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Optimization of Leaf chain in Counterweight Balancing of Machine Tool by Finite Element Method

Rishabh Gupta[1], Hariram Chandrakar[2]
[1, 2]Department of Mechanical Engineering, S.S.G.I. Bhilai

Abstract: ***Whenever the sudden motion take place in a counterweight balancing of machine tool due to inertia effect of the heavy mass of machine tool head with counterweight exert large amount of forces in the chain link and in order to prevent failure of the chain vertical motion of the machine tool head take place at lower velocity, by increasing the efficiency of a leaf chain, we could further increases in the vertical motion of machine tool head and is still a challenges for the designer to provide not only the better stress resistance or wear resistance of a chain but also the weight saving in a chain material during its design, this could increases the chain performance as well as it could be cost efficient. The design parameters on which the efficiency of the leaf chain depend should be considered by the designer, by analyzing fatigue life and strength of a leaf chain. The CAD model of the leaf chain is developed using a Creo parametric software and finite element analysis is conducted by the help of ANSYS software, under which analysis is done by plotting sensitivities graph for the various design parameters and the factor effecting strength and fatigue life of a leaf chain, considering effect on chain link plate under a Response surface Methodology.***
Keywords: Leaf chain, FEA Analysis, Response Surface Optimization, Fatigue life, Pin diameter, Load inertia ratio, Counterweight balancing

I. INTRODUCTION

Whenever the machining operation are required to perform on the large area of the work piece, which also required a machine tool of the larger size in order to perform the desired operation. This consist of the machine tool with the high power and high cutting speed due to that its self-weight of the tool increases a lot, and whenever these larger work pieces are under various machining, it is not possible to move the work piece according to the required operation performed and due to that we have to move machine tool head its self to reach the desired position in which the operation are to be performed on the plane of the work piece. In the whole process machining operation, machine head which consist of the tool in its head, it have to move from one position to another position with a certain speed according to the requirement for that particular operation, which consist of the 3D motion of the machine head in a horizontal plane and also in vertical plane. For this type of the machine tool which consist of the moving head with tools in it and have easily performed horizontal motion or in case of some machining tool its bench consist of the moving platform for the motion of the work piece in a positive as well as negative axis in a horizontal plane.

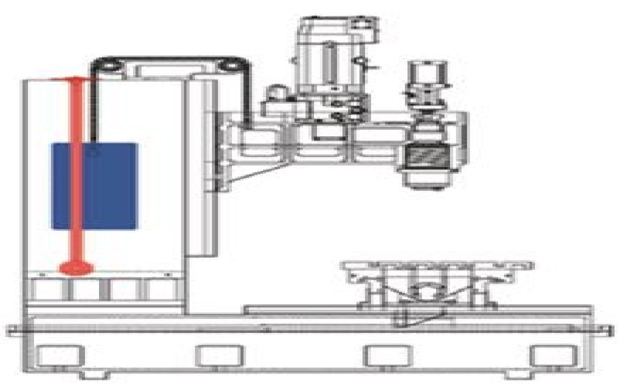

Figure 1: Machine tool with counterweight balancing

Lacing of leaf chain is basically the arrangements of number of plates in an odd and even plate combinations in order to achieve the desired strength for the given working load conditions

1) *Odd Plate Combinations:* In this type of combinations the inner link of leaf chain containing the odd numbers of link plate while the outer links contains the even number of link plates, on the other hand a leaf chain with odd plate combination shows a optimum strength in fatigue and a link with larger face provide optimum resistance to wear.

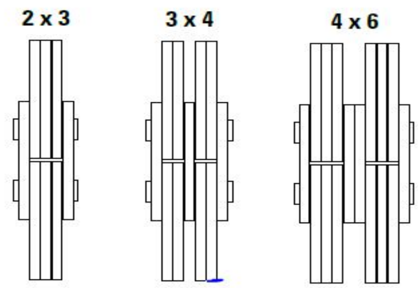

Figure 2: Odd plate combination of leaf chain

2) *Even Plate Combinations:* In this type of combinations the inner link of leaf chain as well as the outer link of the leaf chain contains the same number of link plates, as this type of leaf chain comes under the "AL" type chain configuration and this are generally used for machine tool weight balancing as under its working conditions experiences a lighter weight as compared to "BL" type leaf chain

