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Effective Optimisation Technique Using Bivariate Interpolation Methods

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I. Abstract:

Optimisation is a must for every engineering design so as to increase the performance of every mechanical system. Trial and error methods are mostly used to check for stresses and validate the design which is not optimum. A new optimisation technique is found out by using bivariate interpolation method or surface fit method. From multiple variables, the problem is reduced to 3 variables (x, y, z). The variation of x with respect to z, keeping y constant and variation of y with respect to z, keeping x constant are found out. These sampling points are combined to get the relating surface of z= f(x, y) using Bivariate interpolation methods. The surface plot is obtained and for specific value of z, the 3D surface plot is chopped off, the resulting surface will be optimum curve which satisfies all the design considerations. This method is applicable for all types of problems. In this paper, taking an example of spring, keeping the various parameters like free length, effective no of coils, spring stiffness as constant, the variation of spring index and diameter of wire is calculated monitoring deflection and factor of safety. A surface is fit to obtain which relate FOS to diameter of coil and spring index, for a particular value, say FOS=1.5, the obtained surface is chopped off. The surface obtained after chopping off is the optimum curve for which all the design considerations are satisfied. Thus, this method can be effectively used for the optimisation of any 2 variable parameters with respect to the third.

Keywords: Diameter of wire (d), Mean diameter of spring (D), Free length (L_f), Factor of safety (FOS), Spring constant (C), Solid length (L_s), Wahl stress factor(k), Root Mean Square(R-Sq), Ultimate stress(G1, G2, G3,G4).

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II. Introduction:

In simpler words optimisation is obtaining the wiser answers from the wise answers. Optimisation of the system makes the design simpler and use the resource to utilize to its best and obtain precise results. Whenever the optimisation of mechanical system is concerned the intension is to increase the efficiency, performance and to decrease the weight of the system.

Growing usage of mathematics in the physical system will leads to evolution of new techniques. When these kinds of systems are available and reliable, it may be possible for us to reduce time to do observations and experimentation. Bearing the above things in mind we can say that applied sciences are strongly coupled with mathematical world. Statistics is one of the most prominent methods in predicting the answers. Interpolation methods are one among them which gives approximate solution. If somehow the approximate value of interpolation is made closer to real and true answers then interpolation methods are best suitable for optimising the mechanical system.

This paper throws some lights on the bivariate interpolation methods which can be used for optimisation of any mechanical system.

III. Concept:

Any given problem is reduced to 3 variables x, y & z. The variation of z with respect to x, keeping y constant and variation of the z with respect to y, keeping x constant are noted down, those can be called as sampling points. Now, if we look at the system closely the two variations are different interpretation of the same event. This can be said that variation of z with respect to x is a side view and variation of the z with respect to y is a front view. In fact both can be made as the surface to form a same event.

Using Any of the bivariate interpolation method, The Relation z =f(x ,y) is obtained. The surface is then plotted using the obtained equation. The surface plot is chopped off for the required value of z, so that the surface obtained using the chopping is a curve satisfying the considered design parameters and the resulting curve an optimum curve.

This concept can be applied to any mechanical systems such as optimisation of tubular chassis, suspension system for a car, thermal insulation of the material etc.

But in this paper the optimisation technique has been explained with respect to the spring for a specific application in a speed breaker unit.

IV. Application to the spring for speed breaker.

A. Problem statement:

Here an Electro Mechanical unit is implemented on one way busy roads as a substitute for road humps which has a constrained Inclined plate designed which gets displaced when a vehicle travels over it by spring actuation assembled to it at angle to the ground. The plate retracts back to its initial position gradually when the vehicle has completely passed over it. This displacement induces a torque which drives the shafts keyed to the sprockets linked by chain drive which in-turn drives the shaft keyed to Flywheel. The Flywheel shaft then transmits this torque to the generator shaft as both are coupled together leading to power generation by the Generator. Hence by this repeated cyclic to and fro motion of the inclined plate throughout the day a large amount of Electrical power can be generated using the unused power due to vehicle travelling over it. The Flywheel serves as an energy storage device for self-sustained power generation by driving the generator shaft even when there is no travel of vehicle on the inclined plate for a small time period. The Generator which converts mechanical energy to electrical energy helps in storing this energy in the batteries used for various applications. Speed breaker is a concept developed in India in order to generate power from the vehicle weight on roads. This type of power generation is very appropriate in country like India where there is a scarcity for electricity.

