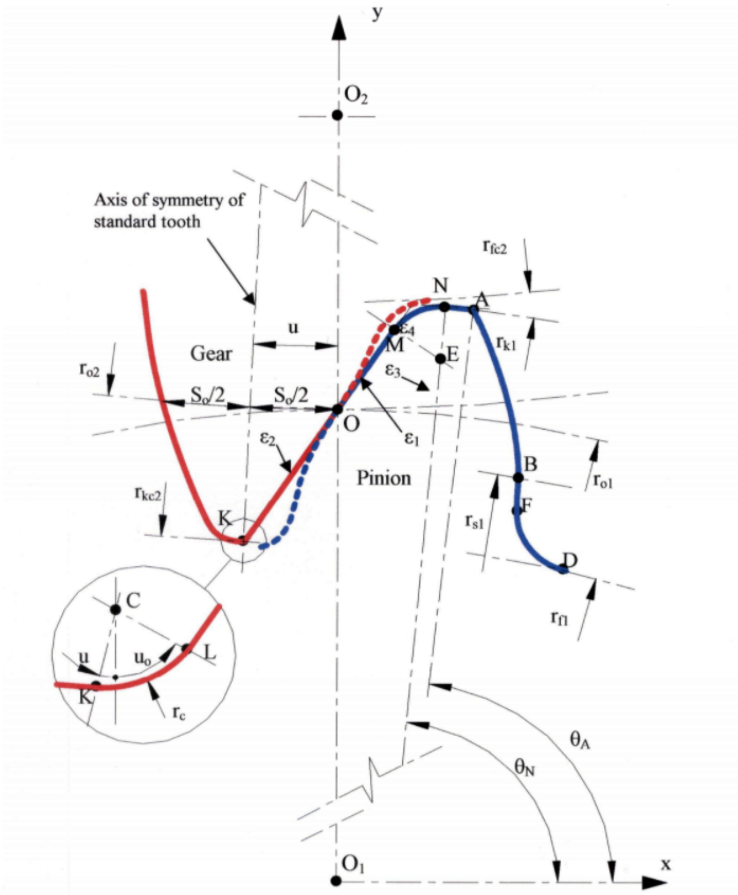

Fig. 3: Asymmetric gear geometry [4].

The level of asymmetry is expressed as k. For the gearing running clockwise and also anti-clockwise the asymmetry is not really great and the value of k is near 1. Tooth asymmetry leads to the different tension in tooth dedendum, which can be seen in Fig. 3.

About modification from standard to asymmetric gearing and their comparison is written for example in Optimized asymmetric gear tooth design [4]. There is a description of a modification to asymmetric gearing with standard pressure angle (20°) on meshing side of the tooth and a calculation which changes pressure angle on a coast side. The aim is to narrow width of an addendum and extend the width of a dedendum of a tooth.

