ROBUST DESIGN OF LOWER ARM SUSPENSION USING STOCHASTIC OPTIMIZATION METHOD

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STUDENT'S DECLARATION

I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurrently submitted in candidate of any other degree.

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Last but not least I acknowledge without endless love and relentless support from my family, I would not have been here. My father, mother, and brothers that always support and encourage me to success.

ABSTRACT

This project presents the development of robust design of lower suspension arm using stochastic optimization. The strength of the design analyze by finite element software. The structural model of the lower suspension arm was mode by using the solidworks. The finite element model and analysis were performed utilizing the finite element analysis code. The linear elastic analysis was performed using NASTRAN codes. TET10 and TET4 mesh has been used in the stress analysis and the highest Von Mises stress of TET10 has been selected for the robust design parameter. The development of Robust design was carried out using the Monte Carlo approach, which all the optimization parameter for the design has been optimized in Robust design software. The improvements from the Stochastic Design Improvement (SDI) are obtained. The design capability to endure more pressure with lower predicted stress is identified through the SDI process. A lower density and modulus of elasticity of material can be reconsidered in order to optimize the design. The area of the design that can be altered for the optimization and modification is identified through the stress analysis result. As a conclusion, the robust design by using stochastic optimization was capable to optimize the lower arm suspension. Thus, all the result from this project can be use as guideline before developing the prototype.

ABSTRAK

Projek ini menerangkankan pembangunan rekabentuk robus untuk “lower arm suspension” mengunakan pengoptimum “stochastic”. Kekuatan rekabentuk telah di kaji mengunakan perisian “finite element”. Struktur model “lower arm suspension” telah di buat dalam “SolidWork”. Model “finite element” untuk rekabentuk dan juga analisis telah dijalankan menggunakan kod “finite element”. Analisis kekenyalan elastik telah dijalankan menggunakan kod NASTRAN. Analisis “TET4” dan “TET10” telah digunakan dalam analisis terikan dan nilai terikan “Von Misses” tertinggi dari “TET10” telah digunakan sebagai parameter di dalam struktur robus. Pembangunan struktur robus telah dijalankan menggunakan kaedah “Monte Carlo” , dimana kesemua telah di optimumkan di dalam perisian struktur robus. Penambahbaikan daripada “Stochastic Design Improvement (SDI)” telah dijalankan. Struktur telah dikenalpasti berupaya menahan tekanan yang lebih tinggi dengan daya terikan yang lebih rendah melalui proses “SDI”. Ketumpatan dan juga “Modulus of elasticity” yang lebih rendah boleh digunakan untuk sruktur “lower arm suspension”. Area putih yang dikenal pasti di dalam analisis terikan telah menunjukkan area tersebut dapat di ubah untuk mengoptimumkan struktur. Kesimpulanya, kesemua hasil yang telah diperoleh di dalam kajian ini dapat digunakan sebagai petunjuk dan panduan bagi pembangunan prototaip “lower arm suspension”.

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LIST OF SYMBOLS

x	is the stochastic variable
y	is the stochastic variable
r	Pearson correlation
u	Mean value
r_s	Spearman correlation
R_i	is the rank of $x_i s$
S_i	is the rank of $y_i s$

LIST OF ABBREVIATIONS

CDM	Continuum Damage Mechanics
DOE	Design Of Experiment
FEA	Finite Element Analysis
FEM	Finite Element Modelling
GRA	Gray Relation Analysis
HIC	Head Injury Criterion
MRR	Material Removal Rate
MCS	Monte Carlo Simulation
OA	Orthogonal Array
RSM	Response Surface Methodology
SPC	Statistical Process Control
SED	Statistical Experimental Design

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

In the automotive industry, the riding comfort and handling qualities of an automobile are greatly affected by the suspension system, in which the suspended portion of the vehicle is attached to the wheels by elastic members in order to cushion the impact of road irregularities. The specific nature of attaching linkages and spring elements varies widely among automobile models. The best rides are made possibly by independent suspension systems, which permit the wheels to move independently of each other. In these systems the unsprung weight of the vehicle is decreased, softer springs are permissible, and front-wheel vibration problems are minimized. Spring elements used for automobile suspension, increasing order of their ability to store elastic energy per unit of weight, are leaf spring, coil spring, torsion bars, rubber-in-shear devices, and air springs.

Following a bump, the undammed suspension (without shocks) of a vehicle will experience a series of oscillations that is cycle according to the natural frequency of the system. Ride is perceived as most comfortable when the natural frequency is in the range of 60 to 90 cycles per minute (CPM). When the frequency approaches 120 CPM (2 Hz), occupants perceive the ride as harsh. Consequently, the suspension of the average family sedan will have a natural frequency of about 60 to 90 CPM. A high-performance sports car have a stiffer suspension with a natural frequency of about 120 to 150 CPM (2 to 2.5 Hz) (Riley.,2003).

For this project, the design of the lower arm suspension will be study. The lower arm design will be create base on robust design and optimize by using the stochastic optimization method. This is ensure that improvement can be made to the basic design of the lower arm suspension with better performance and marketability.