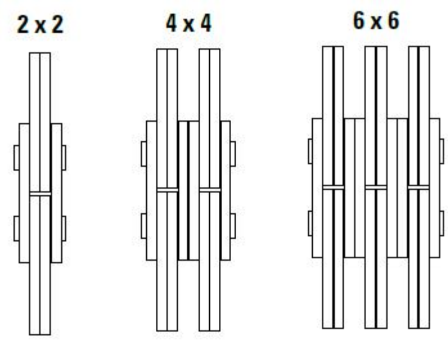

Figure 3: Even plate combination of leaf chain

II. LITERATURE REVIEW

Kim Gyung-Ho [1] machine tools are designed to performed motion in all of the 3-Dimensdional axis of the work space, and motion in these axis are required to performed their machining operations for which machine tools are designed, but the machine tools which have a very large amount of its own weight, which are designed to use in a heavy machining operations, these machine tools could easily performed horizontal motions with a little effort or no such issues arises when the horizontal motion take place, or for the horizontal motion some machine beds are available in a configuration in which work-piece can be moved horizontally in a positive as well as negative x-axis, but in the case of vertical motion (which is along the y-axis) of the heavy weight machine tools head its often seen that these machine tool have worse performance, and this performance differences arises due to the structure differences for the motion along x and y axis in a working space of machine tool, the major contribution for the worse performance during vertical motion it the large self-weight of the machine tool attached with counterweight in order to balance it and due to counterweight motion with the help of leaf chain could develop a vibration in a machine tool structure and it also limited the moving velocity of machine tool head along vertical axis to prevent chain link failure.

C.W. Huang [2] as we know machine tool with counterweight balancing system during motion in vertical direction generates lots of vibration in a machine tool structure this affect the machining operations as well as motion of the tool in a work space, during motion of the counterweight in a heavy machine tool system inertia effect in a whole causes elastic jump in a leaf chain structure and releases of the potential energy in the whole structure of the connected chain, this could lead to the failure of the connected link chain, investigation of these effect can be analysed with the help of the software called Nastran, as we know in a machining process tool have to move in pre-planned path in order to perform their functions on the work piece, during that motion sudden stop and sudden start of the machine tool head generated extra amount of forces on the whole structure connected with the chain link arrangement.

Zheng Zhang [3] while designing machine tool for the various machining operations for the machine tool head move with a high acceleration as well as the high velocity the feed of that machine plays important role and this consist of the subsystems which make more complicated for analysis purpose, so for the analysis purpose new method is adopted in which the detailed analysis of the resembling characteristic between inertia ratio and required motion process, by this method output results show that when feed system of the machine tool are operated for the low velocity and low acceleration the inertia ratio have very little effect on the system, whereas when feed system are operated at higher velocity it play important role while designing for the machine tool moving mechanism.

Facai Ren [4] chain drives are one of the critical component while dealing with the heavy loads or the power transmission on a heavy load capacity escalators. Performance of the chain drives in this specific areas are extremely important, so for the checking of the service time of a new chain drives are done by breaking test of that chain. As the operation of chain in escalator required a continuous motion of the chain over the supporting frame that include the sheaves or sprocket according to the requirement for the safe limits of loads, this also required a greater number of factor of safety for that chain drives. And for the determining the real fatigue life of the chain the test should be perform in a manner of cyclic loads under the influence of lubrication and optimum environmental conditions and also a test which include a cyclic loads under an extreme working conditions for the chain drive. The above test help to analyse the true fatigue conditions under the influence of working conditions which are of different kinds.

C. Cenac [5] as the demand of the working mechanical components are increasing nowadays, so it require not only wear performance against the working conditions but also require a better fatigue performing chain links. Last few decades includes series of development in the performance of the chain links and the selected material properties would spread of modern analysis techniques, which made possible because of availability of high performance computers with their high processing power. These analysis techniques are known as 3 dimensional dynamic simulation and finite element analysis, it will describe elaborately, how 3 dimensional dynamic simulation can help to determine and calculate the load cycles in a chain and how this loads have a impact on fatigue life of a chain, so the designer can get a parameter through which by improving or chaining this parameters could lead to have a improved fatigue performance of a chain links which are going to be designed. This technique will go on to illustrate the various and variety of different stages of a complete cycles of a fatigue improvements for a leaf chain and its links and also for a roller chains with multiple strands. Using these technique including the 3D dynamic simulation and the finite element analysis provides a key advantages is that one can do a optimisation of each single link or a component and to look at the final end result on the whole chain without actually manufacturing it as a real leaf chain.

