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A Heuristic Approach for 3D-Optimization of 3-Stage Gear Train Using PSO

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Optimization the volume/weight of the gear train is more important for industries and researchers. In this paper using particle swarm optimization algorithm a general gear train is optimized. The main idea is to optimum the volume/weight of the gearbox in 3 directions. So, the optimization process based on PSO algorithm occurs along height, length and width of the gearbox to achieve the smallest possible gearbox. The constraints divided into three types of constraints: geometrical, design and control constraints. The optimization process presented for two and three stage gear trains and by choosing different values for the gear ratio, input power and hardness of gears the practical graphs for value of the optimum weight/volume and all the necessary design parameters of gearbox such as number of stages, position and modulus of gears, face width of gears and diameter of shafts are presented. The results are validated by comparing to the results reported in the previous publication.

***Keywords**: Optimization layout gears-Weight/volume optimization- Particle swarm optimization (PSO)- Gear train.*

Introduction

Domain of engineering problems is large scale and has a different variable consist of linear and nonlinear constrain and equations so many researchers studied on heuristic methods to solve them. heuristic methods don't need derivatives of the functions and are powerful method compare with traditional method. Heuristic methods find best global solution. Hence, Gear train optimization has more attractive for many researchers in recent years. The volume of gear trains depends on the configuration of affected parameters such as, location of gears, number of gears, number of teeth and so on. To achieve the best parameter for gearbox, many researchers used different method for optimization. Patwal et al. [1] proposed TVAC-PSO-MS and used particle swarm optimization for production programing of pumped storage hydrothermal. Panda et al. [2] researched on weight optimization for single-stage gearbox consist of spur gear. They used different evolution algorithm to achieve optimum weight of spur gear set in a single stage gearbox. They compared the results with other modern algorithm. Chenge and Jin. [3] worked on a new way to incorporate particle swarm optimization and social learning mechanisms for scalable optimization. Zolfaghari et al. [4] worked on volume optimization of straight bevel gears by employing evolutionary algorithm. To achieve this purpose, they used two optimization techniques include Genetic Algorithm and simulated annealing algorithm (SA). Miler et al. [5] utilized Genetic algorithm to optimize weight of a gear pair and

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studied on design of spur gear with considered profile shift. Garg. [6,7] worked on optimization of the constrained problems with hybrid PSO-GA and used heuristic methods (artificial bee colony algorithm) to approach better solutions for structural engineering design problem and proposed novel hybrid GA-GSA algorithm to improve the performance of the mechanism. Fesharaki and Golabi.[8] used particle swarm optimization algorithm to find best place for piezoelectric actuator to reduce stress concentration around hole in plate. Marjanovic et al. [9] studied on optimization of spur gear trains. They studied on position of shaft axes in gear train for reducing the volume of gearbox. Their strategy for selecting the optimal parameters has three stages: optimal materials, gear ratios and position of shaft axes. They presented gear trains with 22% reduction in volume. Salomon et. al. [10] worked on Optimization of gearbox design using active robust considered requirements with uncertain load. Golabi et al. [11] worked on design optimization of multistage gear train based on minimum volume\weight. They used F-mincon method to optimize the different parameter of gear train such as gear ratio, input power and strength of material. They presented the design parameters with some graphs such as number of stages, modules, shafts diameter and face width of gears. But in their research, the location of gears is considered to change in two directions (height and length).

In this paper, the optimum volume/weight of a gear train is investigated that the location of gears is varied in 3-dimensional direction (height, length and width). In this point of view, the presented gearbox in this paper has the lowest possible weight for gear trains. The effective constraints are divided into 3 kinds of variables: geometrical, design and control constraints. To optimize the problem, particle swarm optimization (PSO) algorithm is used. By using fitness function and constraints a code is developed that named 3DGO_PSO (3D Global Optimization_ Particle Swarm Optimization) to solve and optimize the problem. The algorithm optimized (minimize) the weight of gearbox and presented the location of gears in gear train, number of teeth, module, the width of gear and helical angle for each gear. The optimum parameters for the gearbox are presented as practical graphs for use. Finally, an example is presented to show how to use the graph and obtain the best parameters for each gearbox. The presented results are validated by comparing the results with those reported in previous works.