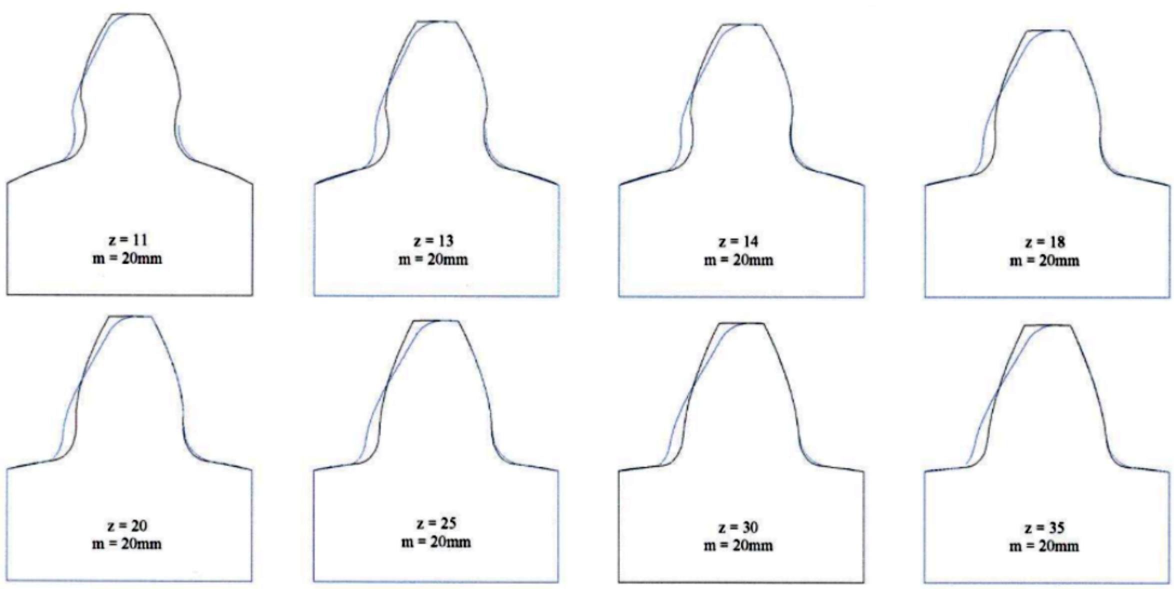

Fig. 4: Standard and asymmetric teeth comparison [4].

According to [5] for decrease of a bending tension in a tooth there should be small value of pressure angle on a meshing side. On the other hand, for decrease of meshing pressure, noise and vibrations there is a need to have bigger value of a pressure angle.

One of the advantages of asymmetric gearing in comparison to unconventional gearing is using standard production tools, assuming production of a gear is via cutting tools. In Fig. 4 there can be seen comparison of standard and asymmetric teeth for the same number of teeth in a gear and the same module.

The asymmetry causes changes in scatter tension in a tooth, which is shown in Fig. 5 with FEA analysis. It is clear, the areas of high tension are smaller in asymmetrical tooth, visual difference is best seen in dedendum of coast side of the tooth.

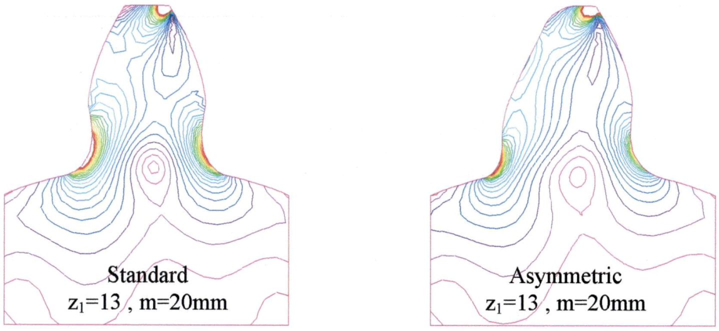

Fig. 5: Von-Misses stresses obtained by FEA [4].

Percentage decrease of maximum values of tension with asymmetric gears is available to see in next Fig. 6, where it is also described the reduction of tension is different for each number of teeth in a gear. The lower the number of teeth, the higher tension reduction.

