OPTIMIZATION AND SIMULATION OF COMPOSITE DRIVESHAFT FOR AUTOMOBILE APPLICATIONS

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ABSTRACT

Optimization of stacking sequence in laminates will greatly improve the mechanical properties without weight penalty. In this paper an attempt has been made to optimize ply stacking sequence of single piece E-Glass/Epoxy, Boron/Epoxy, and Kevlar 49/Epoxy composite drive shafts using particle swarm optimization algorithm (PSOA). Particle swarm optimization algorithm is a population based evolutionary stochastic optimization technique, which is a heuristic search method where mechanics are inspired by swarming or collaborative behavior of biological population. PSOA programme is developed using MATLAB V 7 to optimize the ply stacking sequence with an objective of weight minimization by considering design constraints as torque transmission capacity, fundamental natural frequency, lateral vibration, torsional buckling strength and number of laminates, ply thickness, and stacking sequence as design variables. The weight savings of the E-Glass/Epoxy, Boron/Epoxy, and Kevlar 49/Epoxy composite shaft are 51%, 85% and 61.26% respectively considering weight of steel shaft as reference. Simulation analysis is carried out for optimized PSOA results using solver
ABAQUS/CAE 6.7. The results of simulation is compared with theoretical values and found that they have good agreement with each other. The optimized single piece composite shaft can be used as a potential replacement of conventional two piece steel drive shaft for automobile applications.

Key words: Composite driveshaft, Optimization, ply stacking sequence, PSOA, MATLAB, Simulation

1. INTRODUCTION

Composite material are preferred in automotive applications because of their high strength to weight ratio, high stiffness to weight ratio and other designable properties compared with metals. Composite drive shaft applications have received new impetus during last decade. Many researchers [1, 2, 3, 4, & 5] have investigated the composite shaft for drive line application.

As composites are increasingly used, optimization technique becomes more and more important in the design of laminate because of the complexity and enormous design space. In structural optimization, a number of efficient optimization algorithms like genetic algorithm, simulated biological growth, simulated annealing, ant colony, particle swarm algorithm etc., mimicking natural phenomena and physical processes have been applied. T. Rangaswamy et al. [6 & 7] have used genetic algorithm for ply stacking sequence optimization of composite drive shaft.

Recently particle swarm optimization has become a common heuristic technique in the optimization community, with many researchers exploring the concepts, issues, and applications of the algorithm. Particle swarm optimization algorithm (PSOA) is an evolutionary computation technique developed by James Kennedy and Russell C. Eberhart [8 & 9], which is inspired by the social behavior of bird flocking and fish schooling. From the literature review, it is observed that a number of papers [12, 13, &14] have published in past few years to solve engineering structural problems.

R.E. Perez and K. Behdinan [15] and Nan Chang et al. [16] have used PSOA to generate optimal stacking sequence for structural optimization problems. But the PSOA has not been applied for the ply stacking sequence optimization of composite drive shafts for automobile applications until now.
In this work, an optimized ply stacking sequence of single piece E-Glass/Epoxy, Boron/Epoxy and Kevlar 49/Epoxy composite drive shafts is obtained using particle swarm optimization algorithm and composite drive shaft simulation is performed by rotating at a speed of 6500rpm using ABAQUS 6.7 solver.

2. PROBLEM FORMULATION

All automobiles having rare wheel drive have to transmit torque from the engine to the differential gear box. It is known that the fundamental bending natural frequency of the shaft or critical speed of the shaft is inversely proportional to the square of the shaft length. Hence to increase the critical speed, the conventional rear wheel transmission shafts are used in two pieces. The use of two piece drive shafts results in increase in manufacturing costs, less efficiency, more weight. It is possible to replace a two piece steel drive shaft with a single piece composite drive shaft having high fundamental bending natural frequency, reduced weight, high torsional buckling capability, and more torque transmission capabilities.

The common goal in designing a composite drive shaft is to obtain lighter weight shaft under the given functional and geometrical constraints such as static torque transmission capability, torsional buckling and the fundamental natural bending frequency.