Mathematical model - Objective function

Working on optimization design of gearbox have been more attractive for researchers. In Gear trains, the location of gears can affect the minimum volume of the gearbox. The volume of a gearbox is the outcome of multiplying length (L), width (W) and height (H) of the gearbox. In this paper, the location of gears change along the three directions in the gearbox and so, after implementation the optimization algorithm the lowest possible volume/weight for the gearbox is identified. It should be considered that the volume of gearbox depends on the layout of the gears so a suitable layout provides compact gearbox. Figure 1 shows the optimum layout of gears in a gear train.

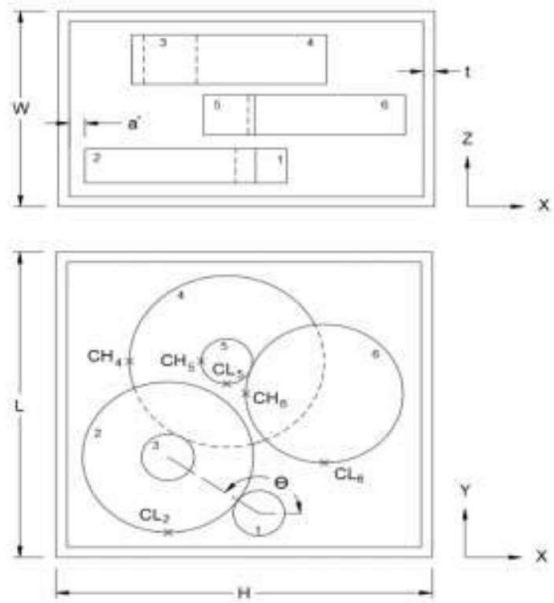

Fig. 1: The layout of gears in gear train

To find the optimum volume/weight for the gearbox, the objective function must be specified first. But because all components in gearbox have almost identical density, the volume/weight function for optimization process can be changed to the volume of the all components of the gearbox. This volume of gearbox material is the sum of the volume of shell, shafts and gears:

Volume of Material = Vshell + V gears + V shafts (1)

And the considering volumes are presented as:

Volume of shell = (W× H × L) –[(W -2t) × (H-2t) × (L -2t)] (2)

Volume of shafts = (3)

$$\frac{\pi.d_1^2}{4} \times (L_{in} + W) + \sum_{i=2}^{n-1}\left(W \times \frac{\pi.d_i^2}{4}\right) + \frac{\pi.d_n^2}{4} \times (L_{out} + W)$$

Volume of gears = (4)

$$\sum_{i=1}^{2s} b_i \times \frac{\pi.(d_i^g)^2}{4} - \sum_{i=2}^{n-1}(b_{2i-1} + b_{2i-2}) \times \frac{\pi d_i^2}{4} - b_{2s} \times \frac{\pi d_n^2}{4} - b_1 \times \frac{\pi d_1^2}{4}$$

Table 1: Geometrical Constraints

Calculating the width of the gear train (W)	$W=2a`+2t+\frac{b_{first\,gear}}{2}+\frac{b_{end\,gear}}{2}+z$	(5)
Calculating the height of gear train "H"	$H=diff_H+2a`+2t$	(6)
Calculating the length of gear train "L"	$L=diff_L+2a`+2t$	(7)

Where "z" is the distance between the center of first and end gear in the z-direction, diffH is the difference between the top point of the gears and the lowest point of the gears in gear train and diffL is the difference between the first point of the first gear and end point of the end gear along the "y" direction as shown in Fig. 1.

Mathematical model - Constraints

To find the optimum volume/weight for gear train, the necessary constraint must be considered. The constraints affect the optimum values of volume/weight of gear train, divided into three types of constraints as geometrical, design and control parameters constraints.