The design of the spring is to be in such a way that the spring should deflect completely when a small vehicle, like bike passes on it and should not be stressed more even if a heavy loaded truck of 40,000 kg passes on it. To solve this problem we have come with a solution of assembling the spring 100 mm below the ground with the free length of 200 mm without action of any load. But while designing the spring, we have to make sure that the spring is pre-stressed with the Plate of (3200 mm x 200 mm x 8 mm) which weighs approximately 27 kg.

B. Defined boundary condition.

Pre-stressed plate is of 27 kg.
Max kg- force of vehicle that should pass is 200 kg.
Max deflection for max load is 76 mm
Free length = 200 mm.

C. Property of spring

The special properties of spring which made us to choose this concept is as follows

1. Fatigue load is always pulsating in case of spring, but not reversed
2. Yield Strength varies with the diameter of the wire
3. Wahl’s stress factor takes care of direct stress as well as bending stress.
4. Overload just closes the gap between coils (reduces pitch) without a dangerous increase in the deflection.

The above mentioned properties will take care of all the worst case scenarios that can occur in the Speed Breaker application. The second property will give relation between yield strength and wire diameter, hence optimization of the diameter will take care of material requirements. Fourth property will take care of the overloading factor, if it is made sure that the compressed length of the spring is not equal to the solid length, there will not be any breakdown because of over stress in the spring, hence this same reason the spring is kept 100 mm inside the ground.

V. Optimization:

Initially varying the carbon percentage the properties of the spring is found out in order to relate material property with spring diameter.

Patented and cold drawn spring steel is taken and all four grades of the steel is analyzed.

A. Grade 1

The grade 1 Spring Steel have following properties:
Carbon – 0.50% - 0.75 %
Silicon – 0.15% - 0.35%
Manganese – 1.00%
Copper- 0.120 %

Using Minitab statistical software, the relation between the tensile strength of the material with respect to the wire diameter is found out with 99.99% Confidence Interval and the R-sq value is found to be 99.6% which is much greater when compared to allowable percentage of 75%, hence this method can be used to for the further use.

The equation is found out to be:

σ_{ut}=1733-166.8d+12.80d^2-0.3699d^3

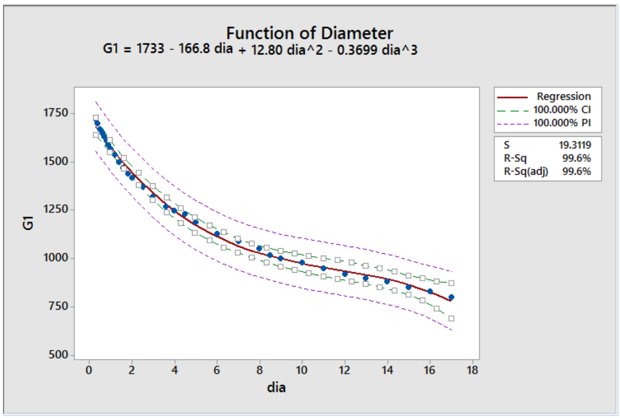

Fig-1. Grade 1 Spring Steel Strength as a function of wire diameter

B. Grade 2 Steel

The grade 2 Spring Steel have following properties:
Carbon – 0.60%-0.85%
Silicon – 0.15%-0.35%
Manganese – 0.80%
Copper- 0.120%
The relation between ultimate tensile strength and diameter of wire is found out and equation is found to be:

σ_{ut} =2097-208.d+15.29d^2-0.4195d^3

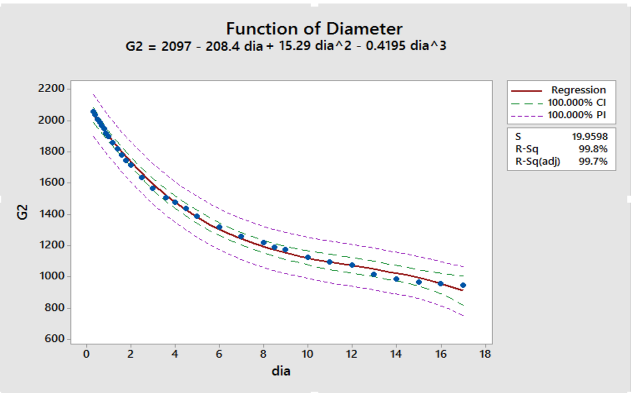

Fig-2. Grade 2 Spring Steel Strength as a function of wire diameter

C. Grade 3 spring steel

The grade 3 spring steel have following properties:
Carbon – 0.75%-1.00%
Silicon – 0.15%-0.35%
Manganese – 0.80%
Copper- 0.120%

