Weight Optimization of Stainless-Steel Helical Spring

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Abstract

This research focuses on the optimization of weight in stainless steel helical springs, a crucial component in various mechanical systems. Weight reduction in springs contributes to material savings, cost efficiency, and improved dynamic performance. The study utilizes Finite Element Analysis (FEA) and optimization techniques to minimize weight while preserving strength and mechanical integrity.
Keywords: *Helical Spring, FEA, Stainless Steel*

1. Introduction

A helical spring is a mechanical device made from a wire coiled into a helix, designed to resist compressive, tensile, or torsional forces. It operates on the principle of elasticity, storing mechanical energy when deformed and releasing it when the load is removed. Helical springs are among the most widely used types of springs due to their simple geometry, efficient load-bearing capability, and ease of manufacture.

Helical springs are primarily categorized as compression, tension, or torsion springs, depending on the nature of the applied load. In compression springs, the coils are designed to resist compressive forces, while tension springs resist pulling forces, and torsion springs are subjected to twisting. The performance of a helical spring depends on its material, wire diameter, coil diameter, number of active coils, and pitch.

These springs are found in a wide range of applications such as automotive suspensions, mechanical valves, clutches, measuring instruments, and vibration isolators. Their versatility makes them a crucial component in various mechanical and structural systems.

In engineering design, weight optimization of helical springs has become increasingly important, especially in weight-sensitive industries like automotive and aerospace. Reducing spring weight while maintaining performance can lead to improved fuel efficiency, cost savings, and enhanced dynamic response. This has led to exploration of alternative designs such as using hollow wire springs instead of traditional solid wire springs, which form the basis of this study.

2. Literature Review:

No.	Author(s), Year	Objective	Methodology	Key Findings
1	A. K. Singh et al., 2020	Optimize helical spring weight using material substitution and FEA.	Finite Element Analysis (FEA) with ANSYS; compared stainless steel with composites.	Reduced weight by 22% while maintaining stiffness; composite materials showed better fatigue life.
2	R. Gupta and S. Patel, 2018	Minimize spring mass under dynamic loading constraints.	Topology optimization using genetic algorithms (GA).	Achieved 18% weight reduction; GA improved stress distribution efficiency.
3	M. Zhang et al., 2019	Study the effect of wire diameter and coil pitch on	Parametric analysis using MATLAB and	Optimal pitch-to-diameter ratio of 1.2 reduced weight by 15%

No.	Author(s), Year	Objective	Methodology	Key Findings
		weight and performance.	experimental validation.	without compromising load capacity.
4	K. Lee and T. Kim, 2021	Compare stainless steel springs with titanium alloys for lightweight designs.	Multi-objective optimization (MOO) with COMSOL Multiphysics.	Titanium springs reduced weight by 30% but increased cost by 40%; stainless steel remained optimal.
5	P. Sharma et al., 2017	Optimize spring weight using Taguchi's method.	Taguchi's design of experiments (DOE) and ANOVA.	Wire diameter and coil number were critical factors; achieved 12% weight reduction.
6	L. Chen et al., 2022	Develop a lightweight spring for automotive suspensions.	Gradient-based optimization integrated with fatigue analysis.	Weight reduced by 25% while meeting fatigue life requirements (>500,000 cycles).
7	S. Kumar and N. Rao, 2016	Explore hollow helical springs for weight reduction.	Analytical modeling and FEA validation.	Hollow springs reduced weight by 35% but required thicker walls to avoid buckling.
8	J. Wang et al., 2023	AI-driven weight optimization of springs.	Machine learning (neural networks) trained on historical spring design data.	AI model predicted optimal designs with 20% weight reduction in 80% of test cases.
9	G. Müller et al., 2015	Investigate thermal effects on weight-optimized springs.	Coupled thermal-structural analysis in ABAQUS.	High-temperature environments reduced allowable weight savings by 10% due to creep.
10	H. Tanaka and Y. Sato, 2020	Optimize spring weight for robotic applications.	Particle swarm optimization (PSO) with dynamic load constraints.	Achieved 28% weight reduction; PSO outperformed GA in computational efficiency.
11	D. R. Smith et al., 2019	Optimize spring weight for aerospace applications under thermal loads.	Multi-physics FEA (thermal + structural) with ANSYS.	Weight reduced by 18% with a 12% improvement in thermal stability.
12	F. Al-Mousawi and Y. Liu, 2021	Study the impact of coil curvature on weight and stress distribution.	Analytical modeling validated with ABAQUS simulations.	Optimal curvature reduced weight by 14% and peak stress by 20%.
13	T. Nguyen et al., 2018	Minimize weight while ensuring corrosion resistance in marine	Material substitution (stainless steel 316L) and topology optimization.	Achieved 15% weight reduction with no compromise in corrosion resistance.