Geometrical Constraints

A geometrical constraint is defined to avoid the clashes. So, a geometrical constraint should control the area that there is the possibility of the clash between the gear and the next shaft in each stage (as shown in Fig. 2a or the clash between the gears as shown in Fig. 2b. The minimum possible distance for all of the gears in each stage in separate planes can be written as equation 8. Also, to optimize the location of gears, a constraint is considered to search if the gears can place along the location of previous gears in gear train. This constraint formulated in equation 9 and 10 and show in Fig. 2

Table 2: Geometrical Constraints

$r_{2i}\cos(\Theta) < r_{2i+2}\cos(\Theta) + r_{2i+1} + a`$	(8)
$C_{ij} > \frac{d_{i-1}^g}{2} + \frac{d_{j-1}^g}{2}$	(9)
$R_{2i+3} + r_{2i}\cos(\Theta) < r_{2i+2}\cos(\Theta) + r_{2i+1} + C$	(10)

Where, "i"and "j" are the paired gear.

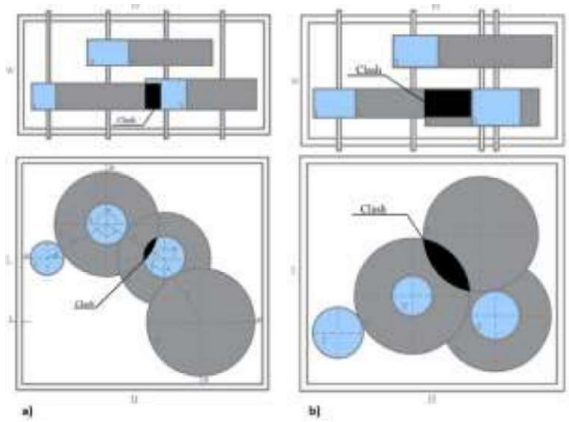

Fig. 2. a): Arranged gear position in gear train in the same or different plane , b) Possible interface (clash) between non-paired in the separate plane (3D optimization)

Design Constraints

Table 1. Design Constraints

Diameter constraint	$d \geq \left\{\left[\left(\frac{M_a}{S_e}\right)^2 + \left(\frac{T_m}{S_y}\right)^2\right]^{\frac{1}{2}} \frac{32S_{FS}}{\pi}\right\}^{\frac{1}{3}}$	(11)
	$\sigma_{Bending} \leq \sigma_{allowable(bending)} K_V F_t k_s k_o \frac{K_{BK_H}}{Y_J m_t b} < \frac{Y_N}{Y_Z Y_\theta} \cdot \frac{\sigma_{FP}}{S_F}$	(12)
	$\sigma_{contact} \leq \sigma_{allowable(contact)} (K_V F_t K_S K_O)^{\frac{1}{2}} Z_E < \frac{Z_W Z_N \sigma_{HP}}{Y_Z Y_\theta S_H}$	(13)

Control Parameter Constraints

Control parameter constraints are presented in table 2. These constraints affect the optimization process to achieve the initial value consideration for gear train and satisfy the initial assumptions for gear train such as considering the ratio or modulus selecting :

Table 2. Control Parameter Constraints

$Minimum\ teeth:\ N^P \geq \frac{2\cos(\delta_{2i-1})}{\left(2\left(\frac{N^g}{N^p}\right)+1\right)sin^2(\varphi_t)}\left(\sqrt{\left(2\left(\frac{N^g}{N^p}\right)+1\right)sin^2(\varphi_t)+\left(\frac{N^g}{N^p}\right)}+\frac{N^g}{N^p}\right)$	(14)
Overall ratio : $R_e = \prod_{i=1}^{s-1}\frac{M_{2i-1}}{M_{2i}}$	(15)
reduction the ratio of the gear train $N^p \leq N^g$	(16)
Gear face width $3\pi m_t \leq F \leq 5\pi m_t$	(17)
Modulus constant number $1 \leq m^p \leq 50$	(18)
The constraint for modulus of each pair $m^g = m^p$	(19)