2.1 OBJECTIVE FUNCTION

The objective function considered for the optimum design of composite drive shaft is the minimization of weight given by,

\[ w = \rho AL \quad \text{or} \quad w = \rho \frac{\pi}{4} \left( d_o^2 - d_i^2 \right) L \]

(1)

Where \( w \) = weight of shaft, \( \rho \) = density of the shaft material, \( d_i \) = inner diameter of the shaft, \( d_o \) = outer diameter of the shaft, and \( L \) = length of the shaft.

For the optimum design of composite drive shaft the design variables considered with their limiting values is shown in Table 1.
2.2 DESIGN VARIABLES

In optimization techniques, the design variables are very sensitive in altering the value of objective function. The design variables considered with their limiting values are number of plies \( n \), stacking sequence \( \theta_k \) and thickness of the ply \( t_k \) are shown in Table 2. The number of plies required depends on the design constraints, allowable material properties, thickness of plies and stacking sequence. Based on reference [2], the numbers of plies considered are 32.

<table>
<thead>
<tr>
<th>Design variables</th>
<th>Limiting values of the design variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of plies ([n])</td>
<td>( n &gt; 0 ; \quad n = 1, 2, 3 \ldots 32 )</td>
</tr>
<tr>
<td>Stacking Sequence ([\theta_k])</td>
<td>(-90 \leq \theta_k \leq 90 ; \quad k = 1, 2 \ldots n)</td>
</tr>
<tr>
<td>Thickness of the ply ([t_k])</td>
<td>( 0.1 \leq t_k \leq 0.5 )</td>
</tr>
</tbody>
</table>

Table 2 Design parameters of steel and composite drive shafts.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Steel (SM45C)</th>
<th>E-Glass /Epoxy</th>
<th>Boron /Epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D_0 )</td>
<td>Mm</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>( L )</td>
<td>Mm</td>
<td>1250</td>
<td>1250</td>
<td>1250</td>
</tr>
<tr>
<td>( T_{max} )</td>
<td>Nm</td>
<td>3500</td>
<td>3500</td>
<td>3500</td>
</tr>
<tr>
<td>( N_{max} )</td>
<td>Rpm</td>
<td>6500</td>
<td>6500</td>
<td>6500</td>
</tr>
<tr>
<td>( t_k )</td>
<td>mm</td>
<td>3.318</td>
<td>0.4</td>
<td>0.12</td>
</tr>
</tbody>
</table>

2.3 DESIGN PARAMETERS

Design parameters are sensitive in changing the objective function value but required to be kept as constants and parameters considered given in Table 3 taken from reference [2].

Table 3 Input parameters to particle swarm optimization algorithm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertia weight, ( w )</td>
<td>Varies in between 0 to 1</td>
</tr>
<tr>
<td>Random numbers, ( r_1 ) and ( r_2 )</td>
<td>Varies in between 0 to 1</td>
</tr>
<tr>
<td>Leaning Factors, ( C_1 ) and ( C_2 )</td>
<td>2</td>
</tr>
<tr>
<td>Particle Size</td>
<td>50</td>
</tr>
<tr>
<td>Number of swarms</td>
<td>150</td>
</tr>
</tbody>
</table>
2.4 DESIGN CONSTRAINTS

The constraint equations for the problem of optimum design of composite drive shafts are given below.

