International Research Journal of Education and Technology
Peer Reviewed Journal
ISSN 2581-7795

"A Comparative Study of Multi Objective Decision-Making Methods to Design a Spur Gear under Optimum Parameters"

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Abstract - *: The multi objective decision-making methods-based algorithm seizes on the generation of the gradients of the objective functions since it free optimization technique. Heuristic optimization is used to overcome the limitations found in the conventional techniques. It is aim to obtain the optimal dimensions for spur gear design as the gear transmission problem is one the evasive optimization problem due to relation between different variables. The results will be obtained by different meta-heuristic optimization will be compared with conventional analytical methods.*

Key Words: Gear ;algoritham ;optimisation ;conventionnel analytical Methods.

1.INTRODUCTION

A gear is a rotating machine part having cut teeth, which mesh with another toothed part in order to transmit torque. Two or more gears working in tandem are called a transmission and can produce a mechanical advantage through a gear ratio and thus may be considered a simple machine. Geared devices can change the speed, magnitude, and direction of a power source. The most common situation is for a gear to mesh with another gear; however, a gear can also mesh a non-rotating toothed part called a rack, thereby producing translation instead of rotation. The gears in a transmission are analogous to the wheels in a pulley. An advantage of gears is that the teeth of a gear prevent slipping. When two gears of unequal number of teeth are combined a mechanical advantage is produced, with both the rotational speeds and the torques of the two gears differing in a simple relationship.

1.1 Types of Gears

There are many types of gears being designed, manufactured and used for many different applications now days. There is a copiousness of literature on these types of gears, their main characteristics, materials used and suitability of applications. Main types of gears are spur gear, helical gear, bevel gear, worm gear and rack and pinion gear.

1.1.1 Spur Gears

Parallel and co-planer shafts connected by gears are called spur gears. The arrangement is called spur gearing. Spur gears are the most common type of gears. Spur gears have straight teeth and are parallel to the axis of the wheel. The advantages of spur gears are their simplicity in design, economy of manufacture and maintenance. They impose only radial loads on the bearings. Spur gears are known as slow speed gears. If noise is not a serious design problem, spur gears can be used at almost any speed.

Figure 1.1: Spur Gear Pair [1]

1.1.2 Helical Gears

These gears are usually thought of as high-speed gears. Helical gears can take higher loads than similarly sized spur gears. The motion of helical gears is smoother and quieter than the motion of spur gears. Single helical gears impose both radial loads and thrust loads on their bearings and so require the use of thrust bearings. The angle of the helix on both the gear and it must be same in magnitude but opposite in direction, i.e., a right-hand pinion meshes with a left-hand gear.

Figure 1.2: Helical Gear [1]

1.1.3 Bevel Gears

Intersecting but coplanar shafts connected by gears are called bevel gears. This arrangement is known as bevel gearing. Straight bevel gears can be used on shafts at any angle, but right angle is the most common. Bevel Gears have conical blanks. The teeth of straight bevel gears are tapered in both thickness and tooth height.

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Figure 1.3: Bevel Gear [1]

1.1.4 Worm Gears

Worm gears are used to transmit power at 90° and where high reductions are required. The axes of worm gears shafts cross in space. The shafts of worm gears lie in parallel planes and may be skewed at any angle between zero and a right angle. In worm gears, one gear has screw threads. Due to this, worm gears are quiet, vibration free and give a smooth output.

Figure 1.4: Worm Gear [1]

1.1.5 Rack and Pinion Gear

A rack is a toothed bar or rod that can be thought of as a sector gear with an infinitely large radius of curvature. Torque can be converted to linear force by meshing a rack with a pinion. The pinion turns and the rack moves in a straight line. Such a mechanism is used in automobiles to convert the rotation of the steering wheel into the left-to-right motion of the tie rod. The rack and pinion gear type is employed in a rack railway.