Optimization process

To optimize the gear train volume/weight with previous consideration for objective function and constraints, the particle swarm optimization algorithm (PSO) is used. PSO method is the pivotal entry into a computation technique that used meta-heuristic according to stochastic optimization that used behavior of population. The PSO algorithm was introduced by Eberhart and Kenney and this algorithm used the social behavior of birds or fish to find the optimum point of the problem like as food. In PSO algorithm, each bird (particle) wonders in the problem space randomly. They are potential solutions and assumed position of particles, Velocity and final fitness function. Each particle being random searched to find piece of food in problem space and they have same question that where the target or food is but in each iteration the particles just know how far the targets or foods are in space. One of the particle that is nearest to the target or food, is an effective to follow so for govern to optimum target each particles updating generations. For initial step, all particle has a random position and zero velocity. Then, based on the best location for particles the velocity update and the particles move to the new location. The new velocity and new location for each particle update in each iteration so that all particles arrive and converge to one point (optimum point). During the search process in problem space, the best location indeed best fitness value in each iteration for each particle(P Best) and the best location for all particles is historical best value that is maximum food source or value of fitness function obtained(GBest) save and use for next iteration [8]. Two best values (Pbest and Gbest) used for updates velocity and positions vectors for any of the N particles in population. Particle velocity obtained from the way each N particles move all over in problem space. That is consist of three terms: in the first, descripted the inertia or momentum prohibit the particle to extremely changing direction. The second, called the self (individual) intelligence that is tendency of particles toward their own best locations in each particle′s memory. At the last, named the social (group) intelligence, denotes the particle steers to move towards the general (global) best situation (location) of the whole population. In this paper to optimize the considering problem, a code based on PSO algorithm was developed that called 3DGO-PSO. The fitness function and all constraints are considered in the 3DGO-PSO to solve and find the best values for gear train parameters. The implementation steps of 3DGO PSO are presented in Fig. 3.

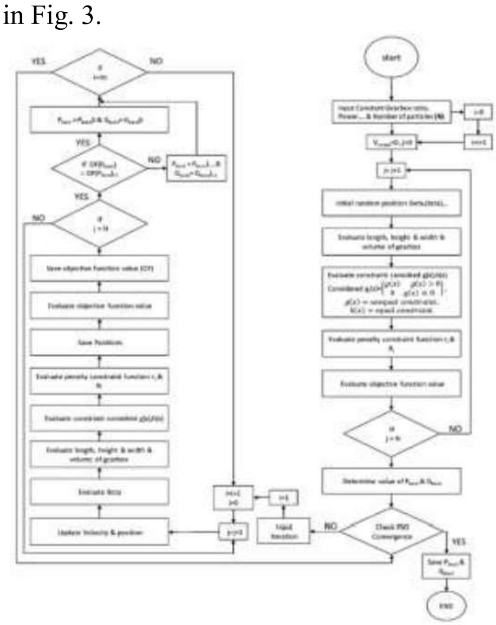

Fig 3: Implementation PSO flowchart

For using the objective function equation (1) and the constrains together, the constrains added to the objective function as penalty functions. So if considering the objective function "V" and the equality constraints as Hi=0, i=1,2,…,n and the inequality constraints as Gj≤0, j=1,2,…,m and considering that the PSO algorithm try to maximize the function, the main objective function in program presented as:

Main objective function = $\frac{1}{1+\varphi}$ Where,

$$\varphi = V + \sum_{i=1}^{n} H_i + \sum_{j=1}^{m} g_j \quad (20)$$

and

$$g_j = max\{0, G_j\}, j = 1,2, \dots, m \quad (21)$$

Results and Example

In this paper for presenting the results the various input parameters for gear train are considered and explained in the 5 steps. Step 1: The input parameters are presented in table 3. Using these parameters for the gearbox, the 3DGO-PSO solve the problems and find the best values for all components of the gear train and all values are presented as a practical graph for gear train. Step 2: To use the practical graph, for selecting the best values for gear train parameters, at the first, the number of stages, comparison between second and third stages parameters (50 hp≤ Power ≤ 200 hp) is extracted for considering the transmission power and overall ratio for gearbox as shown in Figs. 5a. Then the reduction ratio for each stage of third-stage gear train obtain from Figs. 8. Next Figs. 6 to 11, show the optimum parameters for each stage of third-stage gear train.