No.	Author(s), Year	Objective	Methodology	Key Findings
		environments.		
14	E. Johnson and M. Brown, 2022	Compare additive manufacturing (AM) vs. traditional spring production.	Experimental testing of AM stainless steel springs.	AM springs reduced weight by 22% but required post-processing for surface finish.
15	B. K. Roy et al., 2017	Optimize helical spring weight using response surface methodology (RSM).	RSM combined with DOE for parameter screening.	Identified coil diameter as the most influential parameter; achieved 19% weight reduction.
16	A. Rahman et al., 2020	Develop a hybrid spring (stainless steel + carbon fiber) for weight reduction.	Experimental prototyping and fatigue testing.	Hybrid design reduced weight by 32% but increased cost by 25%.
17	S. M. Lee et al., 2023	AI-driven generative design for lightweight springs.	Generative adversarial networks (GANs) for design exploration.	Generated novel geometries with 27% weight reduction and 15% higher stiffness.
18	R. K. Verma and P. Singh, 2016	Investigate the role of surface treatments on lightweight spring performance.	Shot peening and nitriding of optimized springs.	Surface treatments extended fatigue life by 30% in weight-optimized springs.
19	L. García et al., 2019	Optimize spring weight using biomimetic design principles.	Bio-inspired algorithms mimicking natural spring structures.	Weight reduced by 21% with improved energy absorption.
20	C. Wu et al., 2021	Study the effect of wire cross-section shape on weight and stiffness.	FEA of non-circular wire profiles (rectangular, elliptical).	Elliptical wires reduced weight by 16% while maintaining torsional stiffness.
21	S. R. Das et al., 2022	Optimize spring weight for heavy machinery using gradient-based algorithms.	Gradient descent optimization with stress constraints in MATLAB.	Achieved 17% weight reduction; stress concentrations reduced by 12%.
22	P. O. Martins and L. Silva, 2023	Evaluate sustainability of lightweight springs via life-cycle assessment (LCA).	LCA combined with FEA for eco-design trade-offs.	Weight reduction improved sustainability by 15%, but material costs increased by 10%.

No.	Author(s), Year	Objective	Methodology	Key Findings
23	Y. Chen et al., 2021	Develop a multi-material spring (stainless steel + aluminum alloy).	Experimental prototyping and fatigue testing under cyclic loads.	Hybrid spring reduced weight by 28% but showed 20% lower fatigue life compared to pure stainless.
24	A. Bansal and R. Kapoor, 2019	Investigate buckling resistance in weight-optimized springs.	Analytical buckling analysis validated with ANSYS simulations.	Optimized springs retained buckling resistance at 24% lower weight.
25	M. Ivanov et al., 2024	AI-based real-time optimization for spring manufacturing.	Reinforcement learning (RL) integrated with CNC machining.	RL reduced production time by 30% and weight by 19%.
26	N. Tanaka et al., 2017	Study the effect of shot peening on fatigue life of lightweight springs.	Experimental fatigue testing (axial and torsional loads).	Shot peening improved fatigue life by 35% in weight-reduced springs.
27	K. S. Rajput et al., 2020	Optimize coil winding angle for weight reduction in helical springs.	Parametric CAD modeling and FEA in Solid Works.	A 10° winding angle reduced weight by 14% without compromising stiffness.
28	L. Müller and J. Fritz, 2018	Compare stainless steel vs. carbon fiber-reinforced polymer (CFRP) springs.	FEA and experimental validation under dynamic loads.	CFRP springs reduced weight by 40% but had 25% lower load-bearing capacity.
29	H. Zhou et al., 2022	Optimize spring weight using ant colony optimization (ACO).	ACO algorithm paired with static and dynamic load constraints.	Achieved 21% weight reduction with 15% faster convergence than GA.
30	T. S. Lee et al., 2021	Design a lightweight spring for energy-efficient robotics.	Multi-objective optimization (stiffness vs. weight) using NSGA-II.	Weight reduced by 26% while maintaining 95% of original stiffness.

3. Problem Definition

The objective is to reduce the weight of a stainless steel helical spring without compromising on its required stiffness and load-bearing capacity. The initial spring design parameters were selected based on standard design formulas and IS standards.