Figure 1.5: Rack and Pinion Gear [1]

1.2 Gear Selection Criteria

Since there are numbers of machines that have applications for gears, selection of the right type of gear for the appropriate application is quite an elaborate task. In most cases the geometric arrangement of the apparatus that needs the gear drive will dictate the gear selection. If the gears are on parallel axes, then spur or helical gears are the ones to be used. If the axes are at right angles, then bevel and worm gears can be used but are not suitable for parallel axes drives. As already discussed above, the gear selection criteria depends on the application and the design requirement. From here on, only spur gear design and geometry will be considered as a part of research.

1.3 Steps of Spur Gear Design
Design steps are adopted from design data book [2].

1. The pitch circle diameter:
$$d' = mz$$
2. Centre to centre distance:
$$a = \frac{m(z_1 + z_2)}{2}$$
3. Transmission ratio :
$$(i) = \frac{z_1}{z_2} = \frac{n_1}{n_2}$$
4. Number of Teeth :
$$z_{\min} = \frac{2}{\sin^2 \infty}$$
5. Beam Strength of Gear Tooth :
$$s_b = mb\sigma_b Y$$
6. Wear Strength of Gear Tooth :
$$s_w = bd_p QK$$
$$Q = \frac{2Z_g}{Z_g - Z_p}$$
$$K = 0.16\left(\frac{BHN}{100}\right)^2$$

Where, BHN= Brinell Hardness Number.

7. Effective Load on Gear Tooth:
   - For ordinary and commercially cut gears made with form cutters with v < 10 m/s
   $$C_v = \frac{3}{3+V}$$
   - For actually hobbled and generated gears with v < 20 m/s.
   $$C_v = \frac{6}{6+V}$$
   - For precision gears with shaving, grinding and lapping operations and with v> 20m/s.

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$$C_v = \frac{5.6}{5.6+V}$$

8. The pitch line velocity :

$$V = \frac{\pi d' n}{60*10^3}$$

The effective load between two meshing teeth is given By

$$P_{eff} = \frac{C_s P_t}{C}$$

e = sum of errors between two meshing teeth (mm)

$$e = e_p + e_g$$

Where, e_p =error for pinion

e_g =error for gear

9. Estimation of Module Based on Beam Strength:

$$m = \left[\frac{60*10^6}{\pi} \left\{ \frac{(kW) C_s (f_s)}{z n C_v \left(\frac{b}{m}\right) \left(\frac{S_{ut}}{3}\right) Y} \right\} \right]^{1/3}$$

10. Estimation of Module Based on Wear Strength:

$$m = \left[\frac{60*10^6}{\pi} \left\{ \frac{(kW) C_s (f_s)}{z^2 n_p C_v \left(\frac{b}{m}\right) QK} \right\} \right]^{1/3}$$

11. Gear Design for Maximum Power Transmitting Capacity:

$$P_t = P_d = \frac{S_w}{2}$$

1.3.1 Spur gear Force Analysis

The normal force F can be resolved into two components; A tangential force Ft which does transmit the power and radial component, Ft = F cos Ø

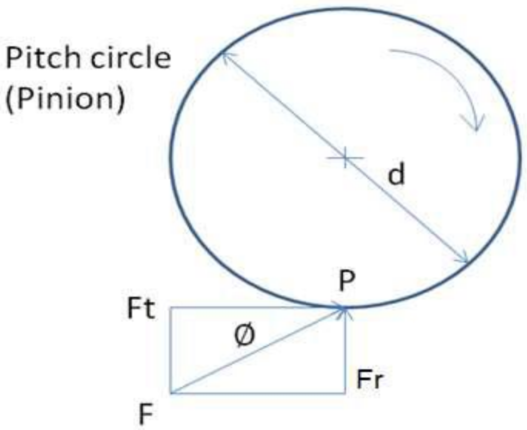

Figure 1.6: Spur Gear Force Analysis

1. Fr which does no work but tends to push the gears apart,

Fr = F sin Ø

From equation (2)

Fr = Ft tan Ø

1.3.2 Spur Gear - Tooth Stresses

Stresses developed by Normal force in a photo-elastic model of gear tooth. The highest stresses exist at regions where the lines are bunched closest together. The highest stress occurs at two locations:

1. At contact point where the force F acts
2. At the fillet region near the base of the tooth.

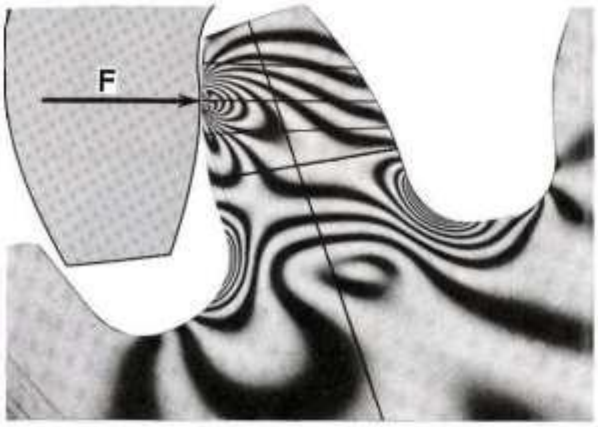

Figure 1.6: Spur Gear - Tooth Stresses [3]

1.4 Material for Spur Gear

Spur gears must be built of materials that are easily fabricated and molded, but also strong and durable.

- Cast iron is relatively inexpensive, rust resistant and easy to mold.
- Stainless steel is highly resistant to oxidation, and like acetal, it is resistant to abrasions and other weakening blemishes.
- Acetal is stiff, strong and resistant to abrasion.
- Alloy steel provides superior durability and corrosion resistance. Minerals may be added to the alloy to further harden the gear.
- Cast steel provides easier fabrication, strong working loads and vibration resistance.
- Carbon steels are inexpensive and strong, but are susceptible to corrosion.
- Aluminum is used when low gear inertia with some resiliency is required.

1.5 Application in Various Machinery

- Metal cutting machines
- Marine engines
- Mechanical clocks and watches
- Fuel pumps
- Washing Machines
- Gear motors and gear pumps
- Rack and pinion mechanisms
- Material handling equipment
- Automobile gear boxes
- Steel mills
- Rolling mills

International Research Journal of Education and Technology
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1.6 Need of spur gear design optimization

Many problems in today's world rely on the trial-and-cut method which in return takes a considerable time to obtain the optimal solution. Gear is a machine element which has widespread application in industries. It transmits power with great accuracy. While designing a gear we usually use the trial and cut method to determine various factors such as rotation frequency, bending strength, input power and torsional strength. However, these methods do not include the method of optimizing gear weight and center to center distance. Nevertheless, solving engineering problems involve a large number of conflicting objectives. In conventional methods, gear drive design requires a large number of calculations based on recommendations of gear standards, trial and error methods, etc. This is a very time-consuming process and may often end with inadequate design outcomes.

2.INTRODUCTION TO OPTIMIZATION

2.1 Optimization

The word "optimum" is Latin, and means "the ultimate ideal;" similarly, "optimus" means "the best." Therefore, to optimize refers to try to bring whatever optimize. The optimization means the progressive evolution towards the result. Optimization is the search for a max or min in the value of a certain response function under given condition [15]. To clarify the concepts of local and global optimist, the map of landscape with mountain, in which lines indicate regions of similar response, is frequently used as a metaphor. The peak of a mountain always is a local optimal, because in its direct neighborhood there are no higher places. However, only the peak of the superior mountain is the global optimal. In many optimization problems, obtaining the global optimum is the challenging task, and the presence of many local optimal complicates the problem significantly. In the same vein, local optimizers are methods that always find the (usually local) optimum near the starting position, and global optimizers are methods that end up at the soaring peak, no matter from where the search started.

