iJRASET
International Journal For Research in Applied Science and Engineering Technology



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 5 **Issue:** XI **Month of publication:** November 2017

DOI:

www.ijraset.com

Call: 08813907089 | E-mail ID: ijraset@gmail.com

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor:6.887
Volume 5 Issue X1, November 2017- Available at www.ijraset.com

An Efficient Approach for Reliability Analysis and Reliability Based Design Optimization of Helical Spring

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Abstract: ***As the mathematical tools with the help of modern computers has widely been applied to most of the engineering design and problems, the performance of the modern engineering systems are achieving the best of it. The implementation of deterministic design optimization tools to the machine element design and manufacturing systems are certainly improved the overall productivity in all fields But there had been the presence of inherent uncertainties by nature in every design and analysis due to the error that occurs by man, machine, material, methods, measurements and service conditions, the failure of the particular product is unavoidable after a certain period of functioning. In this work, the optimization considering the inherent uncertainty in the mechanical element's geometry (helical spring) design, yields more reliability of components during its service. In reliability based design optimization of spring, the mathematically modeled failure probability was intruded in the optimization algorithm (Genetic Algorithm) and the failure probability was calculated with the help of Monte Carlo simulation, the model used in this simulation was derived from the Response surface Regression method. And the reliable optimum values were compared with the deterministically optimized values.***

Keywords: Deterministic design Optimization, Uncertainties, Reliability, Genetic Algorithm, Probability, Monte Carlo simulation.

I. INTRODUCTION

The components that are designed to perform a certain function to fulfill the human needs are carefully analyzed with the help of modern computational tools to achieve the maximum performance of those designed components. Also the products are expected with very high functional aspects, more reliability, more durability, higher qualities and especially at lower prices. So, in the globally competitive marketplace, many industries have endeavored to improve the quality of the design procedures and manufacturing processes for their products. So an efficient computational tool for estimating the reliability of system of a given design is required in order to optimize the design, while maintaining a prescribed life. RBDO is one of the design optimization tools to quantitatively define the trade-off between the performance and reliability. Where an objective function is optimized for performance by satisfying the constraints of reliability, where the reliable constraint is formulated by considering the uncertainties occur in design parameters. RBDO incorporates probabilistic analysis into the optimization process to ensure that the optimum design is likely to stay in the feasible region of the design space despite the variability occur in the design variables.

Springs are important members often used in machines to exert force, to absorb energy and to provide flexibility. In mechanical systems, wherever flexibility or relatively a large load under given circumstance is required, some form of spring is used. Helical spring is one of the common types of spring used in mechanical systems . A designer must choose the right spring having greater strength and flexibility for use in the system. The designer can use synthetic tools to some extent, as they use only numerical optimization methods. Further, real time problems demand better spring designs. Hence dynamic optimal design is more desirable.

This paper presents an optimal design in a dynamic way for a cylindrical helical spring using

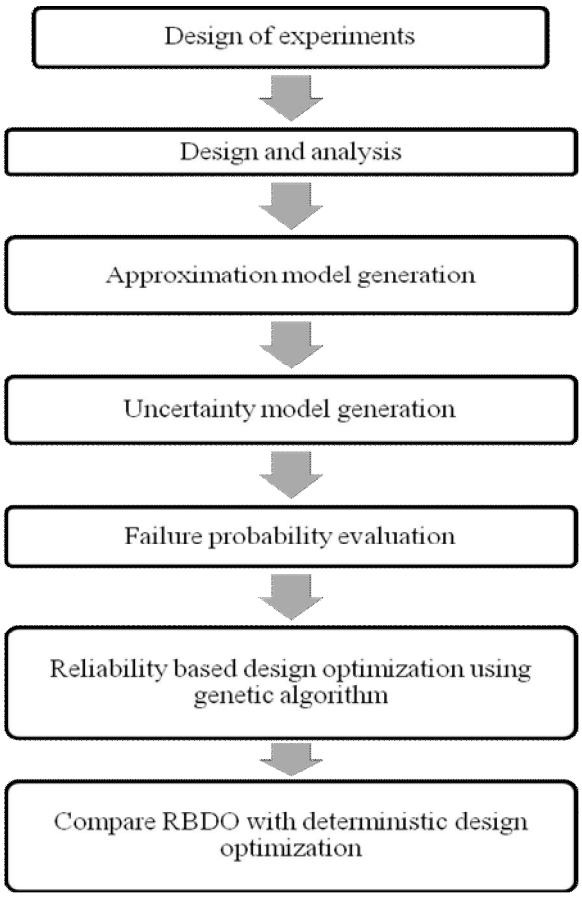
II. METHODOLOGY

Traditionally, the reliability based design optimization problem has been formulated as a double loop optimization problem. In a typical RBDO formulation, the critical hard constraints from the deterministic formulation are replaced by reliability constraints. They are either constraints on probabilities of failure corresponding t o each hard constraint or are a

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single constraint on the overall system probability of failure. The flow chart of classical approach/double loop method is as shown below.

A. Rbdo methodology



III. DESIGN CONSIDERATIONS FOR SPRING

A. Application

In the wide range of application of helical compression springs, for the design and analysis purpose, the shock absorber springs in two-wheelers are selected.

B.Material

Since the Hard drawn wires of ASTM A227 standard are widely used for two-wheeler's suspension system, the same standard of wire with the following specifications is taken for the analysis.