B. Fischer [6] these chain links are flexible in nature, so that are often used as a connecting link between chain and a hook through which load is to be lifted. By studying the purpose of the leaf chain one can find that it should be designed for the very large tensile load, so it is not designed for the diagonal pulls, rather than this it is design for clean tensile stress. In practice little effect of diagonal forces, which is a result of diagonal pull situations are often inevitable, while designing these chain a certain degree of security should be assured while such unscheduled load cases or uncertain force of action acting on leaf chain, this condition help to predict the production engineer that leaf chain may behave “tenderly”. In the present analysis of failure, the chain link delivered were no longer tempered or quenched, rather than this it is case hardened, which make it more resist to wear while performing its operation but it make also less tolerable against the various kind of bending forces which is a result of uncertain bending loads inevitably occurring with uncertain amount of diagonal pulls. As a result of these uncertain diagonal forces, leaf chain may get fractured and break while performing its operation, which leads to a dropping of loads during the lifting.

Andre l. Khuri [7] mainly the evolution of the RSM (response surface methodology) involves three parts. During the initial stage of the RSM methodology when it was introduced it includes only the review of basic parameters required for the experimental design to be fitted in a linear response surface model, in brief of this method includes determination of operating conditions which is optimum for the experimental design. Second part in addition to the response surface optimization includes a more robust parameters design technique which is Taguchi method which act as alternate to the RSM technique. Third part in this optimization technique is that random or unwanted effect that may arises during the experimental scenario, the generated response surface model are concerning about that and taken it in account for which generalised linear model are formed and various graphs are plotted to comparing the response surface design.

K.H. Wehking [8] chains with different embodiments or simply a optimum design arrangement are used in many areas of technology and have a corresponding longer history of improvement which make it further development according to its needs. Earlier applications of the chain link as a mechanical element for transmitting power was already used in 1stcentury B.C, it was also used by Roman architect and in Marcus Vitruvius engineering in the form of forged chain link on a bucket elevator which was used for the lifting of water from the well or for lifting materials, as a development of chain take place and one of the important factor where manufacturer should pay attention while designing the chain link is the fatigue life of a chain.

III.OBJECTIVE

The objective of this research is to increase in fatigue life of chain so that chain should withstand with high moving velocity and at higher acceleration of the machine tool head by examine the effects of geometrical parameters on leaf chain link plate, determined by using ANSYS software. To analyse the effect of different input variables on the output design parameters like fatigue life of a link plate, equivalent stress generation and maximum stress intensity, by the help of response surface methodology.

IV. RESEARCH METHODOLOGY

The analysis of the leaf chain link plate structure is performed by the help of ANSYS software, in which Finite Element Analysis of the structure are to be done, which involves the following steps.

1) With the use Computer Aided Design, model of the leaf chain link plate structure are to be developed according to standard dimension of leaf chain link plate for “BL” type leaf chain, with lacing of 2*3 combination of plate, exporting model to ANSYS software where meshing operation with fine refinements are to be performed on the edges of pin diameter hole on a link plate and then application of design loads and boundary conditions take place.
2) This stage generate solution for the given leaf chain link plate structure by taking in account the various input parameters and the constrains, various matrix operation are performed by the formulation in matrix, which involves inversion and multiplications matrix, on assemble this calculated operation to form the global and element stiffness matrix.
3) Last stage of this analysis involves the investigation of the generated output results from the variable input parameters which consist of plotting various 2-D and 3-D graphs between the upper and lower bound value of the input variables to the output of various design parameters. This generated output result provide solution to optimization of the structure for a given loads conditions.

The CAD model of leaf chain link plates and pin is developed using CREO parametric software. This modelling involves design of leaf chain link plate and a pin of a BL series of 2x3 lacing leaf chain for considering a load under working condition of fork lift. Dimensions value for the followings BL type leaf chain are taken under the ISO 4347.The parameters are assigned in modelling software.

Table 1: Dimensions of leaf chain link plate

Pitch of plate (p)	12.7mm
Plate thickness (s)	2.032mm
Plate height (g)	11.6078mm
Pin diameter (d1)	5.08mm

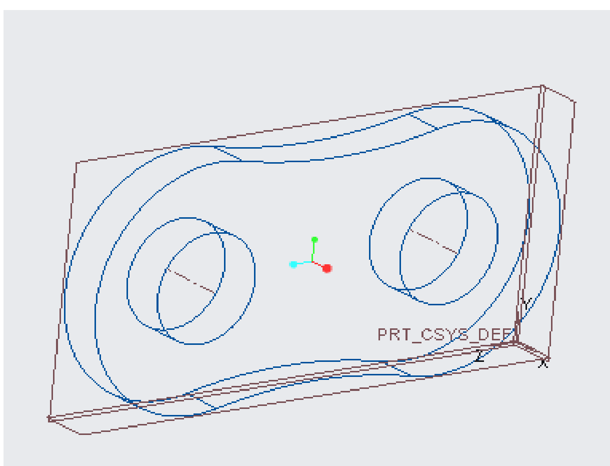

Figure 4: Sketching in Creo parametric software

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The developed CAD model are meshed in a ANSYS software by using a refinement area method, as we can assume that the area where maximum stress are to be involved, so by selecting a refinement method in a mesh, it could generate larger number of nodes and element for a particular as compared to the whole structure, which could leads a more accurate solution towards the problem. The parameters for the mesh was set to adaptive size function and fine sizing was done, inflation to be normal. As a result of all the setup there are 38082 numbers of nodes are generated and 25378 numbers of elements are generated.