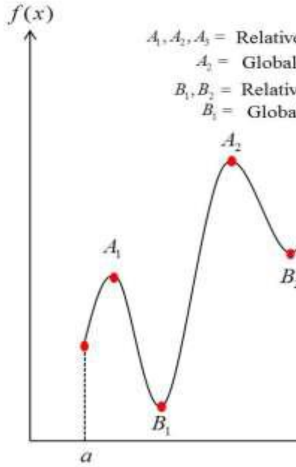

Figure 2.1 Relative and Global Minima & Maxima

Such optimizations are usually executed in an iterative fashion (figure 3.2). The search is begun either from one or more random positions or from a set of random points, picked according to some criteria [33]. In the evaluation stage, the quality of the current point is evaluated by experiments. Several criteria may be used to stop the optimization, such as the no. of experiments, or the quality of the solutions found so far. If no stopping criterion put on, the next stage is to accept the solution as a starting point for new solutions, or to reject and to proceed from some other solution. This process is called selection. Finally, the optimization method renders one or more new candidate solutions. These in turn are assessed and the cycle enters in its next iteration. Such optimizations are usually executed in an iterative fashion (figure 3.2). The search is begun either from one or more random positions or from a set of random points, picked according to some criteria [33]. In the evaluation stage, the quality of the current point is evaluated by experiments. Several criteria may be used to stop the optimization, such as the no. of experiments, or the quality of the solutions found so far. If no stopping criterion put on, the next stage is to accept the solution as a starting point for new solutions, or to reject and to proceed from some other solution. This process is called selection. Finally, the optimization method renders one or more new candidate solutions. These in turn are assessed and the cycle enters in its next iteration.

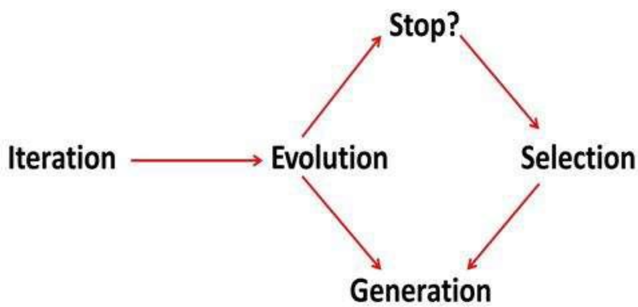

Figure 3.2 The basic iterative optimization cycle

2.2 Standard Form of Optimization Problem

Generally, optimization problem written in the following way,

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$$\text{Find } X = \begin{Bmatrix} x_1 \\ x_2 \\ . \\ . \\ . \\ x_n \end{Bmatrix} \text{ which minimize f(x)}$$

Subject to the constraints

$g_j = (X) \le 0$, where j=0,1,2,3……m

$I_j = (X) \le 0$, where j=0,1,2,3……m

Where X is an n-dimensional vector called the design vector, f(X) is called the objective function and are, respectively, the inequality and the equality constraints.

2.3 Optimization Methods

Many distinct optimization methods exist and can be sorted in a number of ways. Multi Objective Decision Making is classified under classical approach as shown below. The classical optimization methods are useful in finding the optimum solution of continuous and differentiable functions [15]. These methods are analytical and make use of the techniques of differential calculus in locating the optimum points. The non-classical optimization methods described in here have been specifically developed for those cases, where the classical techniques were not suitable high dimensional search problems with many local optimal [16]. Because the no. of evaluations may be quite high they usually are applied in connection with computer experiments rather than with laboratory experiments. Stochastic optimization methods have been created to counter the weaknesses of classical methods in high dimensional search problems. Instead of following a fixed path that is only observed by the pick of the starting point, they feature a strong random component, mainly to avoid getting cornered in local optimal. Constrained Multi Objective Decision Making based on classical approach is classified as:

Multi Objective Decision Making based on classical approach

Classical Optimization		**Non-classical Optimization**
-Direct Substitution		-Genetic Algorithm
-Lagrange Multipliers		-Simulated Annealing
-Constrained Qualification		-Ant Colony Optimization
-Kuhn-Tucker Conditions		-Particle Swarm Optimization
-Convex Programming Problem		-Teaching and Learning Based Optimization

3.4 Selection of Optimization Method

There are so many evolutionary optimization algorithms are available, like Genetic Algorithm, Simulated Annealing, Artificial Neural Network, Ant Colony Optimization, Particle Swarm Optimization etc.