The relation between ultimate tensile strength and diameter of wire and the obtained relation is used for the calculation of fatigue strength of the spring and relation is found out to be:

σ_{ut}=2490-272.3d+21.38d^2-0.6025d^3

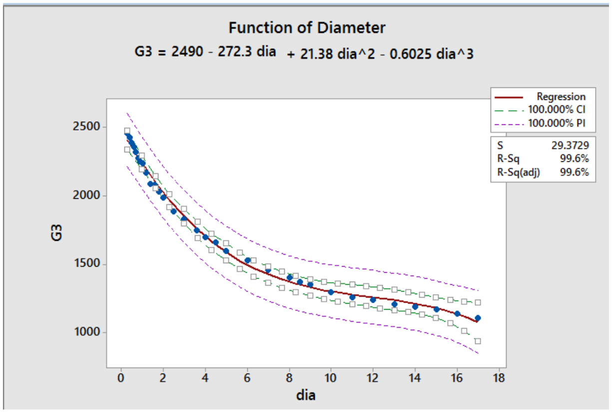

Fig-3. Grade 3 Spring Steel Strength as a function of wire diameter

D. Grade 4 steel

The grade 4 spring steel has following properties:
Carbon – 0.75%-1.10%
Silicon – 0.15%-0.35%
Manganese – 0.80%
Copper- 0.120%
The relation between ultimate tensile strength and diameter of wire and the obtained relation is used for the calculation of fatigue strength of the spring and relation is foundout to be:

σ_{ut} =2699-301.9d+25.10d^2-0.7343d^3

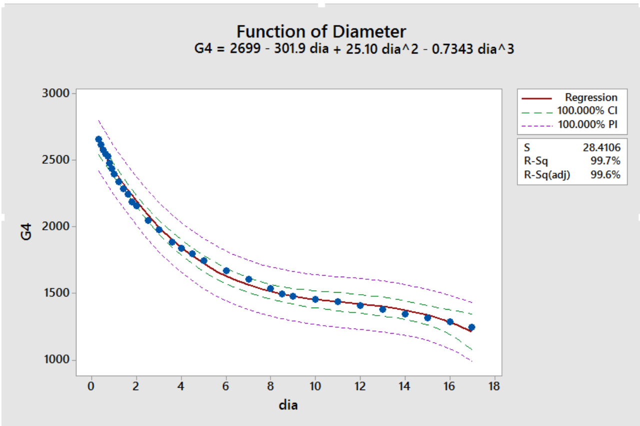

Fig-4. Grade 4 Spring Steel Strength as afunction of wire diameter

From the above graphs it is observed that the graph tries to shift upwards as the grade increases and the carbon content increases. This means as the grade increases the ultimate strength also increases. Increase in carbon content increases the yield strength of the spring. As the grade 4 steel is stronger when compared to all other, the optimisation is done on this grade.

The Factor of safety is kept in z axis varying diameter of the wire and the spring in x and y axis respectively to obtain the relation.

20 sampling points are tabulated from the above interpretations, all though 9 to 16 sampling points are enough to get the exact points.

Table 1: Sampling Points

d/c	6	8	10	12
6	0.55881	0.43961	0.896281	0.307733
8	0.92143	0.72488	0.59668	0.50677
10	1.38408	1.08847	0.896281	0.76121
12	1.96465	1.53135	1.26052	1.07057
14	2.566291	2.01888	1.66183	1.411409

E. Reduction to 3 variable form

The problem is reduced to 3 variables by following empirical relations

- Diameter of the spring is related to spring index and wire diameter
- Ultimate strength is related to diameter of wire
- Carbon content is related to ultimate strength and in turn diameter of the wire
- Pitch is related to spring FOS and diameter of wire.
- Free length and active number of coils are constant.

VI. Surface Plot:

The bivariate interpolation of the above samples is carried out and equation of factor of safety as a function of spring index and diameter of wire is found.