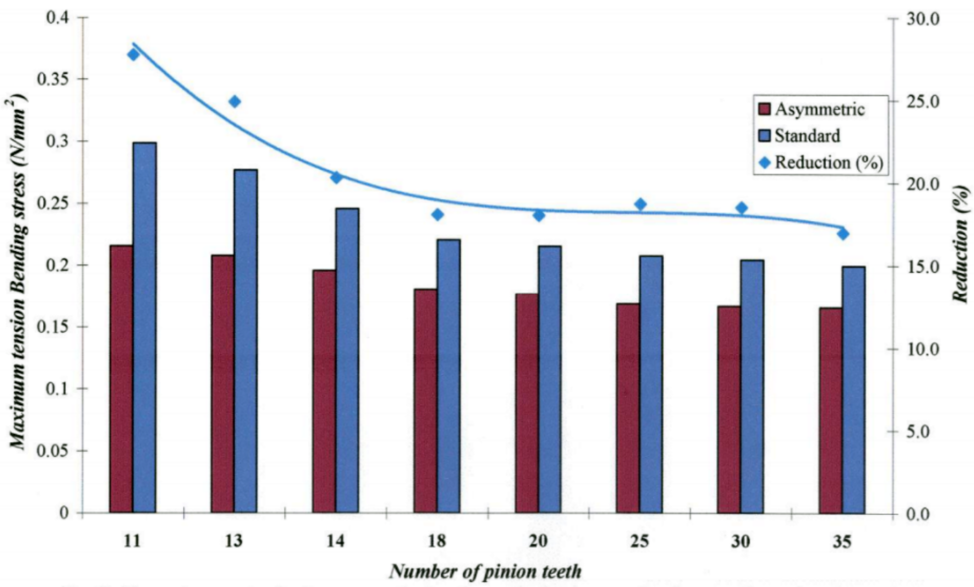

Fig. 6: Comparison of tension in a tooth [4].

So, thanks to using asymmetric gearing it is possible to stay on the same load capacity of a tooth while increase of number of teeth on a gearing (which requires decrease of width in tooth addendum). According to [6] it occurs to connection of gear advantages with smaller and bigger pressure angle. The tooth has advantages of wider dedendum and involute and at the same time reaches the height of the tooth higher than the standard one.

Asymmetric gearing in gear pumps, where bigger number of teeth is used, can be seen in Danfoss's products with marketing name Shhark. Thanks to the extreme asymmetry a nineteen-teeth gear pump was born from standard eleven-teeth pump (Fig. 7), which was consequently modified to the helical.

Danfoss company in their cataloque [7] declares the reduction of pulsations of 78%, how it is documented on flow-pulsation chart (Fig. 8). There is a comparison of a standard pump and Shhark shown. In their documentation there is also written a reduction of 10 dB of noise level thanks to the decrease of these pulsations.

Fig. 7: Gearing – Shhark [7].

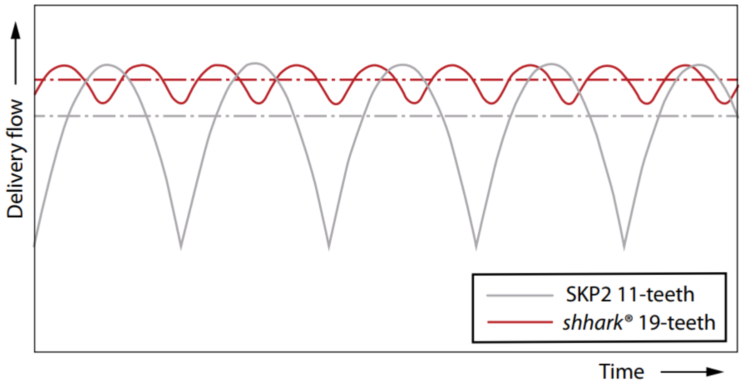

Fig. 8: Flow-pulsation comparison chart [7].

4 Continuous contact gearing

One of the newest phenomenon in silent gearing in gear pumps are continuous contact gears (Fig. 9). These pumps are offered for example by Settima [8] or Bosch Rexroth [9].

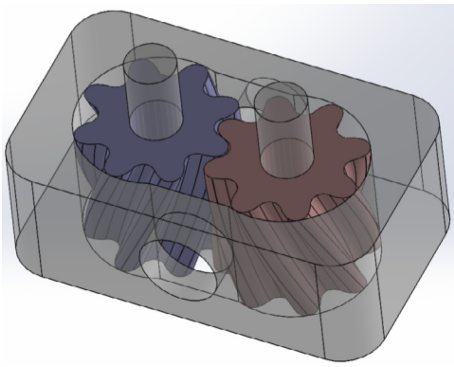

Fig. 9: Continuous contact gearing [10].

This type of gearing has its basis in Root-type blower [10], which is based on rotation of two cycloid elements. These elements are meshing in every point of their contact (Fig. 10).