Non-classical optimization has applied to multi-objective problems in which the objective function comparison takes pareto dominance into account when moving the particles and non-dominated solutions are stored so as to approximate the pareto front. Non-traditional optimizations techniques do not need any mathematical premise to the problems and have better search power over traditional techniques. Populations of points are taken for starting procedure instead of single design point. Nontraditional optimization technique uses values of objective function. The derivatives are not used in search procedure. The objective function values related to a design vector play a role of robustness according to given objectives.

3. FORMULATION OF SPUR GEAR OPTIMIZATION PROBLEM & METHOD OF SOLUTION

3.1 Introduction

Any optimization problem includes an Objective function, Constraints, and Decision variables. So it is necessary to formulate the optimization problem, the worm gear design mainly based on three variables like a module, pitch circle diameter, face width and these variables are taken as a decision or design variables. There are so many objective functions for worm gear. Optimization of worm gear design includes mostly following objective function:

- Minimizing face width
- Minimizing center distance
- Increasing contact ratio to reduce vibrations and noise
- Maximization of power transmission capability
- Speed ratio is to be maintained.

Here, objective function is taken as minimizing center distance, and so many design constraints which are discussed in subsequent topic.

3.2 Formulation of Objective Function

Minimum weight can be given by following equation. > 0.0

Total Weight = Pinion Weight + Gear Weight

$$W = P_w + G_w > 0.0$$

Taking, $P_w = \pi p(R_1^2)x_3$

$G_w = \pi p(R_2^2)x_3$

$W = \pi p(R_1^2)x_3 + \pi p(R_2^2)x_3$

Finally, objective function becomes,

$$f(x) = \rho_1 \pi \left(\frac{x_1}{2x_2}\right)^2 x^3 + \rho_2 \pi \left(\frac{Nx_1}{2x_2}\right)^2 x^3$$

3.3 Formulation of Design Constraints

Face Width to Pinion Diameter: Increase face width up to the pitch diameter of the pinion (to increase the dynamic beam strength of the gear) < 0.5.

International Research Journal of Education and Technology
Peer Reviewed Journal
ISSN 2581-7795

$$FD = \frac{FaceWidth}{PinionDiameter}$$

$$FD = \frac{F}{d_1}$$

$$FD = \frac{x_3}{d_1}$$

$$FD = \frac{x_3}{2R}$$

$$FD = \left[(x_3)/(2(0.5/x_2)\right] < 0.5$$

Center Distance: Minimum center distance can be obtained based on surface compressive stress. It's given by following equation. < 0.0

$$a = R_1 + R_2$$

Taking, $R_1 = x_1 / 2x_2$

$$R_2 = 0.5(x_1 / x_2)(Nx_1 / x_2)$$

$$a = 0.5(x_1 / x_2)(1+N)$$

Transmitted Force: Transmitted force depends on the accuracy of the gears.so dynamic load factor is added to take care of this.

T = Force(F_t) × Distance(R_1)
T = Ft × R_1

$$F_t = \frac{T}{R_1}$$

$$F_t = \frac{HP * 63028 / \omega}{(x_1 / 2x_2)}$$

Pitch Line Velocity: Increase pitch line velocity to decrease error > 0.0.

$$V_p = \frac{\omega(x_1 / 2x_2)\pi}{6} > 0.0$$

3.4 Simplified form of Optimization Problem

Subject to design constraints;

$$g(1) = \frac{x_3}{2(0.5x_1 \times x_2)} < 0.5$$

$$g(2) = 0.5(x_1/x_2)(1+N) > 0.0$$

$$g(3) = \frac{HP * 63028 / \omega}{(x_1 / 2x_2)} > 0.0$$

$$g(4) = \frac{\omega(x_1 / 2x_2)\pi}{6} > 0.0$$

$$g(5) = x_1 > 0$$

$$g(6) = x_2 > 0$$

$$g(7) = x_3 > 0$$

3.5 Method of Solution

Many non-classical optimization techniques such as the Genetic Algorithms and the Simulated Annealing have been hired to solve mechanical design problems [17]. The Teaching and learning based algorithm is a recent powerful performance algorithm used as an optional to the genetic algorithms and the simulated annealing. From this point of view, this study renders use of the Teaching and learning based algorithm to seek a global optimal solution to problem.