Table 3. Elected Specific input data

Input parameters	Transmission power (hp)	Hardness of material (BHN)	Gear train ratio
Elected Specific values	50, 80, 100, 150, 200	400	1.5, 2, 3, 5, 8, 10, 15, 20, 40, 50

Step 3: In order to explain how to use the practical graph, an example for selecting the best parameters for a special gearbox is presented. Step 4: But the considering example is the same as considered in reference [11] to compare and validate the results of this paper and those reported in reference [11]. The input data for considering example are presented in table 4. As mentioned above, by using flowchart from figure 3, the best number for reduction stages are extracted from Figs. 5a as 3 stages gearbox. Next, the partial ratio for gear train achieved from Fig. 5b. Finally, the optimal values for the considering gear train are obtained from Figs. 6 to 11.

Table 4. Input data for applicable example consideration with Golabi et al. [11]

Input parameters Example	Transmission power (hp)	Hardness of material (BHN)	Gear train ratio
Example input data	150	400	15

Final step (validate): The results obtained from the practical graph in this paper and those obtained from reference [11] are presented in table 5. Golabi et al. [11] worked on optimization weight/volume of the multistage gear train in 2 directions length and width. But in this paper the optimization process implemented in 3 direction length, with and height of gear train. The result presented in this paper shows that the optimum volume has about 15% less than the volume reported by Golabi et al. [11]. Figure 5 illustrated the trend of the fitness function during the optimization process.

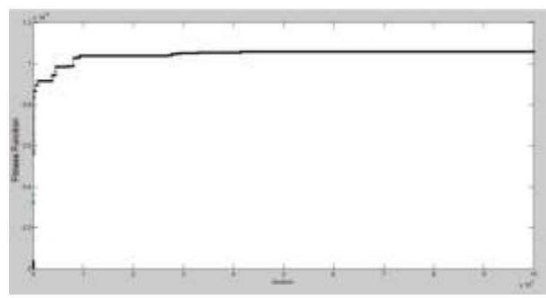

Fig. 4:. trend of the fitness during the optimization

Table 5. Comparison between results obtained from presented paper and previous publication by Golabi et al. [11]

Total Ratio=15, Power=150 hp, hardness of material=400 BHN			
Description		Ref [24]	Presented Research
u1	First Stage	2.6	2.7
u2	Second Stage	2.6	2.6
u3	Third stage	2.2	2.2
Module	First Stage	5	6
	Second Stage	8	9
	Third stage	10	8
Face Width (mm)	First Stage	51	77
	Second Stage	82	81
	Third stage	170	112
Shaft Diameter (mm)	First Stage	35	33
	Second Stage	43	41
	Third stage	125, 72	87, 68
Gear Position Angle	First Stage	-	130
	Second Stage	-	240
	Third stage	-	210
Volume (mm^3)		2.6 e7	2.2 e7
Difference		-15 %	

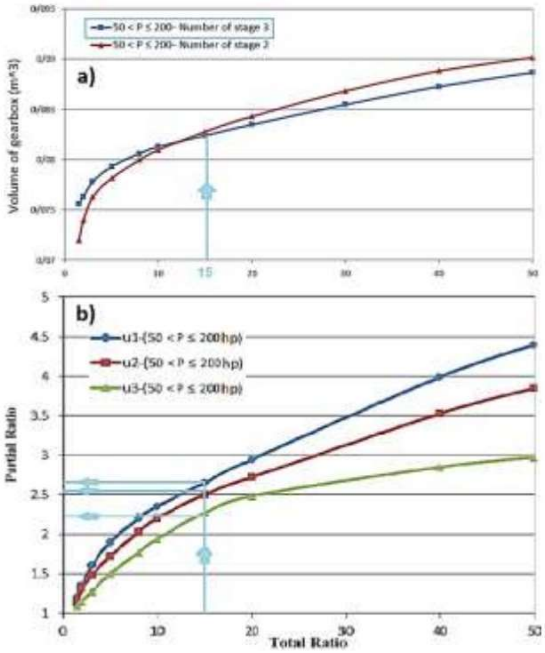

Fig 5: a) The optimum number of stages, the comparison between second and third stages parameters, 50 hp ≤ Power ≤ 200 hp- b) The optimum partial ratio of third-stage, 50 hp ≤ Power ≤ 2