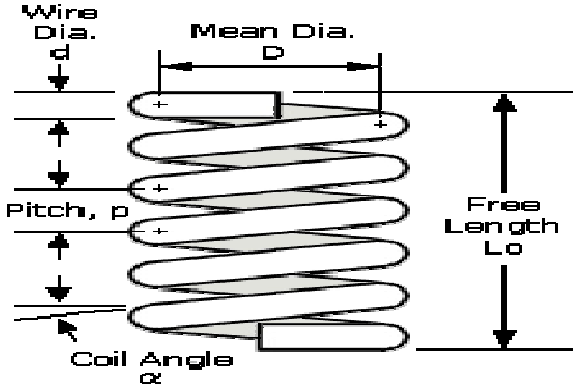


Fig 1. Spring variables

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Table 1.Material properties

PROPERTIES	VALUES
Nominal Chemistry	C: 0.45-0.85% , Mn: 0.60-01.30 %
Minimum Tensile Strength (MPa)	CLASS I : 1014 - 1951 CLASS II : 1179 - 2234
E - Modulus of Elasticity(MPa x103)	207
Design Stress % Minimum Tensile	40
Modulus in Torsion ,G (MPa x 10^3)	79.3
Maximum Operating Temperature °C	121
Rockwell Hardness	31^0 C - 52^0C
Density (g/cc)	7.85

C. Deflection of the spring due to load

The deflection-force relation can be obtained using Castigliano's theorem. The total strain energy in the spring wire has two components torsion and shear. By applying Castigliano's theorem, the deflection of the spring is,

$$y = \frac{F}{k} = \frac{8FD^3 n_a}{Gd^4}$$

D. Shear stress in the spring

The maximum shear stress τ_{max} in a helical spring occurs on the inner face of the spring coils and is equal to

$$\tau_{max} = \frac{8WD}{\pi d^3} F_{max}$$

where *W* is the Wahl correction factor and *C* is the spring index (D/d) is given by,

$$W = \frac{4C-1}{4C-4} + \frac{0.615}{C}$$

The allowable shear stress induced in spring = 0.40%(minimum tensile strength) as per ASTM A227 standard.

Allowable stress , S_a= 0.40 * (1470 MPa) S_a = 588 MPa

E. Load assumptions

The approximate load acting on a single helical spring used in the shock absorber of a two-wheeler = 1677 N

IV. DESIGN OF EXPERIMENTS

Experiments help us in understanding the behavior of a (mechanical) system.

Data collected by systematic variation of influencing factors helps us to quantitatively describe the underlying phenomenon or phenomena.

Sensitivity analysis is done by identifying the variable, which affects the strength by more than 2%, when the there is a variation in the input variable by 1%. Out of those analyses it is found that, geometry variables affect the strength very much than other variables.

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A. L9- Orthogonal Array:(3 factor – 3 level)

The formation of the following table is done using the MATLAB 17.1.0.

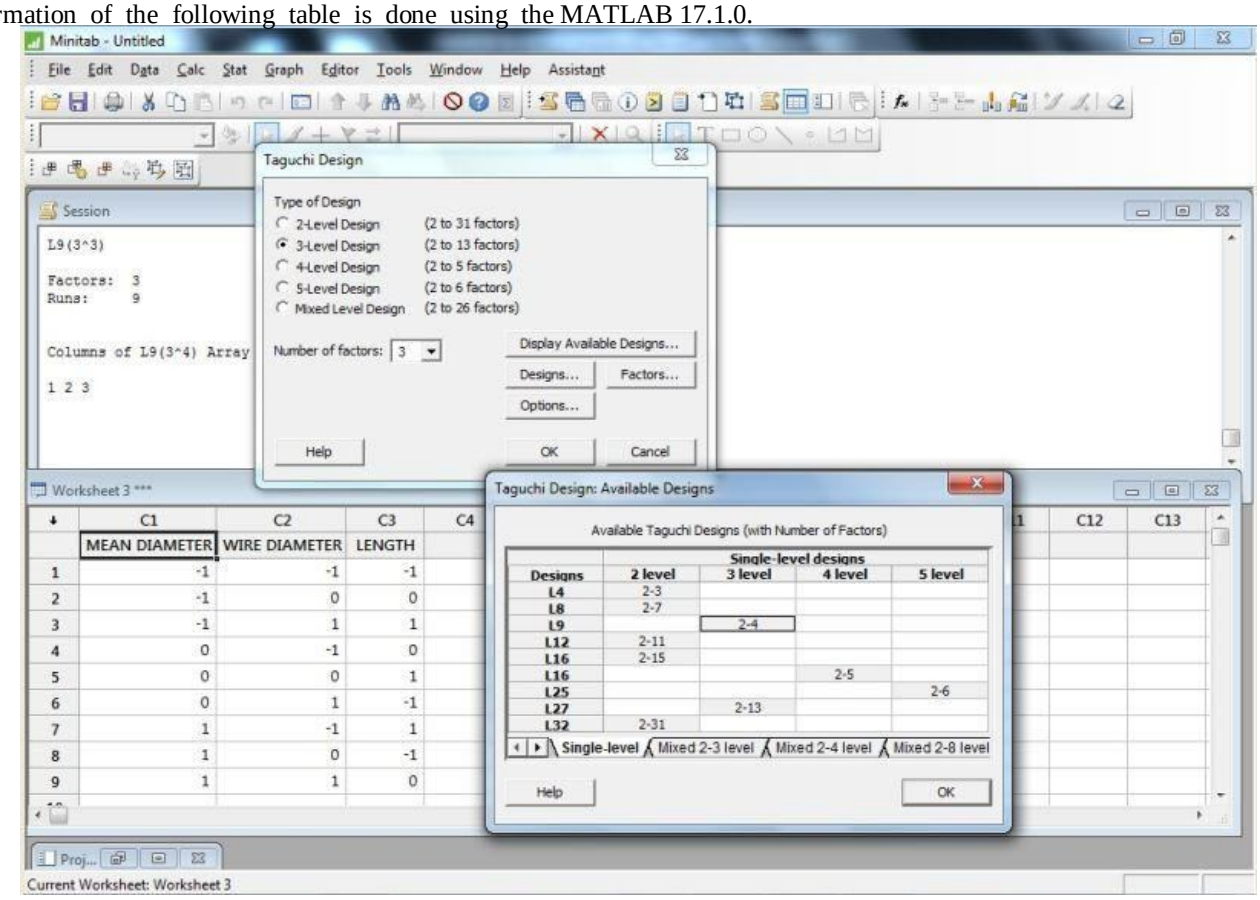


Fig.2 L_9- orthogonal array

The considered spring's geometry variables and its ranges are,

1) Mean diameter (Dm): 28 mm to 35 mm
2) Wire diameter (Dw): 6 mm to 7.5 mm
3) Length of spring (L): 180 mm to 250 mm.