3.5.1 Genetic Algorithm

GAs is general optimization methods based on the principles of natural selection and evolutionary theory. The algorithm is provided with a set of possible solutions (represented by chromosomes) called a population. The solutions of a population are taken and used to form a new population. This is motivated by the hope that the new population will achieve better than its predecessors. The solutions chosen to form new solutions (excluding springs) are selected according to their reliability - the better they are, the better their chances of being reproduced. This selection process is repeated until a predetermined condition. The procedure for solving the discrete optimization problem mentioned using GA is shown in Figure 3.1.

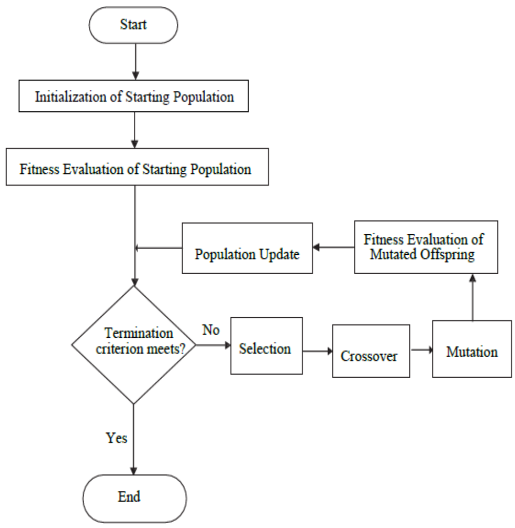

Figure 3.1: Flowchart of GA for solving problem

3.5.1.1 Genetic algorithm operators

Selection is the first genetic operator. Fitness function is evaluated for each individual in the population and at least two individuals with low fitness function are selected to form next generation. Crossover is the second genetic operator that allows producing off-spring by recombining the chromosomes of two in dividuals table.

Crossover	
Parents	
Parent1	**00000000000000** 01110110
Parent2	10100011001010 **11100100**
Off springs	
Offspring1	0111011010100011001010
Offspring2	1110010000101001011111

Table 3.1 Crossover Operation [4]

Mutation	
Individual gene before mutation	1110010**0**00101001011111
New individual gene after mutation	1110010**0**00101001011111

Table 3.2 Mutation Operation [4]

3.5.2 Teaching–learning-based optimization Algorithm

We have various types of real life optimization problem in the area of engineering. All optimization algorithms based on evolutionary intelligence and swarms require common control parameters such as population size, number of generations, elite size, and so on. In addition to the common control parameters, different algorithms require their own parameters specific to the algorithm. For example, GA uses the probability of mutation and the probability of crossing and the selection operator; The PSO uses weight of inertia and social and cognitive parameters; The ABC algorithm uses the number of bees (scout, spectator and employee) and limit. The appropriate setting of these algorithm-specific parameters is a very important factor that affects the performance of the algorithms. Inappropriate setting of the algorithm-specific parameters increases the computational effort or produces an optimal local solution. Thus, it is necessary to develop an algorithm that does not require any parameter specific to the algorithm and the pedagogical optimization (TLBO) is such an algorithm. The TLBO algorithm is an algorithm inspired by the pedagogical learning process depending on the effect of a teacher's influence on learner output in a class. The algorithm describes two basic modes of learning: (i) through the teacher (known as the teacher phase) and (ii) through interaction with other learners (known as the phase learning). In this optimization algorithm, a group of learners is regarded as a population and the various subjects offered to students are considered different design variables of the optimization problem and the result of the learner is similar to the value " physics "of the optimization problem. The best solution in the whole population is considered the teacher. The design variables are in fact the parameters involved in the objective function of the given optimization problem and the best solution is the best value of the objective function. The work of TLBO is divided into two parts, 'Teacher Phase'

and 'Learning Phase'. [4]