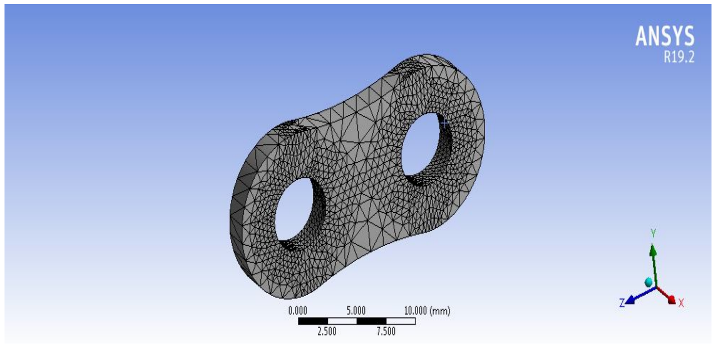

Figure 5: Meshing of leaf chain link plate

After meshing of the given structure in a software a tensile load of 2000N is applied horizontally to the structure as a leaf chain link plate are under a pure tension while running over the sheaves and at the one end of the plate link a fixed load is applied, in order to applied load create a generated effect on the plate as shown in the figure below.

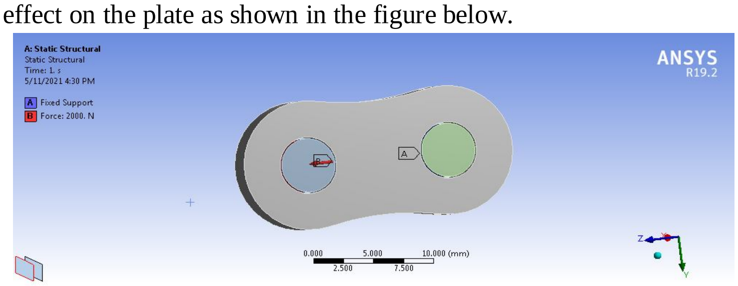

Figure 6: Loads and Boundary Conditions

V. RESULTS AND DISCUSSION

By using ANSYS software structural analysis is done on a given structure for a number of parameters, which are shown by the various graphical visualization in a software which include an equivalent stress (von-misses) generated in link plate of leaf chain, stress intensity in link plate, total deformation take place in a leaf chain link plate.

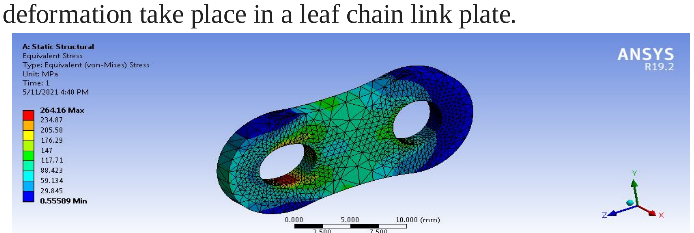

Figure 7: Equivalent stress on chain link plate

From the above figure it is clearly seen that the maximum equivalent stress of 264.16 MPa is induced at the edges of the pin hole diameter, as excepted this area is under a large amount of stress in the whole structure, this is because it is the hole created for the pin to be fitted on it, as we know that pin is the only member which acts as a connector of all the members in the chain configuration and for all the load induced on the chain pin exerted a large amount of tensile stress on the cross-section of the link plate

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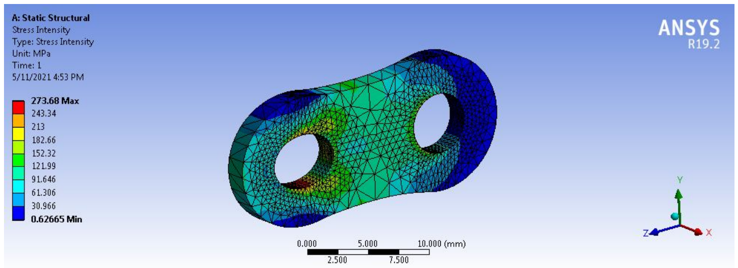

Figure 8: Intensity of stress induced on plate

The maximum deformation of about 0.010262mm take place at the direction in which the pin of a chain exerted a tensile load of 2000N on the cross-section area of the material between the plate height and the pin diameter.