Table 2 L_9- Orthogonal Array

MEAN DIAMETER (Dm) in mm	WIRE DIAMETER (Dw) in mm	LENGTH (L) in mm
28	6	180
28	6.7	208
28	7.5	250
35	6	208
35	6.7	250
35	7.5	180
45	6	250
45	6.7	180
45	7.5	208

And according to the array formed, the design can be modeled.

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V. MODELLING AND SIMULATION

A. Modeling Details

Various models were built for the parameters derived from the Design of Experiments table (orthogonal array) and exported to the ANSYS 13.0. Package. No. of active coils =15

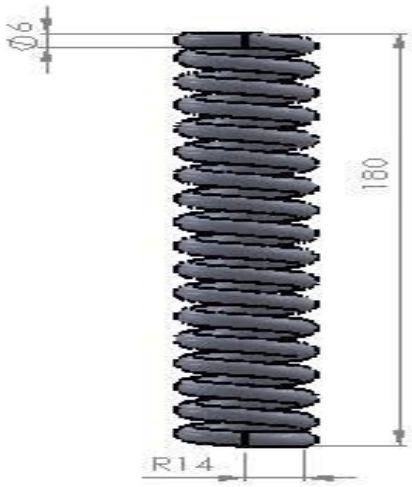


Fig. 3 Solid modeling of spring in Solidworks

B. Analysis Details

Element type chosen: solid 185 (brick 8 node 185)

Material property

Young's modulus, E = 1.965 * 10^5 N/mm^2

Poisson's ratio, r = 0.3

Density = 7850 kg/mm^3

The portion of the meshed solid model, from the ANSYS 13.0.during the analysis is given below.

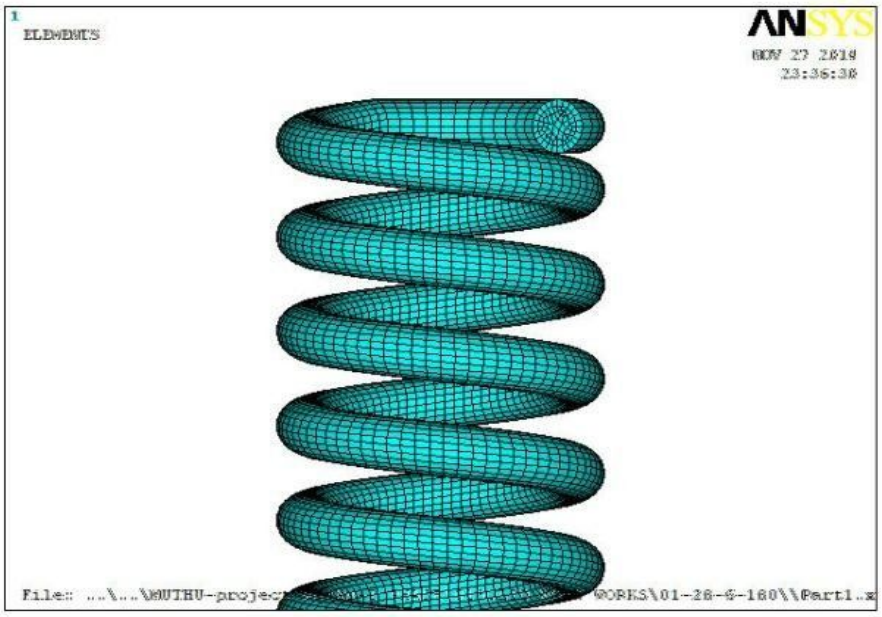


Fig. 4 .Potion of meshed solid model

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C. Boundary conditions

The meshed solid model is allowed for analysis by arresting its degree of freedom at one of the ends. Since there is lot of nodes generated by making a fine mesh, the constraint is applied over the cloud of the nodes selected. By the same way on the other end, the load is applied over many nodes equally.

Load given at one end of the spring = 1670 N.

D. Plotting the Results

The nodal solutions were taken out for,

1) Deflection along y axis,

2) Shear stress on XY plane.

E. Results of Analysis

Few of the analysis results are displayed for the deflection of the spring in Y-direction and the Induced shear stress in XY plane are shown below.

MODEL DEFLECTION OF THE SPRING:

Spring Geometry: Dm = 28 mm; Dw = 6 mm; L = 180 mm

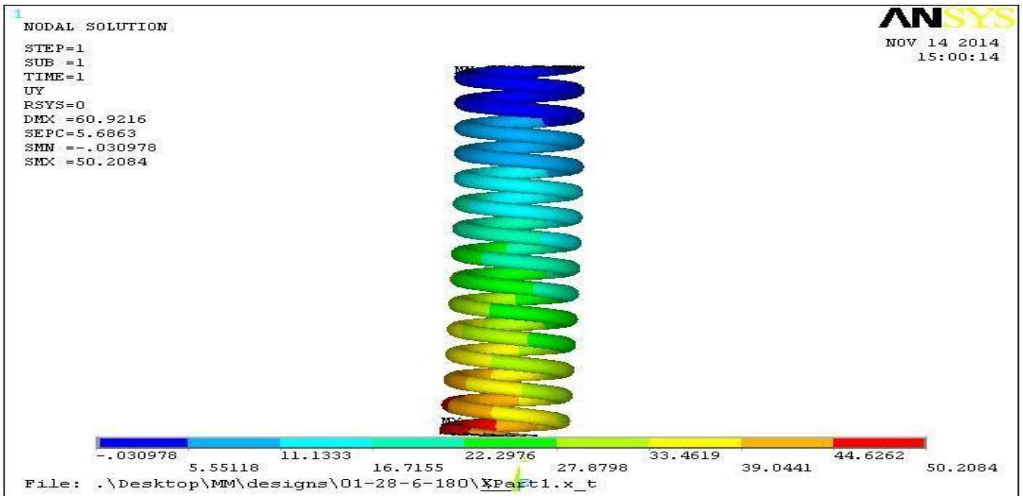


Fig.5.Dflection of Spring

MODEL INDUCED SHEAR STRESS OF THE SPRING:

Spring Geometry: Dm = 28 mm; Dw = 6 mm; L = 180 mm

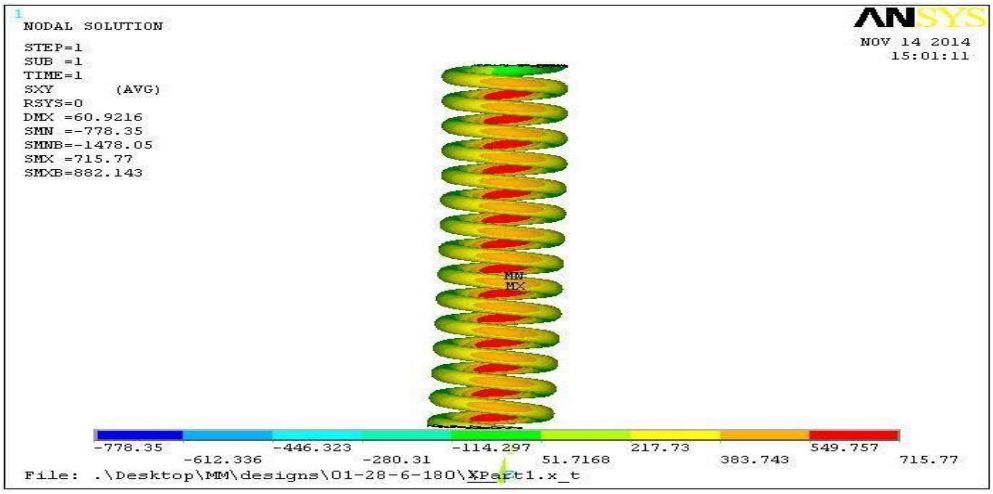


Fig.6 Induced shear stress of spring

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F. Result Summary of Analysis

All the deflection values and the shear stress values are listed out for the comparison.

Table 3 Summary of results from analysis.

MEAN DIAMETER (mm)	WIRE DIAMETER (mm)	LENGTH (mm)	DEFLECTION IN Y-DIRECTION(mm)	SHEAR STRESS INDUCED(Gpa)
28	6	180	50.21	715.77
28	6.7	208	34.52	573.26
28	7.5	250	20.6	431.1
35	6	208	103.86	945.1
35	6.7	250	72.56	711.68
35	7.5	180	42.19	399.4
45	6	250	230.2	1228.9
45	6.7	180	145.34	1583.69
45	7.5	208	92.37	544.37

VI. REGRESSION MODEL GENERATION

A. Regression Equation for Deflection

To reproduce the deflection behavior of the spring, regression equation is generated Using Response Surface method, with the coded units formation in MINITAB 17.0.

Dm – Mean diameter of the spring

Dw – wire diameter of the spring

L- length of the spring.

The regression equation for the deflection is,

$$y = -200.9 + 16.60\ D_m + 27.08\ D_w - 0.8588\ L + 0.1715\ D_m + 6.049\ D_w - 0.000503\ L - 4.259\ D_m*D_w + 0.03134\ D_m*L$$

B. Regression Equation for Induced Shear Stress:

To reproduce the shear stress behavior of the spring, regression equation is generated Using Response Surface method, with the coded units formation.

Dm – Mean diameter of the spring

Dw – wire diameter of the spring

L- length of the spring.

The regression equation for the induced shear stress is,

$$Ss = -9846 + 220.7*D_m + 2752*D_w - 11.61*L + 1.609*D^2 - 186.1*D_w + 0.08465*L - 20.46*D_m*D_w - 0.7917*D_m*L$$

VII. UNCERTAINTY MODEL GENERATION

A. Monte carlo simulation

Monte Carlo simulation technique is a simple form of the basic simulation, it provides a useful tool for evaluating the risk of complex engineering systems. It has been widely used in reliability analysis because of its simplicity and robustness, but it requires a large number of analyses for an accurate estimation of the probability of failure, especially when the failure probability is small. In general, accuracy is a concern when the performance function exhibits highly nonlinear behavior. It has also been pointed out that these methods are not well suited to problems with many competing critical failure modes.

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In this work, the design variables (Mean diameter, Wire diameter, and length) were distributed based on their mean value and standard deviation. Around 100000 trails points were generated according to the type of random data distribution function. Here we use Normal distribution for each design variable to generate 100000 trail points using Minitab Software.

Calculator >Random data > Normal

Distribution > Mean & standard deviation values > ok

After generating all the random design variables, the transfer function is entered. Minitab dialog box is shown in Figure 7.1 for design variables distribution and transfer function for response