Rotating elements are made of two arches. Top spline is possible to define using equations:

$$\begin{aligned} x_1 &= \rho_r \sin\theta, \\ y_1 &= a + \rho_r \cos\theta. \end{aligned} \tag{1}$$

Base spline is compatible to Top spline an it is define as:

$$x_2 = \rho_r \sin(\theta - 2\phi) - a \sin 2\phi + 2r \sin\phi, \tag{2}$$

$$y_2 = \rho_r \cos(\theta - 2\phi) - a \cos 2\phi + 2r \sin\phi, \tag{3}$$

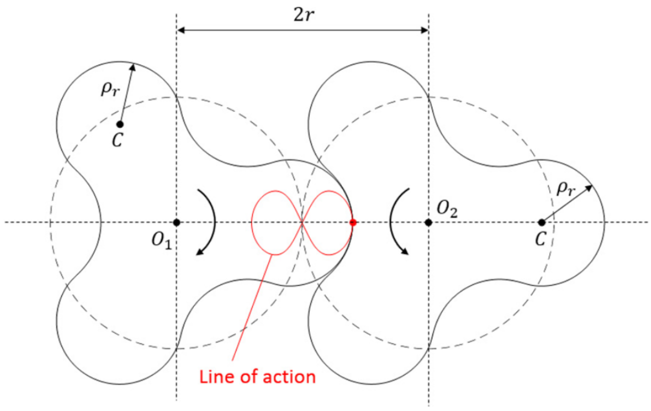

Fig. 10: Continuous gearing geometry [10].

where ρ is radius of an arch, a is the distance between middle of the arch and middle of the element and r is pitch radius. θ is a parameter of a gearing and ϕ is an angle defines element rotation. Two main parameters describing this gearing are number of teeth and ratio a/r. This ratio defines when the gearing is nearly flat or opposite – undercutted (Fig. 11). For preservation of convex-concave shape there is a need for the value of a ratio a/r to remain between 0.5 and 1.

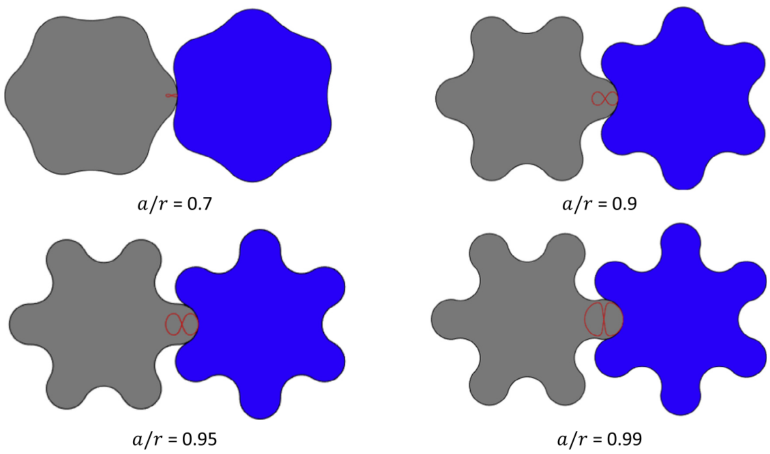

Fig. 11: Continuous contact gearing – different values of a/r [10].

With further modifications and implementation of the involute to the geometry of the gear (Fig. 12) there is a "low noise and pulsations" gearing provided, which combines advantages from involute gearing and gearing coming from Root-type blower. Top and base arch are the same, but the have involute spline connecting them.

Radius of these new arches is defined as:

$$\rho_r = r \cos \alpha \frac{\pi}{2N}, \tag{4}$$

where r is pitch radius, α is pressure angle and N is number of teeth. The position of ending points of the involute B and C is defined as:

$$\theta_B = \tan \alpha + \frac{\pi}{2N}, \tag{5}$$

$$\theta_C = \tan \alpha - \frac{\pi}{2N}. \tag{6}$$

For involute applies:

$$\mathrm{f_{inv}}(\theta) = r_b \begin{bmatrix} \cos(\phi - F) & -\sin(\phi - F) \\ \sin(\phi - F) & \cos(\phi - F) \end{bmatrix} \begin{bmatrix} \phi \\ 1 \end{bmatrix}, \tag{7}$$