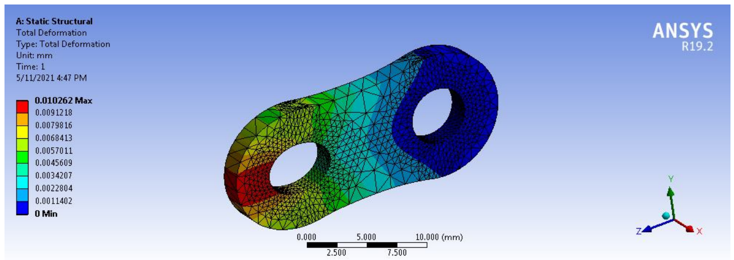

Figure 9: Total Deformation in a structure

As from below figure 10 we can easily see that the for the whole structure of the plate have a maximum fatigue life which is as desirable for the steel structure but for the edges of the pin hole, at a vertically symmetrical region we can get a minimum fatigue life of 36744 of a link plate, as a dynamic stresses varies with time this could cause a region for the starting of plate wear

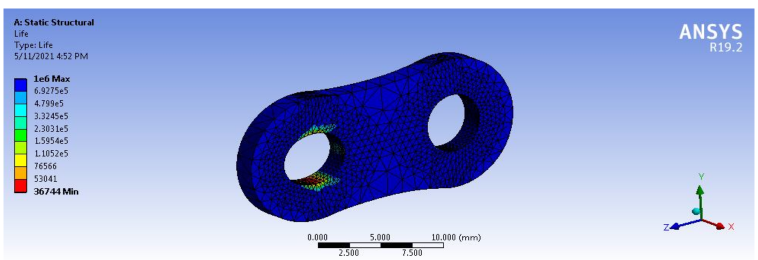

Figure 10: Fatigue life of a link plate

Table of Outline A4: Design Points of Design of Experiments

	A	B	C	D	E	F	G
1	Name	P2 - Pindiameter (mm)	P1 - Height (mm)	P3 - Thickness (mm)	P4 - Equivalent Stress Maximum (MPa)	P5 - Stress Intensity Maximum (MPa)	P6 - Life Minimum
2	1	4.76	5.5	2.032	252.87	263.78	46303
3	2	3.8	5.5	2.032	240.32	255	59334
4	3	5.72	5.5	2.032	286.89	297.76	22498
5	4	4.76	5	2.032	296.37	308.15	18714
6	5	4.76	6	2.032	227.53	238.43	75694
7	6	4.76	5.5	1.8288	284.21	298.79	23878
8	7	4.76	5.5	2.2352	235.72	248.3	64835
9	8	3.9795	5.0935	1.8668	289.65	305.12	21142
10	9	5.5405	5.0935	1.8668	356.18	369.14	7732.8
11	10	3.9795	5.9065	1.8668	250.26	266.71	48789
12	11	5.5405	5.9065	1.8668	269.8	278.4	32638
13	12	3.9795	5.0935	2.1972	246.06	262.51	53030
14	13	5.5405	5.0935	2.1972	300.32	311.19	17579
15	14	3.9795	5.9065	2.1972	216.77	232.42	92287
16	15	5.5405	5.9065	2.1972	232.5	242.28	68945

Figure 11: Design points for DOE

Above figure represent generated design points form the input parameters, which include pin diameter, plate height and plate thickness, output results are calculated which include the output parameters like equivalent stress, stress intensity and minimum fatigue life. From above table we can clearly identified that, we get maximum fatigue life and minimum value of stresses at the 15th point in the table, we identified that for the fatigue life improvement in the chain link plate by dimensional point of view, and we should reduce the pin diameter with in the safe limit.

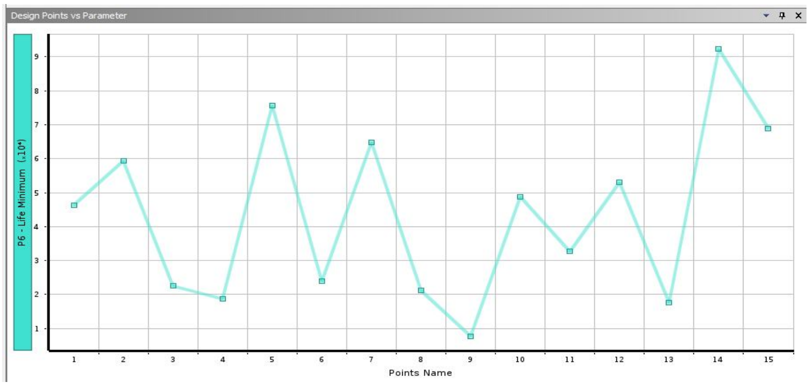

Figure 12: Generated minimum Fatigue life at different design points

This is the graphical representation of the generated minimum fatigue life in the y-axis of the graph with respect to the given numbers of design points in the x-axis, also from the above graph we can conclude that the maximum value of generated minimum fatigue life is occurred at thee design point 15.