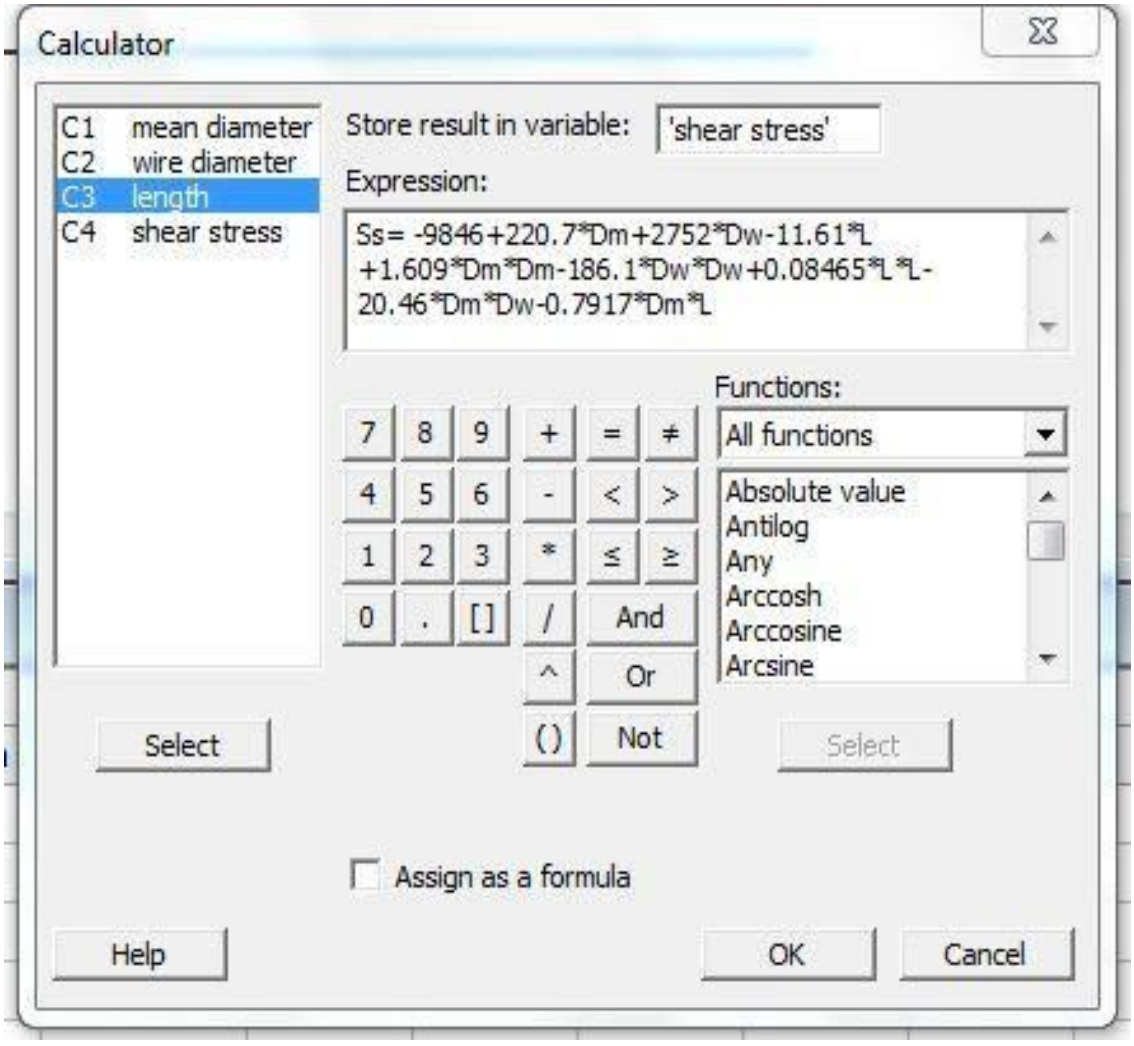


Fig.7. Transfer function and Design Variables

B. Response Distribution:

After distributing each variable according to their mean value and standard deviation, generation of Responses for the distributed points using regression model/equation is done. The response of the system had shown the type of distribution, standard deviation, Maximum and minimum values of Response. This system response is nothing but the Uncertainty Model.

Statistics > Basic Statistics > Graphical summary

In Figure 7.2.uncertainty model of induced shear stress is shown and the standard deviations in response, maximum and minimum response values are tabulated.

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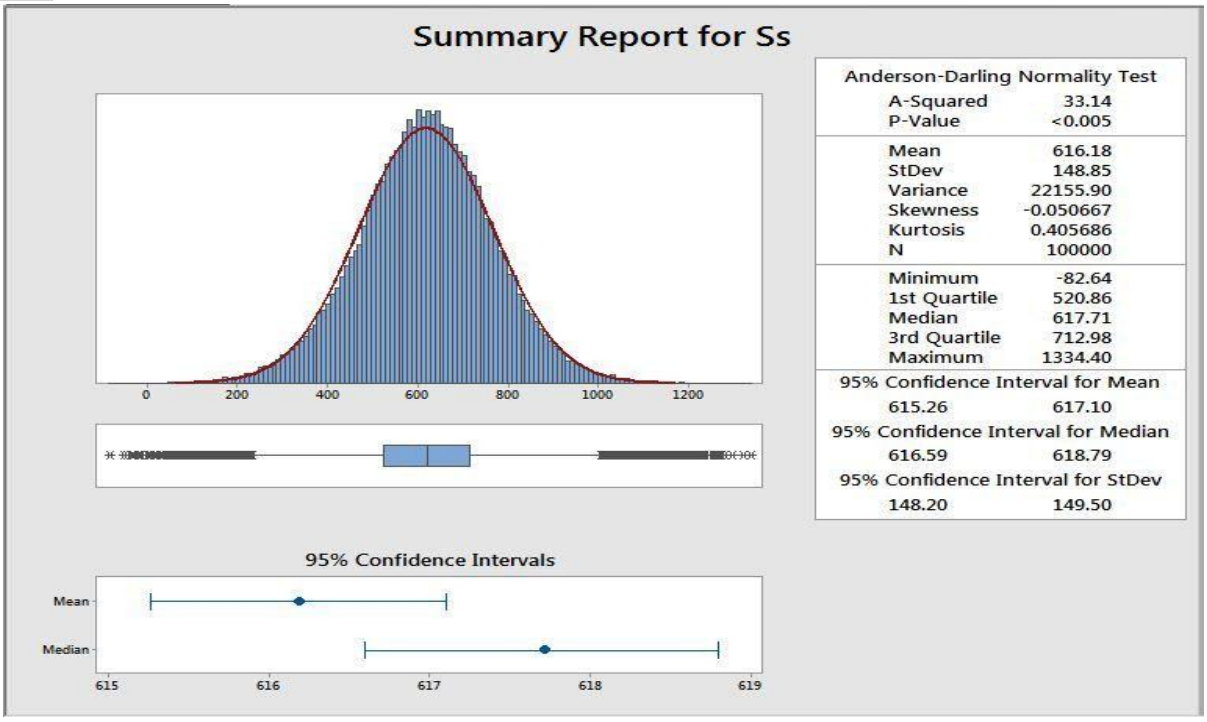


Fig.8 Uncertainty Model for Shear Stress Induced

C. Failure Probability Estimation

From this uncertainty model we can evaluate the failure probability of the spring with respect to induced shear stress.