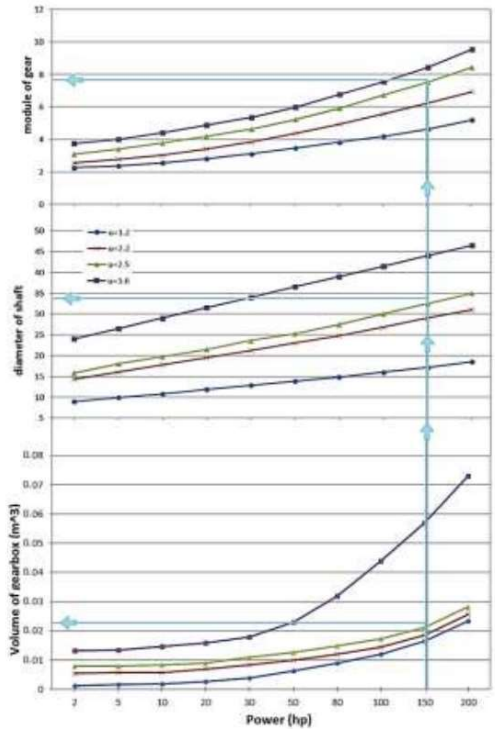

Fig. 6: Volume, shaft diameter and module for 3-stage gear train - BHN = 400- (stage one)

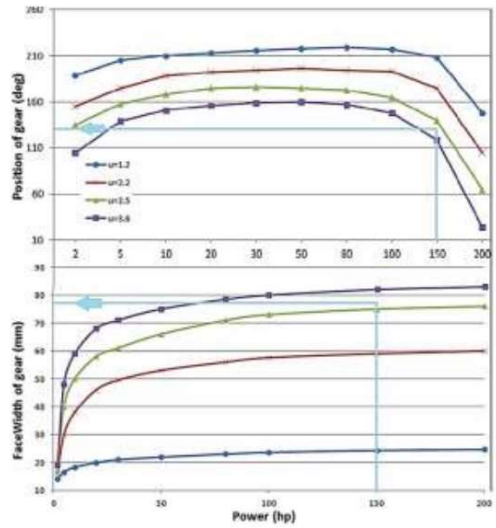

Fig7: Face width and position of gear for 3-stage gear train BHN = 400 – (stage one)

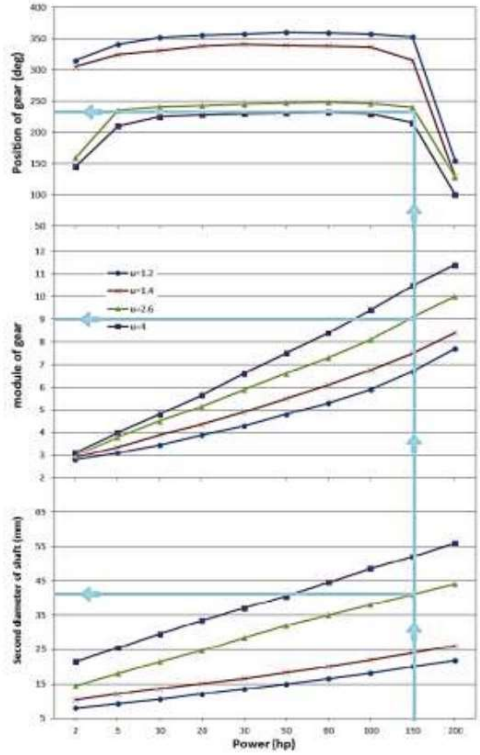

Fig. 8: Shaft diameter, module and position of gear for 3- stage gear train BHN = 400 – (stage two)