where

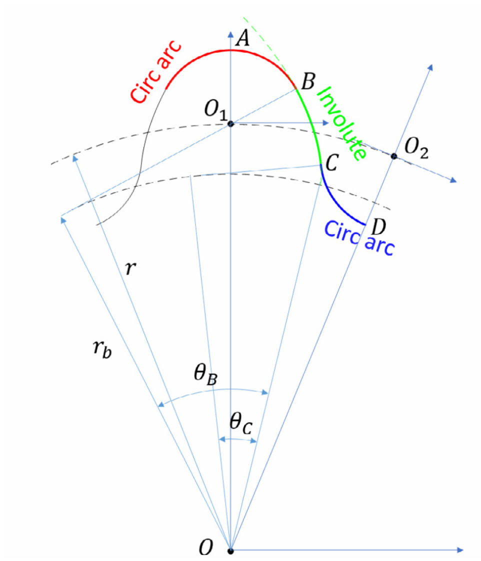

Fig. 12: Geometry of continuous contact gearing [10].

$$F = \tan\alpha - \alpha + \frac{\pi}{2N}. \tag{8}$$

So, arch radius is a function dependent on pressure angle, pitch radius and number of teeth. It is possible to define this geometry by these three parameters. For continuous meshing there is a need to keep right the condition a/r ¿ 0.5.

For even smoother meshing is recommended [8, 9, 10] helical gearing (Fig. 13).

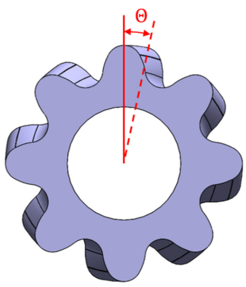

Fig. 13: Helical continuous contact gear [10].

Where helical angle θ is defined as:

$$\theta = \frac{H\tan\beta}{Nm_t\pi}2\pi, \tag{9}$$

where H is total width of a gear, m is module of a gear and β is angle of top arch. Even for helical gear there is a condition which needs to be consisted:

$$CR_{helix} = \frac{\theta}{2\pi/N} \geq 0.5. \tag{10}$$

The result of using helical continuous contact gearing is (according to [8]) decrease of gear pump noise level by 15 dB in comparison to standard gear pump. It also guarantees extremely low pulsations.

Map of noise level in relation to output pressure and rotation speed (Fig. 14), which is to be seen in [9], makes better image about noise level of gear pump based on working mode. It is clear with lower speed and lower output pressure, noise level is on its half values in comparison to standard pumps. Even on top working parameters the noise level values are clearly smaller than standard gear pumps.

Even when continual contact gearing is significantly more quiet, it has its own limits. For gear pumps including this type of gearing it is difficult to reach high volume efficiency. For this type of gearing there is a need for more complex axial balance system [10]. If there is a need to start with this new gearing, it must be

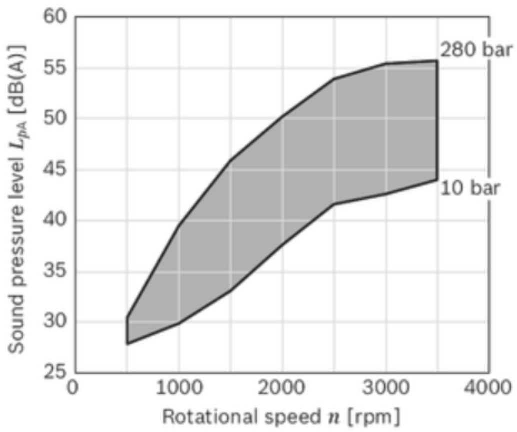

Fig. 14: Map of noise level in relation to output pressure and rotation speed [9].

counted with big investments into technology. Continual contact gearing cannot be made with standard gearing tools.

5 Prediction via mechanical/numerical analysis

There are many possibilities how to improve gear pumps and its gearing. But testing new variations for verification of its impact could be expensive and time taking, because for one gear geometry exist more than dozen possible geometric volumes of the gear pump (geometrical volume is defined via different width of a gearing). Nevertheless there are some suitable approaches, which generate sophisticated mathematical model. With this model there is a possibility to calculate the amount of noise level for every specific gear modification.