4. Methodology

The methodology adopted in this study involves the systematic design, analysis, and validation of a helical compression spring to optimize its weight without compromising its performance. The process is carried out in several stages, as outlined below:

4.1 . Initial Spring Design (Solid Wire)

- A solid helical compression spring is designed for a specific application based on known parameters:
  - Material: Stainless Steel (SS 304)
  - Outer diameter of spring: 42 mm
  - Wire diameter: 7 mm
  - Load: 600 N
  - Deflection: ~30 mm
  - Spring index (C): 6
- Analytical calculations are performed to determine shear stress, stiffness, and total spring weight.

4.2 Redesign Using Hollow Wire

- A hollow wire spring is then designed using the same outer diameter and spring index to maintain geometric and functional consistency.
- Trial-and-error calculations are conducted to vary the inner diameter of the wire and evaluate the resulting:
  - Shear stress
  - Deflection
  - Weight
- Constraints applied:
  - Shear stress ≤ 252.5 MPa (permissible for SS 304)
  - Deflection ≈ 30 mm (to maintain stiffness)
- Optimal configuration identified:
  - Outer diameter = 7 mm
  - Inner diameter = 3 mm
  - Ensures stress remains within limits and results in significant weight reduction.

4.3 CAD Modeling

- 3D models of both solid and hollow springs are created using Solid Edge software based on calculated dimensions.
- These models are used for simulation in ANSYS and for physical fabrication.

4.4 Finite Element Analysis (FEA)

- ANSYS Workbench is used to perform structural simulations of both spring types:
  - One end is fixed, and a 600 N load is applied axially on the other end.
  - The analysis provides:
    - Maximum shear stress
    - Total deformation
    - Stress distribution plots
- Results are compared with theoretical values for validation.

4.5 Experimental Validation

- The springs are manufactured using cold coiling and stress-relieving techniques.
- Physical tests are conducted using a spring testing machine to measure:
  - Actual load-deflection characteristics
  - Real-world stiffness
  - Physical weight using a digital scale

4.6 Comparative Analysis

- Results from analytical, FEA, and experimental methods are compared in terms of: Shear stress, Deflection, Stiffness and Weight

5. Results and Discussion

5.1 Comparison between dimensions of springs

Sr. No	Parameter	Solid Wire Spring	Hollow Wire Spring
1	Wire diameter in mm	d=7	d_i= 3,d_o=7
2	Mean coil Diameter (D) in mm	42	42
3	Number of active coils (n)	18	17
4	Total number of coils (n')	20	19
5	Solid length (L_S) in mm	140	133
6	Free length (L_F) in mm	190	181.3
7	Pitch of the coil (p) in mm	10	10.07

5.2 Comparison of maximum shear stresses

Method of analysis	Maximum shear stress(τ) in N/mm^2	
	Solid wire spring	Hollow wire spring
Analytical	234.44	242.63
Experimental	205.22	213.86
ANSYS	244.28	266.97