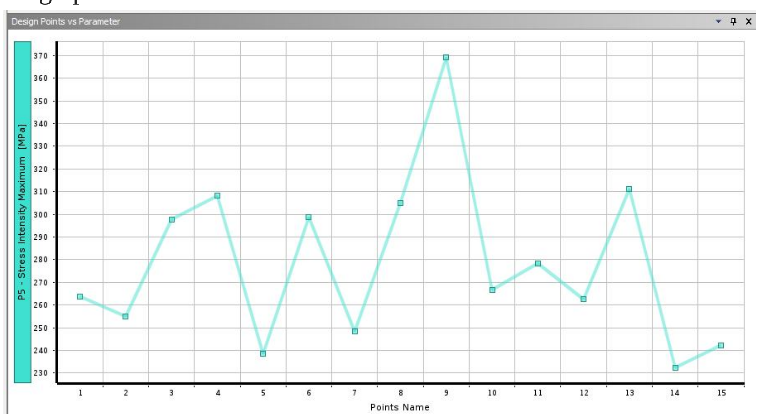

Figure 13: Maximum stress intensity at different design points

From the graphical chart of the maximum stress intensity and given numbers of design points we can optimize the our structure dimensions easily, on a design point 15 we can see that there is minimum stress generation, this dimension we are taken in to our account according to our dimensional need.

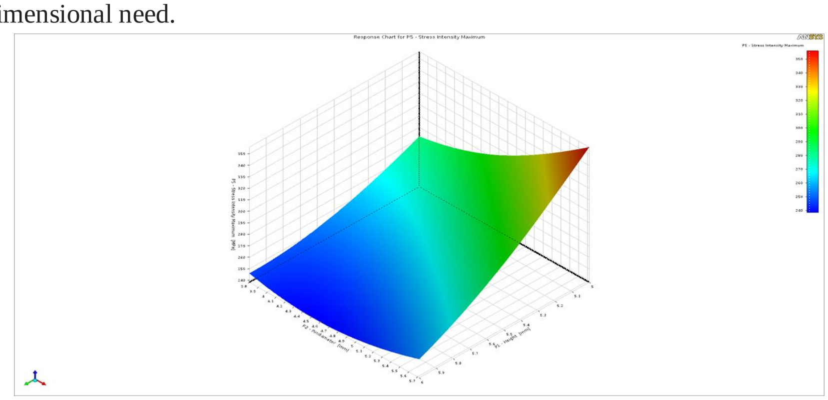

Figure 14: Response surface for stress intensity on a link plate

The generated 3-Dimensional representation of response surface for the stress intensity over chain link plate structure with respect to the plate height and pin diameter. It was noticed that the intensity of a stress reached to its maximum value which was shown by the red zone for the pin diameter of the ranges from 5.2mm to 5.7mm in a combination with the height of link plate variation from 5.3mm to 5mm from the symmetrical centre of the link plate.

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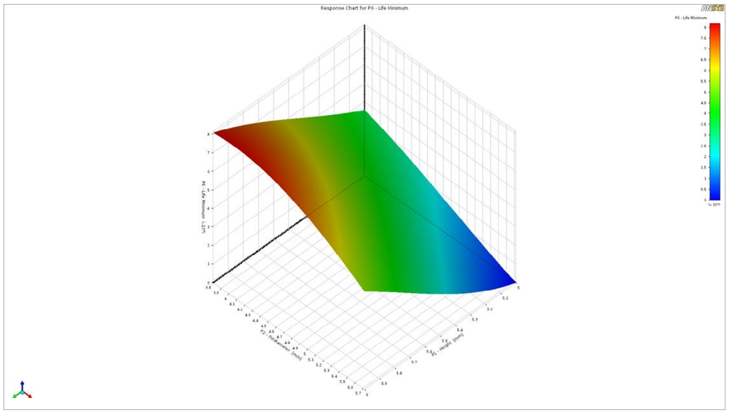

Figure 15: Response surface generated for fatigue life of leaf chain link plate

The above figure 5.9 shows that 3-D representation of generated Response Surface for a fatigue life of a link plate under the load conditions with two input variables, which include the plate height and the pin diameter. From the response generated data it is easy to identified that there is sudden improvement in the fatigue life of link plate for the plate height ranges from 6mm to 5.6mm from the symmetrical centre of the plate in a combination with the pin diameter of a link plate ranges from 4.9mm to 3.9mm.