There is for example program called EgeMATor (External Gear Machine Multi Tool Simulator) [11], developed in Italian Naples and American Minnesota, which connects mechanical model, hydraulic model, cavitation calculations and more. In case of this program there is taken into account other aspects such as roughness of the surface and tolerances. Output results could be reactions in bearings, torque, meshing pressure of the gearing or flow pulsations in the output of the gear pump which affects final noise level. Decrease of pulsations using geometrical modifications from EgeMATor is declared (by developers) up to 61%. In the figure 15 is possible to see a comparison of pulsations between standard gear pump and its optimized version.

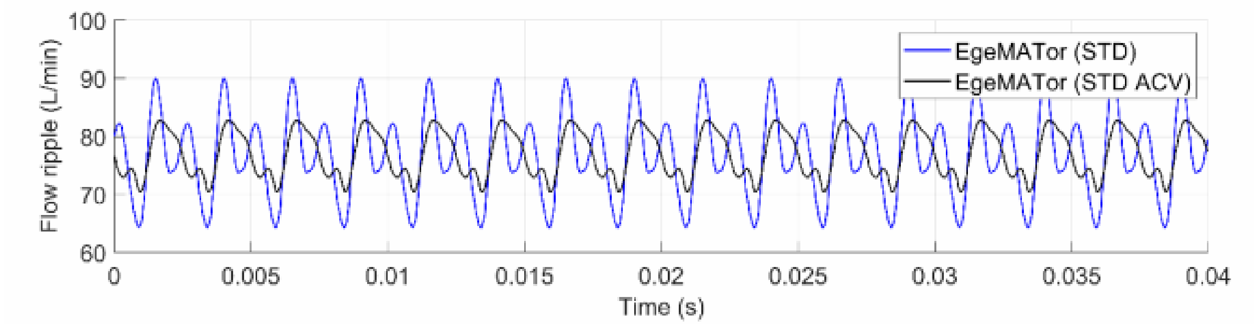

Fig. 15: Comparison of pulsations between standard gear pump and optimized one [11].

The accuracy of all the counting has not been verified yet in comparison with real prototype. Gear pump is still in stage of production.

From different approach there was developed program called HYGESim [12]. Its aim is not to compare pulsations (as in the case before), but level of noise in dB. Basically, it divides noise sources into three categories – mechanical born noise (friction, meshing gears), fluid born noise, air born noise (air contained in fluid). Based on these categories there are separated mathematical models made and consequently brought together into one acoustic model.

Using Ansys Virtual Lab a noise radiation in spheric area around the pump was created (Fig. 16). It

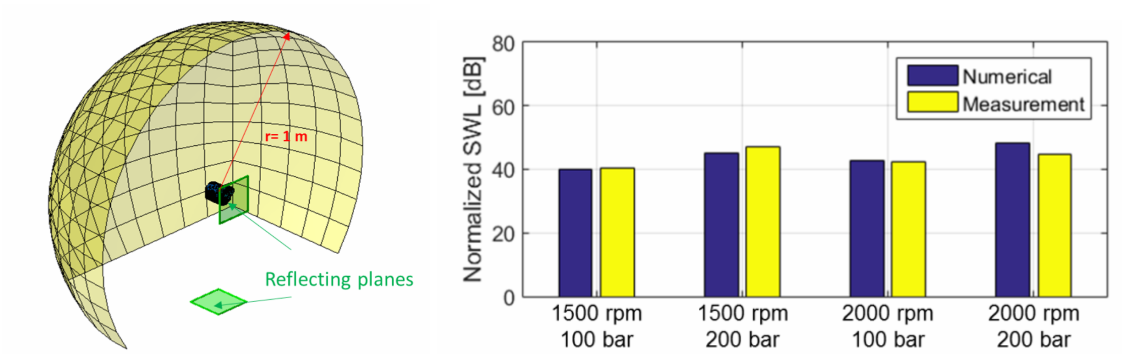

Fig. 16: Model of gear pump surroundig and comparison of noise level from program and real experiment [12].

simulates one meter radius around the pump. Noise level in this area is the result which was compared with real measures. Comparison is shown in Fig. 16.