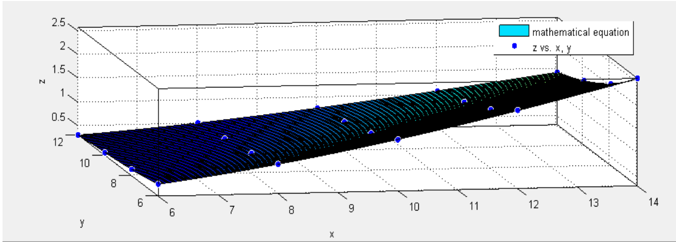

Fig-5 Surface plot obtained in MATLAB

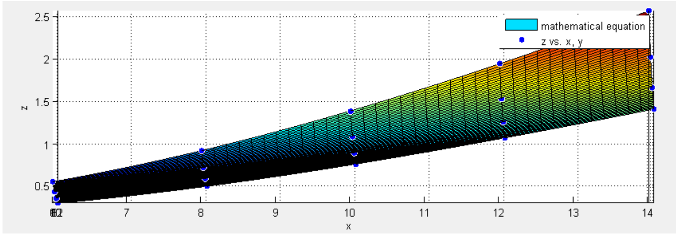

Fig 6: Surface plot as seen from xz plane

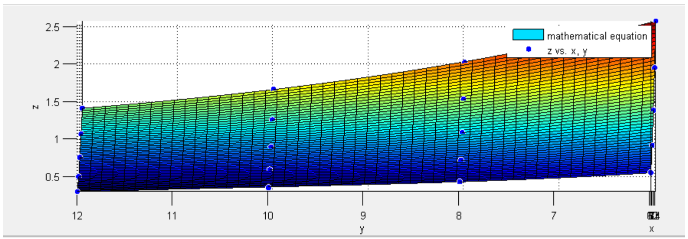

Fig 7: Surface plot as seen form yz plane.

The x (Diameter of wire) is varied only between the limits 6 mm to 15 mm in this but it is not restricted. Whereas for the spring system to be stable, the y (spring index) should be varied only between 6 to 12.

The above graph obtained has the following properties:

SSE: 0.0003092
R-Square- 0.99998
RSME- 0.005561
As the R-square value is greater than 0.75 with the confidence level of 99.98%, the plot can be used for the other applications.

The equation of the plot is:

$$z = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2 + p30*x^3 + p21*x^2*y + p12*x*y^2 + p03*y^3$$

Where co-efficient are:

p00 = 0.3236
p10 = 0.08935
p01 = -0.09792
p20 = 0.02552
p11 = -0.03522
p02 = 0.01963
p30 = -0.000333

p21 = -0.0008153
p12 = 0.00182
p03 = -0.001006

The above equation can be chopped off for the value of z=1 i.e factor of safety=1. The intersection of the surface z=1 and the surface above given is the optimum curve.

The Equation of the surface is given by

Diameter of wire= $8.645-0.5361C+0.1043C^2$.

Within the limits diameter varies from 10 to 15 and spring constant 7 to 12.

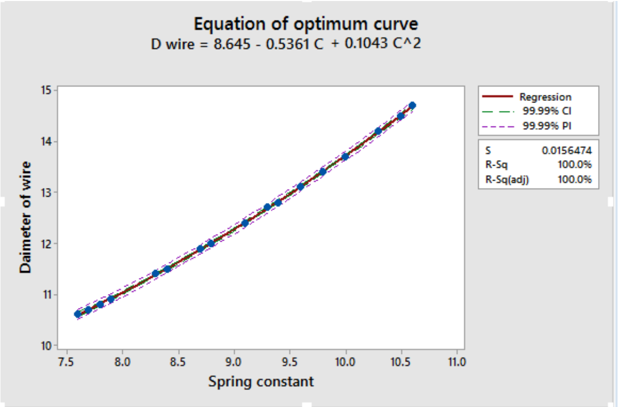

Fig 8.optimum graph

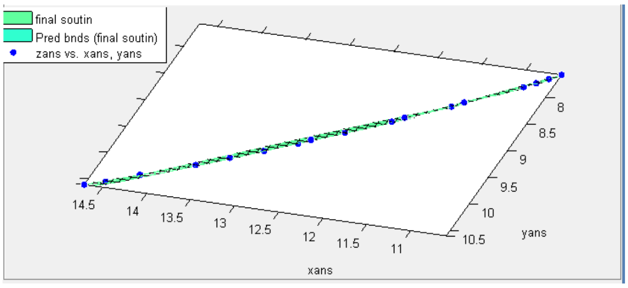

Fig 9: optimum curve in surface form

The value of z=1 and the variation of the x and y is as shown above. The equation of the curve in surface form is found to be

1 = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2

Coefficients (with 99% confidence bounds):

p00 = -0.7795
p10 = 0.357
p01 = -0.09745
p20 = -0.01838
p11 = 0.03398
p02 = -0.0334

The optimum curve satisfies the design considerations, for the application of spring the mean value in the optimum curve has been chosen with mean diameter of spring=12.5mm and the spring index = 8, which satisfies all the design parameters required.

VII. Conclusion:

In this paper we have tried to explain the concept with the help of the spring varying few parameters. Further the same concept can be extended to all design problems which involves 3 variables.

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