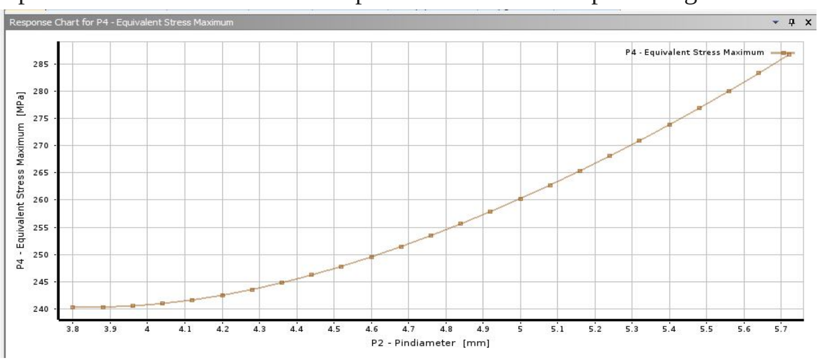

Figure 16: Graph plot for Equivalent maximum Stress vs Pin diameter chain link plate

The above figure 5.10 shows that there is no linear relationship between the pin diameter and the equivalent stress, rather than linear it shows exponential growth for the stress generation when the pin diameter increases. For the analysis purpose we should highly concern about this input parameters for the link plate design because stress generation is a function of pin diameter.

Table of Schematic C3: Response Surface: Tolerances

	A	B	C
1	Name	Calculated Minimum	Calculated Maximum
2	P4 - Equivalent Stress Maximum (MPa)	212.88	387.34
3	P5 - Stress Intensity Maximum (MPa)	225.3	400.04
4	P6 - Life Minimum	-160.72	95582

Figure 17: Minimum and maximum values for parameters

The above table of a generated maximum and minimum value for the various design parameters for the leaf chain link plate, we can easily identified that the upper bound and lower bound for the geometric dimensions of a link plate should not be taken either side of extreme end of the limits. This could generate a maximum equivalent stress as well as the maximum stress intensity on the plate structure, as an effect of this we get a minimum fatigue life of a chain which is not desirable, for minimum stress criteria we can see that the maximum equivalent stress, which are calculated minimum on the basis of input parameters is 212.88MPa, by considering this we could achieve a greater stress resistance capacity of plate structure but this could increases the addition of its dimensions.

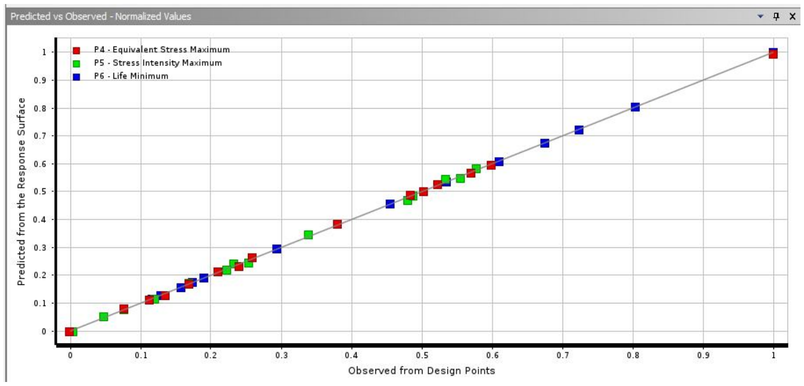

Figure 18: Goodness of fit curve for values of different parameters

The above figure shows the goodness of fit curve, this is basically the plot of a point on a curve on the graph for the value which was predicted or pre-assumed with the help of the response surface over the value which was observed or obtained as a points for design, as we can see the design points which include the equivalent stress, stress intensity and life of a chain shown with red, green and blue dot respectively. Except from the points for the intensity of stress other two design points doesn't show much deviation away from the curve.