So HYGESim analyses with pretty good accuracy noise level of a gear pump, but besides EgeMATor there is not a possibility to optimize geometry of a gear pump for a purpose of noise level decrease.

Noise level could be also investigated via FEA analysis. Results of Von-Misses stresses are transformed using Euler-Lagrange analysis which converts meshing tension to a level of noise as it can be seen in Fig. 17 [13].

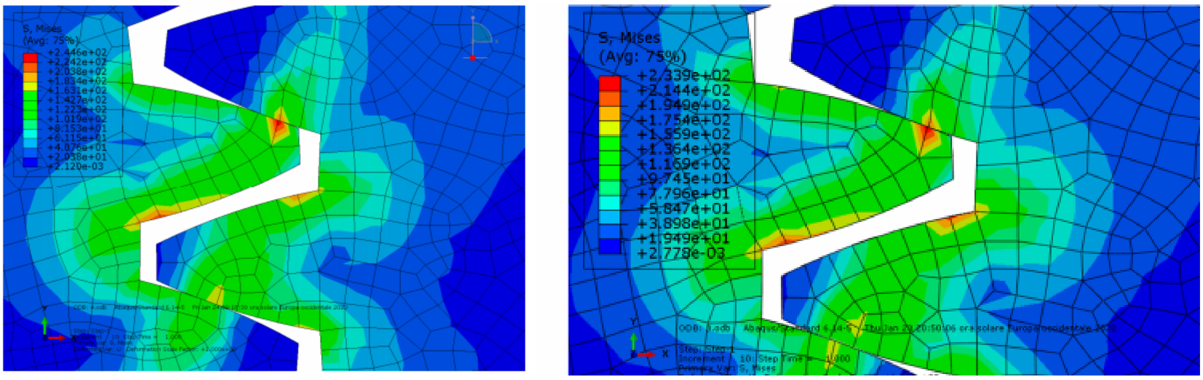

Fig. 17: FEA analysis of meshing gears [13].

In paper [13] it is possible to read about noise level comparisons between some models of gearing (Fig. 18). There are models including different materials or take or not take into account friction in calculations.

So based on FEA results there is a recalculation which reflects noise level of a gearing. With this method there is a possibility to create quick preliminary noise level analysis for different materials or friction variations.

6 Conclusion

Noise level of a gear pump is caused by discontinuous meshing of a gearing, and so discontinuous fluid transfer. For decrease of gear pump noise level there is a need to decrease pressure pulsations and more fluent fluid transfer. Standard possibilities, which are inadequate, are increase of number of teeth, bigger pressure angle or helical gearing.

Increase of number of teeth makes gear tooth thinner and vice versa. With standard involute gearing it is not possible to sufficiently overstep these limitations. Asymmetric gearing allows to maximize pressure angle (e.g. 45°) without making a tooth wider. When the cost side of the tooth is thinner, there is a possibility to increase number of teeth (e.g.: from 12 to 19 teeth). Thanks to this, pulsations happen to be eliminated, so the noise level of the pump also decreases.

Undoubtedly the most quiet are pumps including continuous contact gearing. Gearing is born from Root's blower. It includes not just arches in its geometry, but also partly involute. The result are negligible pulsations, rapid decrease of noise level and it also lower a frequency of noise level which is (for ear) on acceptable level.

The advantage of asymmetric gearing is possibility to produce it using standard tools aimed for involute gearing, for continuous contact gearing it isn't possible and there is a need for special tools. This factor con-