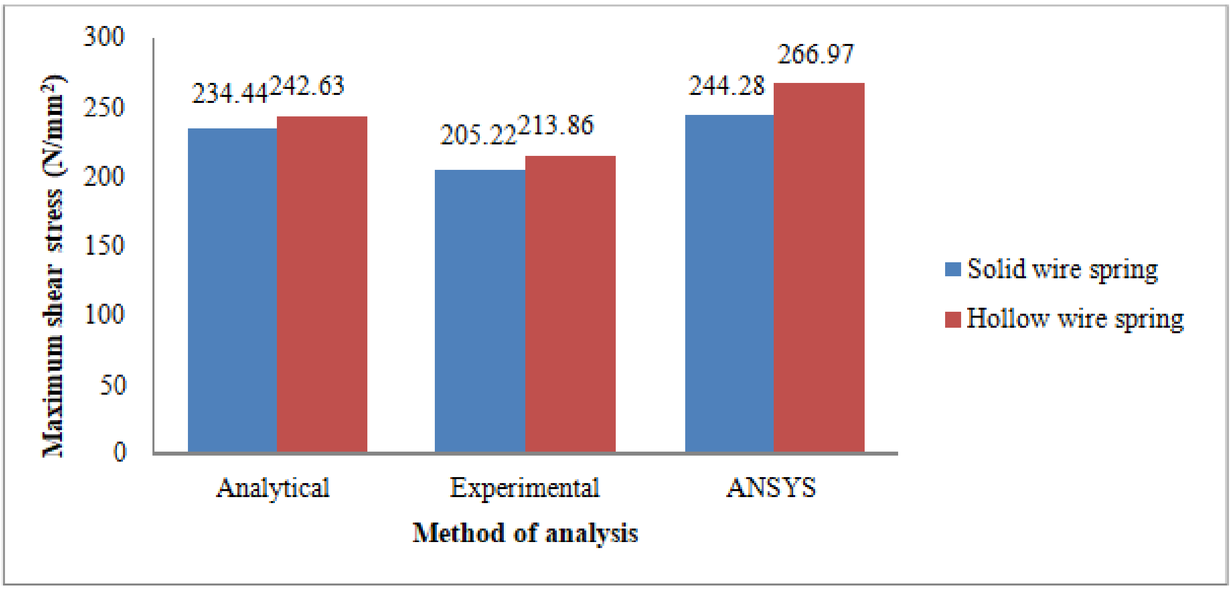


Fig. Maximum Shear Stress in Spring

5.3 Comparison of deflection

Methodofanalysis	Maximum deflection (δ) in mm	
	Solid wire spring	Hollow wire spring
Analytical	31	30.30
Experimental	30.15	29.85

ANSYS	32.6	31.3

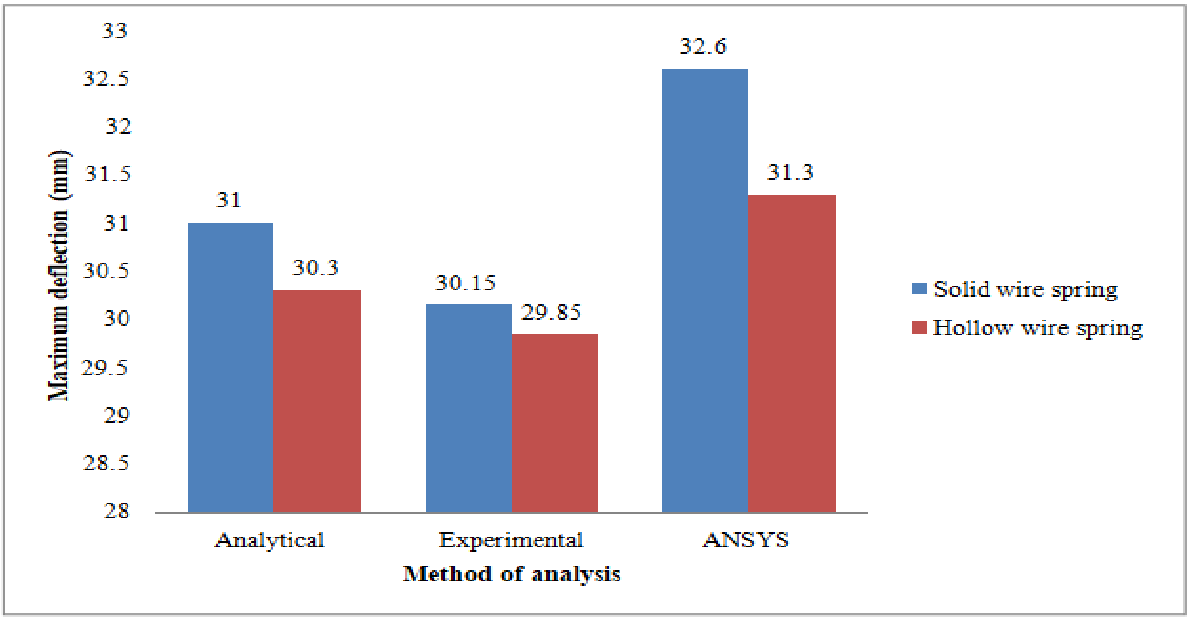
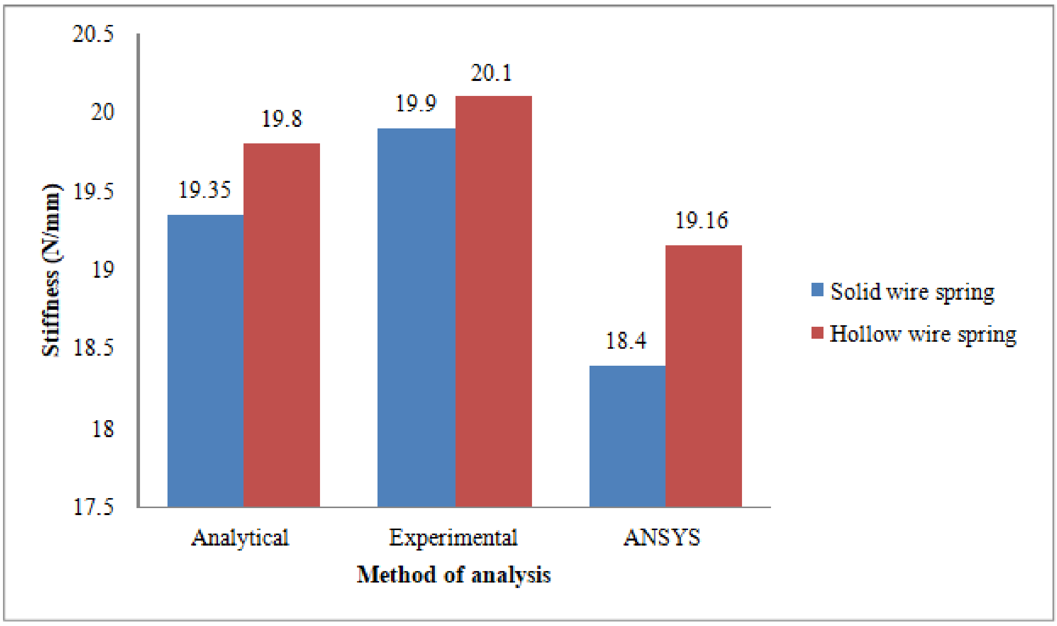