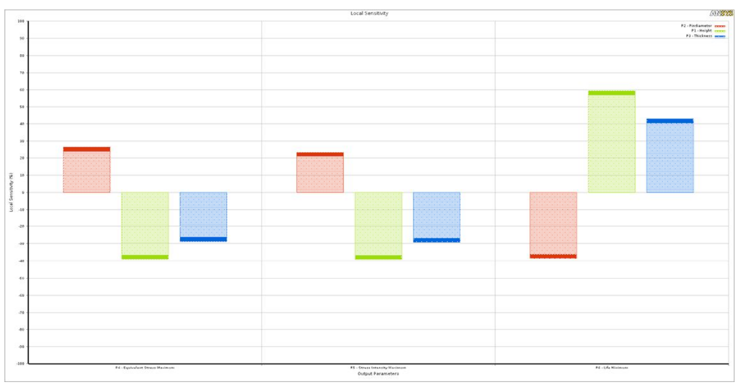
Figure 19: Plot for sensitivity of various parameters

The above figure 5.13 shows a sensitivity plot for the three design parameters over the local sensitivity percentage for the parameters which are input variable (Pin diameter, height of a plate and thickness of the plate)

A. Equivalent Stress

1) Pin diameter of a leaf chain shows positive sensitivity on a graph for equivalent stress with local sensitivity of 28%.
2) Height of a link plate of leaf chain shows negative sensitivity on a graph for equivalent stress with local sensitivity of 39%.
3) Thickness of link plate of a leaf chain shows negative sensitivity on a graph for equivalent stress with local sensitivity of 28%.

B. Stress Intensity

1) Pin diameter of a leaf chain shows positive sensitivity on a graph for stress intensity with local sensitivity of 23%.
2) Height of a link plate of leaf chain shows negative sensitivity on a graph for stress intensity with local sensitivity of 39%.
3) Thickness of link plate of a leaf chain shows negative sensitivity on a graph for stress intensity with local sensitivity of 29%.

C. Fatigue Life

1) Pin diameter of a leaf chain shows negative sensitivity on a graph for fatigue life with local sensitivity of 39%.
2) Height of a link plate of leaf chain shows positive sensitivity on a graph for fatigue life with local sensitivity of 59%.
3) Thickness of link plate of a leaf chain shows positive sensitivity on a graph for fatigue life with local sensitivity of 42%.

Output result after analysis of optimization of chain link in a counterweight balancing of machine tool

a) From the optimization process we could achieved a fatigue life of a chain link around 2.5 times the previous value. This increases the maximum allowable load per link plate around 450 N.

b) Weight saving in a chain material is achieved by analysing the fig 5.14, it is clearly seen that stress generation at the cross-section 1 is higher as compared to the cross-section 2, so prevent fatigue failure we could use optimized dimensions of chain link at cross-section 1, and at the cross-section 2 by reducing pin-diameter up to 3.68mm and also further reducing link plate height (h) up to 10 mm by considering shear stress acting on the pin is around 80% to 85% of tensile stress acting on link plate, as a result we could save around 90.5 mm^3 in volume of each link plate and in around 0.725 grams in mass of each link plate. Under the same load fatigue life of link pate with reduced dimension, it have a fatigue life of 2.7408e5 cycles. Which is much more as compared to cross-section 1.

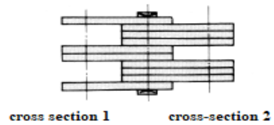

Figure 20: Cross-section of odd combination of leaf chain

VI. CONCLUSION

Finite Element Analysis of the leaf chain link plate are conducted by the use of ANSYS software for the optimization of the link plate or to analyse the structural failure of the plate in order to achieve an optimum dimensions for the leaf chain link plate, which influences the efficiency of the leaf chain as well as the material saving in the chain without compromising the working performance under a load conditions for the forklift truck masts. Which included the structural analysis for the various parameters (fatigue life of leaf chain link plate, equivalent stress and stress intensity). The following output conclusions are:

1) From structural analysis we noticed that initiation of cracks take place at the edges of the pin hole due to the minimum fatigue life at that point, as compared to whole structure. As we know pin is made up of highly treated material in order to resist shear, but also considering the pin material is structural steel in our optimization, we noticed that shear strength of the pin is approximately 80% to 85% of the tensile strength for steel material, so to increases the fatigue life of link plate we could further reduce pin diameter with in safe limit.

2) By using finite element analysis we noticed that maximum equivalent stress is generated at near the edge of pin hole, which moves further towards the height of the plate. As we provide more cross-section area between the plate heights and pin hole this would help us to reduce the generated stress.

3) By setting the upper and lower bound limit with in the response surface method for the pin diameter and other parameters, the output sensitivities and responses provide effective way for the dimensional optimization of the leaf chain link plate.

4) From the weight point of view under dimensions analysis, it is found that in an odd combination of the leaf chain we could save up to 0.725 grams on an each link plate of the leaf chain.

5) As fatigue life of a link chain improved up to 2.5 times the previous value, and maximum allowable load for a chain link plate increased around 450N. this help machine to move at higher acceleration and also we could operate machine tool head at higher velocity as compared to previous conditions, this help to increase in higher rate of machining operations, and increases machine productivity.

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