1. Torque transmission capacity of the shaft : \( T \geq T_{\text{max}} \)
2. Bucking torque capacity of the shaft : \( T_{\text{cr}} \geq T_{\text{max}} \)
3. Lateral fundamental natural frequency : \( N_{\text{crit}} \geq N_{\text{max}} \)

Where \( T \) is torque transmission capacity of the shaft, N-mm, \( N_{\text{crit}} \) is Critical speed in rpm, \( N_{\text{max}} \) Maximum speed of the shaft in rpm, \( T_{\text{max}} \) Ultimate torque, N-m, \( T_{\text{cr}} \) Torsional buckling capacity of the shaft, N-mm

The constraint equations \( C_1 \), \( C_2 \) and \( C_3 \) may be written as:

1. \( C_1 = \left(1 - \frac{T}{T_{\text{max}}} \right) \quad \text{If} \quad T < T_{\text{max}} \)
   \( = 0 \quad \text{otherwise} \)
2. \( C_2 = \left(1 - \frac{T_{\text{cr}}}{T_{\text{max}}} \right) \quad \text{If} \quad T_{\text{cr}} < T_{\text{max}} \)
   \( = 0 \quad \text{otherwise} \)
3. \( C_3 = \left(1 - \frac{N_{\text{crit}}}{N_{\text{max}}} \right) \quad \text{If} \quad N_{\text{crit}} < N_{\text{max}} \)
   \( = 0 \quad \text{otherwise} \) \quad (2)

\[ C = \sum_{i=1}^{3} C_i \quad (3) \]

The constrained optimization can be converted to unconstrained optimization by modifying the objective function as \( \Phi = m \left(1+k_1C\right) \) and for all practical purposes, \( k_1 \) is a penalty constant and is assumed to be 10 taken from reference [2].

3. PARTICLE SWARM OPTIMIZATION ALGORITHM

In particle swarm optimization algorithm [8], each individual in the particle swarm is composed of three D-Dimensional vectors, where D is the dimensionality of the search space.
The algorithm of PSOA is given below,

1. Initialize a population array of particles with random positions and velocities on D dimensions in the search space.
2. Start of loop
3. For each particle, evaluate the desired optimization fitness function in D variables.
4. Compare particle’s fitness evaluation with its pbest, if current value is better than previous pbest, then set pbest equal to the current value, and X equal to the current location X in D-Dimensional space.
5. Identify the particle in the neighborhood with the best success so far, and assign its index to the variable gbest
6. Change the velocity and position of the particle according to the to the following equation

   \[ V_{i+1} \leftarrow V_i + C_1 r_1 (pbest-X_i) + C_2 r_2 (gbest-X_i), \]  

   \[ X_{i+1} \leftarrow X_i + V_{i+1} \]  

Where \( X_{i+1} \) is current position, \( X_i \) and \( V_i \) is the previous best position and the velocity, \( w \) is inertia weight, \( pbest[\ ] & gbest[\ ] \) are particle best & global best, \( rand(\ ) \) is a random number and \( C_1 \) (cognitive parameter), \( C_2 \) (social parameter) are the learning factors.
7. if a criterion is met (usually a sufficiently good fitness or a maximum number of iterations), exit loop
8. End loop

The flow chart shown in figure 1 describes the working of PSOA and the input parameters considered for PSOA are shown in Table 4.
Table 4 Results of particle swarm optimization algorithm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Steel (SM45C)</th>
<th>E-Glass/ Epoxy</th>
<th>Boron/ Epoxy</th>
<th>Kevlar 49/ Epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimum Layers</td>
<td>-</td>
<td>16</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>Thickness, t (mm)</td>
<td>3.32</td>
<td>6.4</td>
<td>1.8</td>
<td>6.8</td>
</tr>
<tr>
<td>T (Nm)</td>
<td>3501</td>
<td>3508</td>
<td>3519</td>
<td>3519</td>
</tr>
<tr>
<td>$T_{cr}$ (Nm)</td>
<td>43858</td>
<td>31967</td>
<td>3850</td>
<td>22925</td>
</tr>
<tr>
<td>$N_{cr}$ (rpm)</td>
<td>9320</td>
<td>6520</td>
<td>9838</td>
<td>6533</td>
</tr>
<tr>
<td>Weight (N)</td>
<td>86</td>
<td>42</td>
<td>12</td>
<td>33.33</td>
</tr>
<tr>
<td>Weight saving in (%) considering steel shaft weight as datum</td>
<td>-</td>
<td>51</td>
<td>85</td>
<td>61.26</td>
</tr>
</tbody>
</table>