Failure probability $P_f = \frac{No\ of\ Failure\ Response}{No\ of\ Simulations\ in\ MCS} = \frac{N_f}{N}$

$= 59995 / 100000 = 0.59995$

$P_f = 60\%$

D. Reliability Index

Already mentioned in the previous chapter the evaluation of this failure probability P_f gives Reliability Index (β).

Another method of finding the reliability index is Inverse of Failure probability. Reliability Index $R = 1 - P_f$

$= 1 – 0.6$

$R = 0.4 = 40\ \%$

E. Reliable constraints formulation

The reliability constraint can be formulated as the probability of shear stress exceeding the allowable stress limit should not exceed the probability of failure,

$$P(S_S\ (Dm,Dw,L) > S_a) < P_f$$

$$P(S_S > 588) < P_f\ (0.40)$$

And this probability can be estimated with the help of the result values of the monte-carlo simulation, such as mean & standard deviation.

The probability density function of the normally distributed event of shear stress is formulated as follows.

The probability density function (pdf),

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$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

Where, μ - mean = 616.18 MPa
σ - standard deviation = 148.85

VIII. RELIABILITY BASED DESIGN OPTIMIZATION

Minimize y(-200.9+16.60*Dm+27.08*Dw-0.8588*L+0.1715*Dm*Dm+6.049*Dw*Dw-0.000503*L*L-4.259*Dm*Dw+0.03134*Dm*L)

Subject to:

28 <Dm< 45

6 <Dw< 7.5

180 < L < 250

$P(S_S(Dm,dw,L) > 588\ MPa) < 0.40$……..reliable constraint

Where $S_S(Dm.Dw,L)$ = -9846+220.7*Dm+2752*Dw-11.61*L+1.609*Dm*Dm- 186.1*Dw*Dw+0.08465*L*L-20.46*Dm*Dw-0.7917*Dm*L

A. General Genetic Algorithm

In applying the GAs to optimization problems, certain steps for simulating evolution must be performed. These are described as follows.

Step (1): Initialize a population of chromosomes.

Step (2): Evaluate each chromosome in the population. Step (3): Create new chromosomes by mating current chromosomes; apply mutation and recombination as the parent chromosomes mate.

Step(4): Delete members of the population to make room for the new Chromosomes.

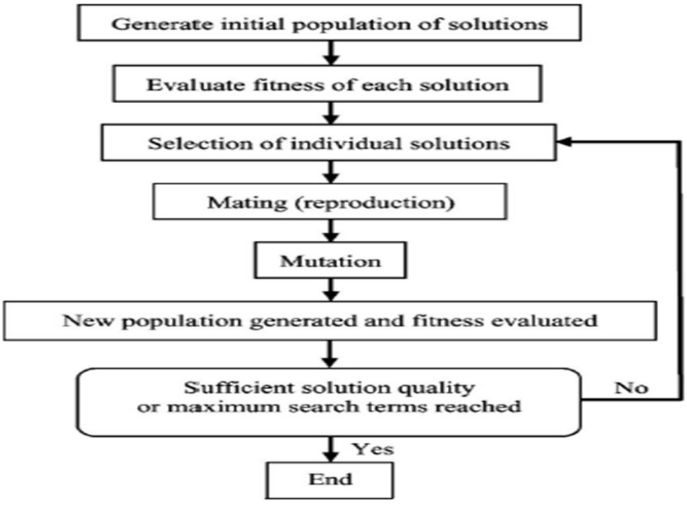
Step (5): Evaluate the new chromosomes and insert them into the population.

Step (6): If the termination criterion is satisfied, stop and return the best chromosomes; or, go to Step (3).

B. Genetic Algorithm Flow

Initially many individual solutions are (usually) randomly generated to form an initial population. The population size depends on the nature of the problem, but typically contains several hundreds or thousands of possible solutions. Traditionally, the population is generated randomly, allowing the entire range of possible solutions (the search space). Occasionally, the solutions may be "seeded" in areas where optimal solutions are likely to be found.

C. The flow chart of Genetic Algorithm



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D. Execution of the Algorithm

This genetic algorithm was executed with the help of the software MATLAB r2010. After running more number of iterations, the deflection value gets minimized with satisfying the reliable constraints. The workspace window after running the program is presented here.