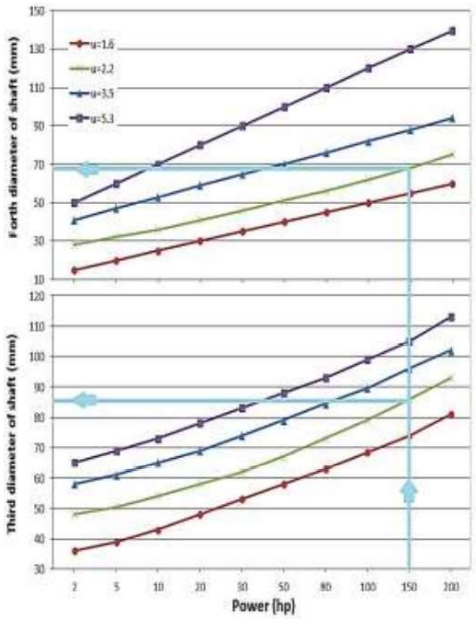

Fig. 9: Shaft diameters for 3-stage gear train BHN = 400

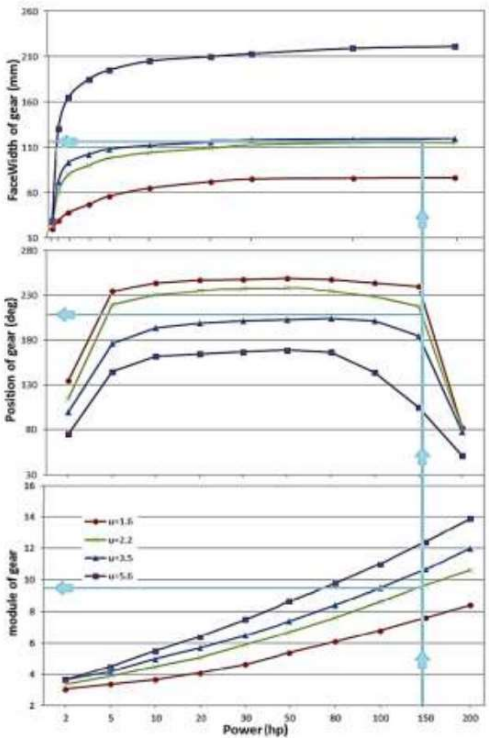

Fig.10: Module, position and face width of gear for 3-stage gear train BHN = 400 – (stage three)