3.5.2.1. Teacher phase

This is the first part of the algorithm where learners learn through the teacher. During this phase, a teacher tries to increase the average score of the class in the subject taught by him according to his ability. For all iterations i, assume that there are a number "m" of subjects (ie, design variables), "n" number of learners (ie. size of (j = 1,2,..., n). The best overall result considering that all the subjects together obtained in the whole learner population can be considered as the result of the best kbest learner. However, as the teacher is usually considered a highly qualified person who trains learners so that they can have better outcomes, the best identified learner is considered by the algorithm as a teacher. The difference between the average existing result of each subject and the corresponding result of the teacher for each subject is given by,

$$Difference\_Mean_{j,k,i} = r_i(X_{j,kbest,i-T_F} M_{j,i}) \text{ ....(4.1)}$$

Where, Xj, kbest, i is the result of the best learner in subject j. TF is the teaching factor that decides the value of the means to be modified, and ri is the random number in the range [0, 1]. The value of TF can be either 1 or 2. The value of TF is decided at random with equal probability because,

TF = round [1+rand (0,1){2-1}] ....(4.2)

TF is not a parameter of the TLBO algorithm. The value of TF is not given as an input of the algorithm and its value is taken at random by the algorithm using the equation. (2). After carrying out a certain number of experiments on many

International Research Journal of Education and Technology
Peer Reviewed Journal
ISSN 2581-7795

reference functions, it is concluded that the algorithm works better if the value of TF is between 1 and 2. The teaching factor is suggested to take 1 or 2 according to the rounding criteria given by the equation. (2). Based on Difference Mean j, k, i, the existing solution is updated in the teacher phase according to the following expression.

X'j,k,i = $X_{j,k,i}$ + Difference_Mean j,k,i ....(4.3)

Where, X'j, k, i is the updated value of Xj, k, i. X'j, k, i is accepted if it gives a better function value. All accepted function values at the end of the teacher phase are maintained and these values become the entry of the learner phase. The learning phase depends on the teaching phase.

3.5.2.2 Learner phase

This is the second part of the algorithm where learners increase their knowledge through interaction between them. A learner interacts randomly with other learners to improve his / her knowledge. A learner learns new things if the other learner has more knowledge than heor she. Given the size of the population of "n", the learning phenomenon of this phase is explained below.Select two learners P and Q such that X'total-P, i ≠ X'total-Q, i (where, X'total-P, I and X'total-Q, up to Xtotal-P, i and Xtotal-Q, i of P and Q respectively at the end of the teacher's phase)

X''j,P,i = X'j,P,i + ri (X'j,P,i - X'j,Q,i) ....(4.4)

If X'total-P,i < X'total-Q,i

X''j,P,i = X'j,P,i + ri (X'j,Q,i - X'j,P,i) ....(4.5)

If X'total-Q,i < X'total-P,i

X''j,P,i is accepted if it gives a better function value.The Equation (4.4) and (4.5) are for minimization problems. In the case of maximization problems, the Equation (4.6) and (4.7) are used.

X''j,P,i = X'j,P,i + ri (X'j,P,i - X'j,Q,i) ....(4.6)

If X'total-Q,i < X'total-P,i

X''j,P,i = X'j,P,i + ri (X'j,Q,i - X'j,P,i) ....(4.7)

If X'total-P,i < X'total-Q,i

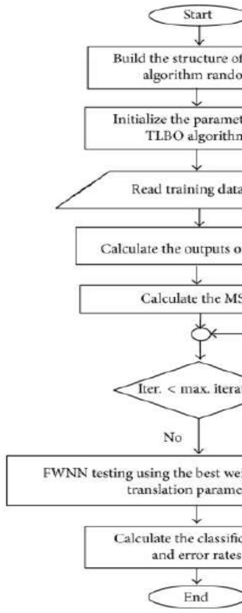

Figure 4.2: Flowchart of TLBO for solving problem.