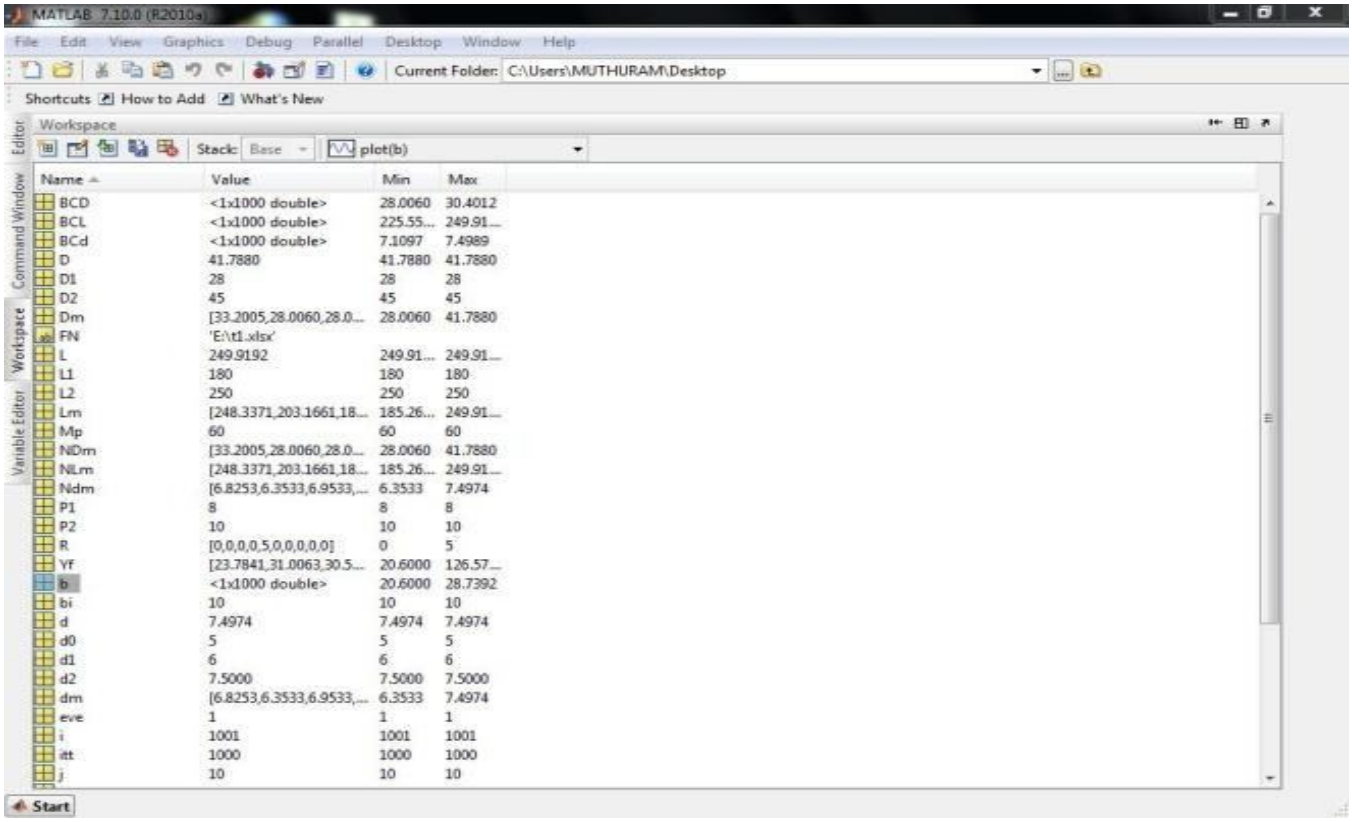


Fig.9. Workspace of Matlab Software

IX.RESULTS AND DISCUSSION

A. Reliable Region

After performing the montecarlo simulation in MINITAB 17.0., a region of space has been found to be reliable region , where any point (corresponding parameters) taken, the design would be more robust to the variation in the input parameters. That reliable region is presented in the following figure, where the shear stresses are measured for the change in mean diameter and wire diameter by keeping the length as constant.

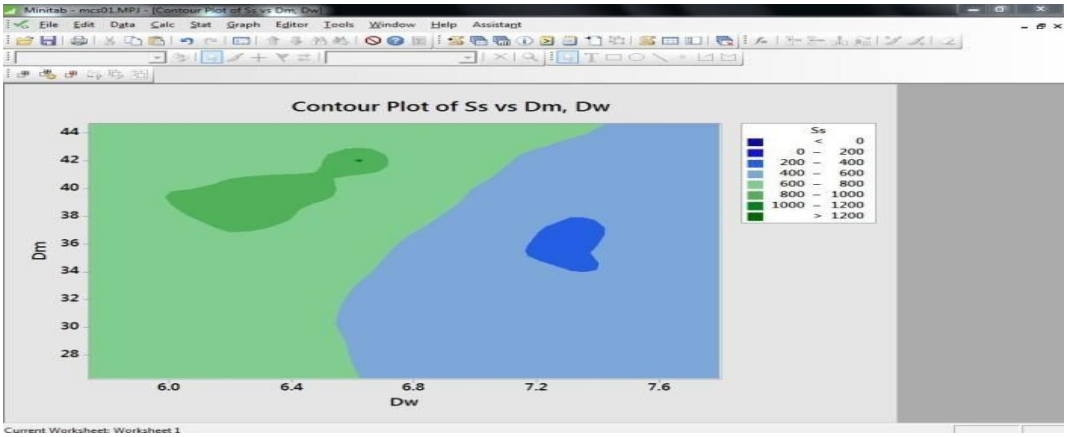


Fig.10 Reliable Region

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B. Reliable Optimum Values

By running a program based on the genetic algorithm, to minimize the deflection function subjected to few limit constraints and a reliable constraint (based on shear stress function) for more number of iterations, the optimum values converge to new reliable optimum design parameters.

The following pictures indicate the convergence of the design parameters Mean diameter, Wire diameter, Length of the spring and the response – deflection, to a reliable optimum values.