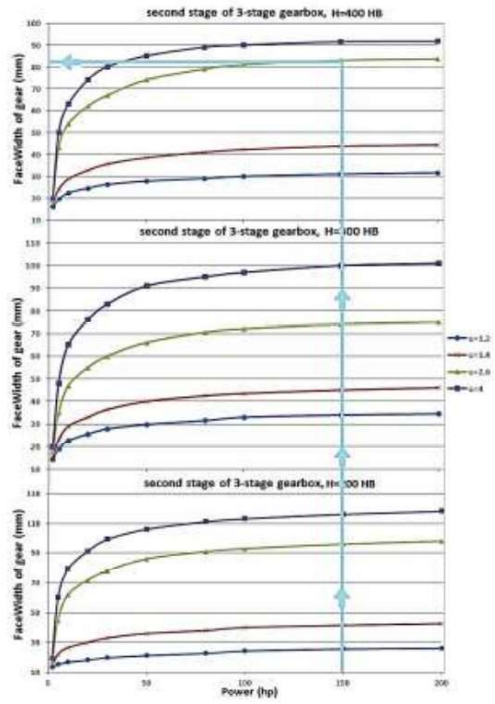

Fig. 11: Face width of gears for 3-stage gear train BHN =200, 300 and 400

Conclusion

Domain of engineering problems is large scale and has a different variable consist of linear and nonlinear constrain and equations so many researchers studied on heuristic methods to solve them. heuristic methods don't need derivatives of the functions and are powerful method compare with traditional method. Heuristic methods find best global solution. Garg, H.[12] used heuristic methods with soft computing to analyses Performance of industrial system. In this paper, Particle swarm optimization method is employed for 3D dimensional and layout optimization process of a multistage gearbox to achieve minimum weight/volume. To achieve the optimal weight/volume of the gearbox, the volume of material of gearbox components is considered as the objective function and the necessary constraints are considered for the optimization process. Highlights features in this paper consist of minimum volume/weight objective function in the 3D general form for gear train is offered, Suitable Practical curves are appropriate for one until three-stages gear trains for obtain the best gearbox parameters are introduced, Optimization process implemented on two and three-stage gear train by selecting different

input data include gear ratio, power and hardness, Number of best stages, gear p/osition angle, modulus, shaft diameter and face width for gears are offered for gearbox. The considering constraints divided into three types as a geometrical constraint, design constraints and control parameter constraints. The optimization process implemented on one, two and three stages for gearbox and all gear trains optimized in 3 direction length, width and height. The input parameters for gear train optimization are included gear ratio, power and strength of materials. Then the practical graphs are extracted from optimization results to achieving the minimum weight/volume of the gearbox. Value of optimum weight/volume and all the necessary design parameters of gearbox such as the position of gears, face width of gears, number of stages, shaft diameter and module of gears are presented as a practical graph. Finally, an example is presented to show how to use the graphs and the results are validating with those reported in the previous publication. The results show that optimization the gearbox in three directions can reduce the volume of material of gearbox components and lead to the smaller gearbox.

References

[1] Patwal, R. S., Narang, N., Garg, H., A novel TVAC-PSO based mutation strategies algorithm for generation scheduling of pumped storage hydrothermal system incorporating solar units. Energy, 142, 2018, 822-837.

[2] Panda, S., Biswal, B. B., Jena, S. D., Mishra, D., An approach to weight optimization of a spur gea, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 231(2), 2016, 189-202.

[3] Cheng, R., Jin, Y., A social learning particle swarm optimization algorithm for scalable optimization, Information Sciences, 291, 2015, 43-60.

[4] Zolfaghari, A., Goharimanesh, M., Akbari, A. A, Optimum design of straight bevel gears pair using evolutionary algorithms, Journal of the Brazilian Society of Mechanical Sciences and Engineering, 39(6), 2017, 2121-2129.

[5] Miler, D., Lončar, A., Žeželj, D., Domitran, Z, Influence of profile shift on the spur gear pair optimization, Mechanism and Machine Theory, 117, 2017, 189-197.

[6] Garg, H., A hybrid PSO-GA algorithm for constrained optimization problems, Applied Mathematics and Computation, 274, 2016, 292-305.

[7] Harish, G., A Hybrid GA-GSA Algorithm for Optimizing the Performance of an Industrial System by Utilizing Uncertain Data. In V. Pandian (Ed.), Handbook of Research on Artificial Intelligence Techniques and Algorithms, 620-654, Hershey, PA, USA: IGI Global, 2015.

[8] Jafari Fesharaki, J., Golabi, S., Optimum pattern of piezoelectric actuator placement for stress concentration reduction in a plate with a hole using particle swarm optimization algorithm, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 229(4), 2015 614– 628.

[9] N. Marjanovic, B. I., V. Marjanovic, Z. Milojevic, M. Blagojevic, M. Bojic, A practical approach to the optimization of gear trains with spur gears, Mechanism and Machine Theory, 53, 2012, 1-16.

[10] S. Salomon, G. A., R.C. Purshouse, P.J. Fleming, Gearbox design for uncertain load requirements using active robust optimization, Engineering Optimization, 48, 2016, 652-671.

[11] S. Golabi, J. J. Fesharaki., M. Yazdipoor, Gear train optimization based on minimum volume/weight design, Mechanism and Machine Theory, 73, 2014, 197-217.

[12] Garg, H., Performance analysis of an industrial system using soft computing based hybridized technique, Journal of the Brazilian Society of Mechanical Sciences and Engineering, 39(4), 2017, 1441-1451