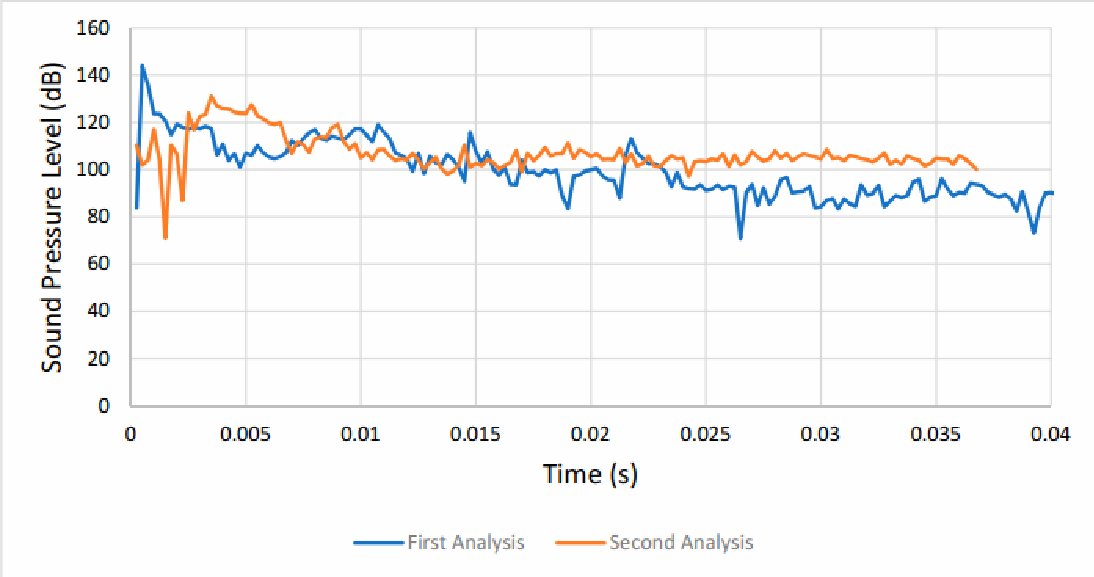

Fig. 18: Course of recounted noise level [13].

siderably influences final price of a gear pump. The question is, how great is a range of hydraulic aggregates, which are in direct contact with a human (where is a bigger need to lower the noise level) and how big range cover gear pump as a key component. And so, if it is useful for gear pump producers to create technological environment for brand new product.

Noise optimalization and design modifications requires following verifying test to prove their effectiveness. It can be financially and time taking. There exist programs as EgeMATor or HYGESim, which are capable to simulate efficiency of modifications or can be helpful with whole optimalization process. Numerical solution of noise level reduction ca be done also with FEA analysis and following recalculation for noise level.

Acknowledgement

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References

[1] J. Bláha, K. Brada, Příručka Čerpací Techniky, Praha, ČVUT, 1997.

[2] P. Huang, et al., Study on Noise Reduction of Gear Pumps of Wheel Loaders Based on the ICA Model, International Journal of Enviromental Research and Public Health. MDPI 13 (2019), doi: 10.3390/ijerph16060999.

[3] Retrieved from: https://www.jihostroj.com/en/hydraulics/gear-pumps-catalogue.html.

[4] G.K. Sfantos, V.A. Spitas, T.N. Constopoulos, Optimized asymmetric gear tooth design 23 (2003).

[5] M. Dymáček, Plastová ozubená kola a jejich analýza pomocí MKP, Brno, (2006).

[6] A. Mehr, Gear Solutions, retrieved from: https://gearsolutions.com/features/the-benefits-of-asymmetric-gears/.

[7] Retrieved from: https://assets.danfoss.com/documents/149364/BC315962412551en-000105.pdf.

[8] Retrieved from: https://www.settima.it/products/continuum-pumps/continuum.html.

[9] Retrieved from: https://www.boschrexroth.com/cs/cz/produkty/skupiny-produktu/mobilni-hydraulika/pumps/external-gear-pumps/azpj.

[10] X. Zhao, A. Vacca, Analysis of continuous-contact helical gear pumps through numerical modeling and experimental validation, Elsevier 26 (2018) 352–378, doi: 10.1016/j.ymssp.2018.02.043.

[11] G. Marinaro, E. Frosina, A. Senatore, A Numerica Analysis of an Innovative Flow Ripple Reduction Method for External Gear Pumps, Energies 22 (2021), doi: 10.3390/en14020471.

[12] S. Woo ,et al., Modeling Noise Sources and Propagation in External Gear Pumps, Energies 20 (2017), doi: 10.3390/e22111306.

[13] A. Liguori, et al., Noise Reduction in Spur Gear Systems, Entropy 17 (2020), doi: 10.3390/e22111306.