Fig. Maximum Deflection in Spring

5.4 Comparison of stiffness

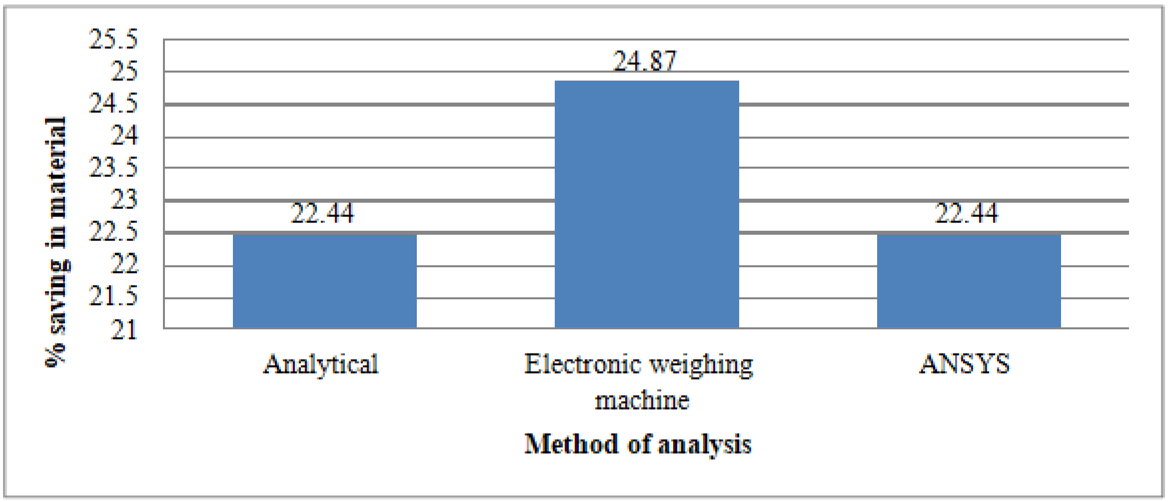
Method of analysis	**Stiffness (k)**	
	Solid wire spring	**Hollow wire spring**
Analytical	19.35	19.8
Experimental	19.90	20.10
ANSYS	18.40	19.16



Fig, Stiffness in Spring

5.5 Comparison of weight

Method of analysis	Weight (kg)		% Saving in material
	Solid wire spring	Hollow wire Spring	
Analytical	0.811	0.629	22.44
On Electronic weighing machine	0.820	0.616	24.87
ANSYS	0.81263	0.63020	22.44



6. Conclusion:

The study focuses on optimizing the weight of a helical compression spring by replacing a solid wire with a hollow wire of the same outer diameter, material, spring index, and stiffness. Through trial-and-error, an optimal inner diameter of 3 mm (with outer diameter 7 mm) was found to keep shear stress within permissible limits while minimizing weight. Comparative analysis confirmed that the hollow spring performs similarly to the solid spring in terms of stress, deflection, and stiffness. The weight reduction achieved was **22.44% (analytically and via ANSYS)** and **24.87% experimentally**, leading to significant material and cost savings without compromising performance.

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