Start

Initialize particles with random position and velocity

For each particle’s position (X), evaluate fitness

Fitness (X) > Fitness (pbest)

Yes  \[\text{pbest} = X\]

No  Reject that Particle

For all particles

$\text{pbest} = \text{gbest}$

Update Particle Velocity and Position

Stop: Giving gbest, Optimal Solution

Figure 1 Flow chart of particle swarm optimization.
4. PARTICLE SWARM OPTIMIZATION PROGRAMME

Particle swarm optimization program is developed and runned using MATLAB V 7 to perform the optimization process and to obtain the best optimal design values. The ply stacking sequence is optimize with an objective of weight minimization by considering design constraints as torque transmission capacity, fundamental natural frequency, lateral vibration, torsional buckling strength and number of laminates, ply thickness, and stacking sequence as design variables.

The design algorithm of composite drive shaft and the flow-chart describing the step by step procedure for optimizing the composite drive shaft using PSOA are shown in Figures 2 and 3 respectively. The optimum ply stacking sequence, torque transmission capability, critical speed, and weight savings for E-glass, Boron /Epoxy and Kevlar 49/Epoxy obtained from PSOA is given in Table 5. The graph of variation of objective function for E-glass/Epoxy, Boron /Epoxy, and Kevlar 49/Epoxy shafts with respect to swarm size are shown in Figures 4, 5 and 6.

Table 5 Comparison of simulated results of shear strength

<table>
<thead>
<tr>
<th>Description</th>
<th>Steel</th>
<th>E-Glass/Epoxy</th>
<th>Boron/Epoxy</th>
<th>Kevlar49/Epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical shear stress (MPa)</td>
<td>175</td>
<td>191</td>
<td>312</td>
<td>461</td>
</tr>
<tr>
<td>Simulated shear stress from FEA(MPa)</td>
<td>185.30</td>
<td>163.10</td>
<td>329.90</td>
<td>329.10</td>
</tr>
</tbody>
</table>
Input material properties, thickness of ply, calculate $q_{ij}$ matrix

Initialize angle of ply, calculate $Q_{ij}$ matrix

Compute $[A] [B]$ & $[D]$ matrix

Find the inversion of $[A] [B]$ &

Compute the laminate properties $E_x$, $E_y$, $G_{xy}$, $V_{xy}$

Calculate the lateral vibration of the shaft by theories Bernoulli theory and Timoshenko theory.

Calculate for torque transmission capacity and torsional buckling strength

Impose design constraints

If $N_{cr}<N_{ma}$

Yes: $C_3 = (1-N_{cr}/N_{max})$

No: $C_3 = 0$

If $T<T_{max}$

Yes: $C_2 = (1-T/T_{max})$

If $T_{cr}<T_{cr_{max}}$

No: $C_2 = 0$

$C = C_1 + C_2 + C_3$

$\Phi = m(1+k_1C)$, where $k = 10$

TO

PSO algorithm

Figure 2 Design algorithm of composite drive shaft.
Randomly Generate Positions and velocities

Evaluate individual Fitness

Store pbest of each swarm and gbest of Smax swarms

Swarm = 1

Randomly Generate position and velocity

Generate values for inertia weight, r1 and r2. Assume C1 = C2 = 2

Compute current velocity and current position

Update pbest

Yes

If Particle < Pmax ?

No

Update gbest

Swarm = swarm + 1

Yes

If swarm ≤ Smax ?

No

Print best values of the variables, constraints and weight.

Stop

Input: Particle Size (Pmax), Swarm Size (Smax), Material Properties, Tmax, Nmax, etc.

Figure 3 Flow chart of PSA based optimal design of composite drive shaft.
Figure 4 Variations of weight in E-Glass/Epoxy drive shafts with swarm size.