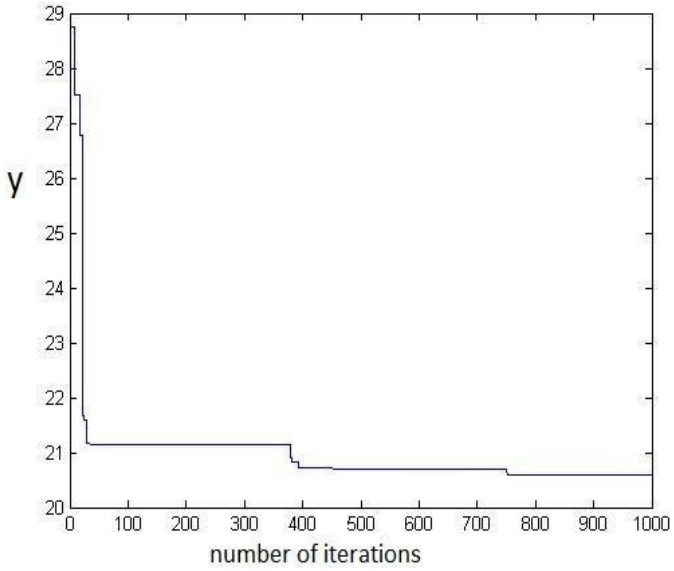


Fig .11 Deflection on spring in mm (response variable)

Table.4 Comparison of non- optimized and optimized parameters

For a minimized deflection,	Mean diameter.D(mm)	Wire diameter.d (mm)	Free length.L (mm)
Non optimized spring parameters	33.3	6.7	208
Reliably optimized spring parameters	28.0154	7.4992	249.9481

X.CONCLUSION

Various mathematical tools and analytical tools were implemented to find out the best spring geometry parameters, which was also reliable when there have been uncertainties. To find out the relationship between geometrical parameters to its mechanical behavior, the minimized number of experiments (through Design of Experiments), were conducted and analyzed. With those results of analysis, the regression model was generated and the model was used to simulate through the Monte Carlo method.

By making 1,00,000 trials in MCS, the failure probability was approximated with reference to the stress limit. Then that modeled reliability was fed to an optimization algorithm as a constraint to minimize the deflection. The optimization was executed in MATLAB 10.0. with the Genetic algorithm approach.

By analyzing the graphs from MATLAB, it is so obvious that the deflection of the helical spring minimizes when Mean diameter ,Wire diameter ,Free length of a spring are at a certain combination ,which is more reliable to obtain particular

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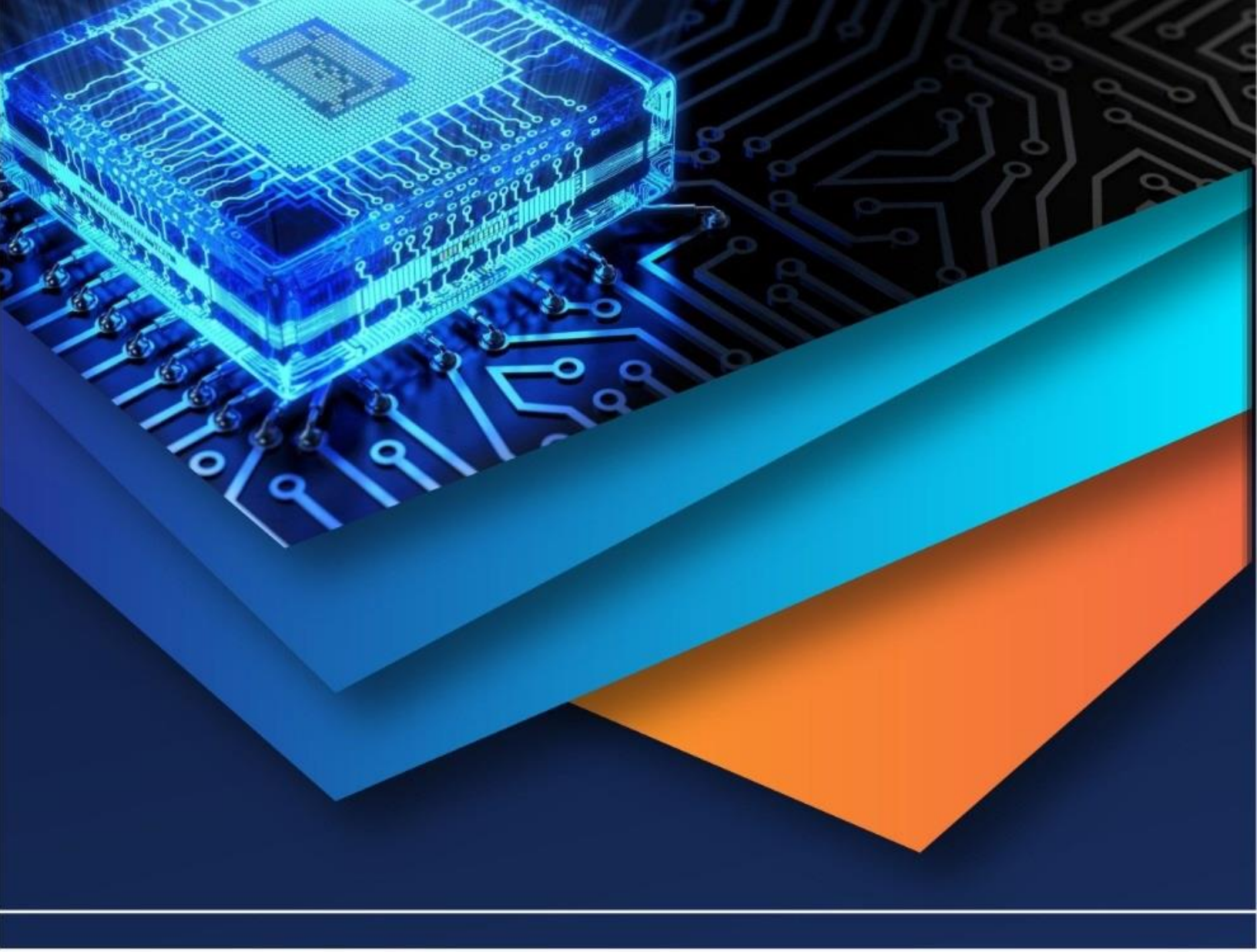
performance despite of the uncertainties and the variations between non-optimized and reliability based design optimized parameters were of ,

1) 16% decrease in Mean diameter of the spring
2) 11.9% increase in Wire diameter of the spring
3) 20.16% increase in length of the spring

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