4. RESULTS AND DISCUSSIONS

4.1 Sample Problem

A design of Spur gear drive problem has been considered for the design optimization of Spur Gear. Here objective function is considered, which minimizes the weight and it is subjected to various constraints,

Case Study	Data
Material Weight Density (ρ)	0.283 lb/in^3
Gear ratio (N)	1.5
Pinion Speed (ω)	4500 RPM
Pinion power (HP)	10 HP
Material	S45C

Minimizing Weight, Objective function,

$$f(x) = \rho_1 \pi \left(\frac{x_1}{2x_2} \right)^2 x^3 + \rho_2 \pi \left(\frac{Nx_1}{2x_2} \right)^2 x^3$$

$$g(1) = \frac{x_3}{2(0.5x_1 \times x_2)} < 0.5$$

$$g(2) = 0.5(x_1/x_2)(1+N) > 0.0$$

$$g(3) = \frac{HP * 63028 / \omega}{(x_1 / 2x_2)} > 0.0$$

$$g(4) = \frac{\omega(x_1 / 2x_2)\pi}{6} > 0.0$$

$$g(5) = x_1 > 0$$

$$g(6) = x_2 > 0$$

$$g(7) = x_3 > 0$$

Center Distance = 0.5(x1/x2)(1 + N)
= 0.5(x1/x2)(1 + 1.5)

$$= \frac{1.25 \times x_1}{x_2}$$

$$\text{Transmitted Force } = \frac{HP63025/\omega}{(x_2/2x_2)}$$

$$= \frac{60 \times 10 \times 63025/4500}{(x_2/2x_2)}$$

$$= \frac{16806.67 x_2}{x_1}$$

$$\text{Pitch Line Velocity } = \frac{\omega(x_1/2x_2)\pi}{6}$$

$$= \frac{4500 \times (x_1/2x_2) \times 3.14}{6}$$

$$= \frac{1177.5 x_1}{x_2}$$

Minimizing Weight, Objective function,

$$weight = \rho_1 \pi \left(\frac{x_1}{2x_2}\right)^2 x^3 + \rho_2 \pi \left(\frac{Nx_1}{2x_2}\right)^2 x^3$$

$$= 0.283 \times 3.14 \left(\frac{x_1}{2x_2}\right)^2 x^3 + 0.283 \times 3.14 \left(\frac{1.5 \times x_1}{2x_2}\right)^2 x^3$$

$$f(x) = 0.8887 \left(\frac{x_1}{2x_2}\right)^2 x^3 + 0.8887 \left(\frac{1.5 \times x_1}{2x_2}\right)^2 x^3$$

Subject to design constraints;

$$g(1) = \frac{x_3}{2(0.5x_1 \times x_2)} < 0$$

$$g(2) = \frac{1.25 \times x_1}{x_2} > 0.0$$

$$g(3) = \frac{16806.67x}{x_2} > 0$$

$$g(4) = \frac{1177.5 \times x_1}{x_2} > 0.0$$

$$g(5) = x_1 > 0.0$$

$$g(6) = x_2 > 0.0$$

$$g(7) = x_3 > 0.0$$

4.2 Sample Problem

Result	Analytical	GA
Number of Teeth(x_1)	20.395	20
Diametral Pitch(x_2)	13.91 in^{-1}	10 in^{-1}
Face Width(x_3)	0.73 in	0.5 in
Weight	1.1376 Pounds	1.1376 Pounds

5. CONCLUSIONS

It is concluded that under given power transmission and gear ratio the weight is minimized. It gives several combinations of face width, teeth and Diametral pitch of spur gear from them one best pair is selected which satisfies all the constraints. While using GA, optimum weight is almost similar to analytical answer.
Results obtained from GA shows that under the satisfaction of all the constraints it gives the optimal weight for design problem, and GA shows the better performance with less computational effort for large scale problem. For the given case study, the results are obtained with PSO and TLBO which are better to find the global minima for any constrained optimization problem. And this algorithm can easily be applied to other optimization problem like design of any components, transportation problem, inventory control and in production planning and control.

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