Figure 5 Variations of weight in Boron/Epoxy drive shafts with swarm size.
5. SIMULATION OF STEEL AND COMPOSITE DRIVE SHAFTS

Simulation is a process of designing a model of a real system to understand the behavior of the system to shorten the product development cycle and to reduce the chances of failure to meet specifications, and reduce the dependence on physical prototyping, the resources, and to optimize system performance.

Simulation analysis is carried out for optimized results of PSOA using solver ABAQUS version 6.7. The finite element model is created for single piece steel and composite shafts and constrained such that the shaft can rotate only about its axis. A rotation of 6500rpm is given to drive shaft to simulate the live shear and vonmises stress distribution as shown in Figure 7 to 13.

![Graph showing variations of weight in Kevlar49/Epoxy drive shafts with swarm size.](image)

**Figure 6** Variations of weight in Kevlar49/Epoxy drive shafts with swarm size.

![Bar chart showing weight distribution in different composite materials.](image)

**Composite materials**

- E-Glass/Epoxy: 42.62%
- Boron/Epoxy: 12.5%
- Kevlar/Epoxy: 33.33%
Figure 8 Shear stress distribution of steel.

Figure 9 Vonmises stress distribution of steel.
Figure 10 Shear stress distributions of E-Glass /Epoxy.

Figure 11 Vonmises stress distribution of E-Glass/Epoxy.
Figure 12 Shear stress distributions of Boron/Epoxy.

Figure 13 Vonmises stress distribution of Boron/Epoxy.
Figure 14 Shear stress distributions of Kevlar/Epoxy.

Figure 15 Vonmises stress distribution of Kevlar/Epoxy.
6. RESULTS AND DISCUSSION

Optimized ply stacking sequence are obtained using PSOA with an objective of weight minimization of composite drive shaft. The variation of objective function found for the first 135 swarm size of E-glass/Epoxy shaft, 90 swarm sizes of Boron/Epoxy and 140 swarm sizes of Kevlar 49 /Epoxy shaft respectively and the weight is reduced to a minimum from generation numbers 120 in E-Glass/Epoxy, 90 in Boron /Epoxy and 125 in Kevlar 49/Epoxy shaft respectively and later they get converged. The percentage of weight savings of E-glass/Epoxy, Boron /Epoxy and Kevlar 49 /Epoxy shafts are 51%, 85% and 61.26% respectively taking weight of steel shaft as basis is shown in Figure 11.

Simulation analysis is carried out for optimized results of composite drive shaft using ABAQUS 6.7 solver. The obtained simulated results of shear and vonmises stress distribution are tabulate in Table 5 and 6 respectively. From the table it is observed that shear stress and vonmises developed in composite drive shaft materials are lesser than their theoretical value, which implies that single piece composite drive shaft are suitable for automobile applications but steel shafts are not suitable.

Table 6 Comparison of simulated results of vonmises stress

<table>
<thead>
<tr>
<th>Description</th>
<th>Steel</th>
<th>E-Glass/Epoxy</th>
<th>Boron/Epoxy</th>
<th>Kevlar49/Epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical Vonmises stress (Mpa)</td>
<td>370</td>
<td>800</td>
<td>1260</td>
<td>1400</td>
</tr>
<tr>
<td>Simulated Vonmises stress from FEA (MPa)</td>
<td>472.20</td>
<td>625</td>
<td>1176</td>
<td>651.80</td>
</tr>
</tbody>
</table>

6. CONCLUSIONS

- PSOA uses less number of function evaluations and has better searching capability and more computationally efficient algorithm.
- An optimal stacking sequence of composite drive shaft is generated using PSOA to minimize the weight to meet the functional and performance requirements.
- E-glass/Epoxy, Boron /Epoxy, and Kevlar 49/Epoxy materials are considered for single piece composite drive shaft.
- Composite materials are best suitable for single piece drive application in passenger vehicles.
Acknowledgement: Prof.(Dr) T. Rangaswamy, Department of Mechanical Engineering, Malnad College of Engineering, Hassan for his valuable suggestions to carry out the research work.

7. REFERENCES