1.2 PROBLEM STATEMENT

Robust design is the process of designing a product or process to be insensitive to the effects of sources of variability. There are external noise, inner noise and unit-to-unit noise. External noise as the name implies comes from outside the product due to effects of elements like temperature and humidity. Inner noise (deterioration noise) is due to aging in products during use or storage. Some examples would include loss of mass of light-bulb filament and weathering of paint on a house. Unit-to-unit noise is the result of never being able to make any two products exactly alike. Typical examples would include dimensions from any metal removing process and batch-to-batch concentration of chemicals (Rakesh, et al.,2002). A stochastic process is a probabilistic model of a system that evolves randomly in time and space. The idea of stochastic optimization consists in combining deterministic optimization methods with uncertainty quantification techniques to measure the sensitivity and the variability of the response. Another objective concerns the reliability-based optimization i.e. the computation of the probability of a risk of failure (Lucor, et al.,2007).With using all these tools, imperfection of the component can be analyzed and can solve in order to find the best solution for the imperfection. The method of robust design can also make sure that a light weight, low cost, and better safety component can be made. By getting all the result in the final process, the component can give a better performance and also give a better market value in the automotive industry.

1.3 SCOPE OF STUDY

The focus is for the robust design of the lower arm suspension using stochastic optimization, the scope for the study are as follows:

i. Structural modeling using Solidwork.

ii. Finite Element modeling and analysis using MSC. PATRAN and MSC. NASTRAN.

iii. Robust design using stochastic optimization method.

1.4 OBJECTIVES OF THE PROJECT

The main objective for this project is to develop a robust design of lower suspension arm using stochastic optimization. The overall objectives are as follow:

i. To design a structural design of lower suspension arm.

ii. To analyze the stress of the lower suspension arm design.

iii. To optimize the lower suspension arm using stochastic method.

1.5 OVERVIEW OF THE REPORT

Chapter 1 gives the brief background of the project. The problem statement, scope of study and the objective are also included in this chapter. Chapter 2 discusses about literature review of the robust designing method, the stress analysis, finite element modeling, and the stochastic optimization method. Chapter 3 presents the development of methodology, finite element modeling and analysis of the lower arm suspension design. Chapter 4 presents the result and discussion of the project. Chapter 5 presents the conclusion and recommendation for the future research of this study.

CHAPTER 2

LITERITURE REVIEW

2.1 INTRODUCTION

The purpose of this chapter is to provide a review of the past research related to the robust design, the stress analysis, and stochastic optimization method.

2.2 ROBUST DESIGN METHOD

In designing part for the automotive industry, robust design method is a very common method that has been use in the industry. The robust design method is very useful in creating or develops a better product for the automotive industry such as lower suspension arm product. Rakesh et al. (2002) were studied about the robust design of a spindle motor. Authors discussed about the way to minimizing variability of products and processes in order to improve their quality and reliability for the spindle motor. The authors also explain about the use of the Response Surface Methodology (RSM) for solving the Robust design problem. The key steps of obtaining a robust design solution through use of RSM are outlined as follows:

1. Identify dominant failure mechanism,
2. Identify the control and noise factors and obtain their feasible ranges,
3. Construct an experimental design,
4. Conduct the design matrix experiments,

5. Use multiple regression analysis to construct the RSM model,

6. Evaluate the mean and the variance either through simulation or through analytical means.

7. Formulate problem and perform a constrained optimisation,

8. Verify the results.

The results of the study show that how robust design techniques could be applied in the design stages of the product development process so as to maximize product reliability.

Zang et al. (2004) was studied about the review of robust optimal design and its application in dynamics. In the studied, the author stated that the objective of robust design is to optimize the mean and minimize the variability that results from uncertainty represented by noise factors. According to the author, most applications of robust design have been concerned with static performance in mechanical engineering and process systems and applications in structural dynamics are rare. The author also stated that the most important task in Taguchi's robust design method is to test the effect of the variability in different experimental factors using statistical tools. The requirement to test multiple factors means that a full factorial experimental design that describes all possible conditions would result in a large number of experiments.

Sreeram (1994) was investigated about the robust design of the automotive suspension system. The author explains about the effective implementation of Statistical Process Control (SPC) and Statistical Experimental Design (SED) methods to improve quality and productivity. The author also explains about the new Quality philosophy was introduced by Taguchi and the combination of some elements of classical design techniques with cost considerations. Author stated that the Taguchi Loss function approach to quality improvement were designed to help find less costly solutions while maintaining high quality and productivity standards. The Response Surface Methodology also mentioned in the author study and has been claimed that these method of robust design is very important for quality improvement which have been used in a number of applications throughout the engineering world and also has been use for the research.

Bharatendra et al. (2004) was studied about the robust design of an interior hard trim to improve occupant safety in a vehicle crash. For this particular study the author aim to achieve the requirements for one such interior component, viz. an interior hard trim that covers the pillar closest to the driver's head on the left-hand side of the vehicle. The author use the finite element analysis tools to build a robust design that gives consistent performance even in the presence of noise factors. From the author definition, a robust design is expected to provide less risk to the occupant and have a lower Head Injury Criteria HIC(*d*) value than a non-robust design. The result of the study stated that to achieve a robust interior hard trim design, the study used separate analyses to identify control factors effecting mean and variability. It helped to achieve low HIC(*d*) values with less variation even under various uncontrollable noise factors.

Kopac and Krajni (2007) was studied about the robust design of flank milling parameters based on grey-Taguchi method. The authors aim for the study dealing with the optimization of the cutting loads, milled surface roughness and the material removal rate (MRR) in the machining of an Al-alloy casting plate for injection moulds. The authors uses the Grey-Taguchi method which combining the orthogonal array (OA) design of experiments (DOE) with grey-relational analysis (GRA), which enables the determination of the optimal combination of flank milling parameters for multiple process responses. From the result of the study using the robust design, the author stated that the flank milling with an end mill with two or three flutes is superior to four-fluted tool. The maximal cutting speed did not yield optimal performance. Reduced feed rates improve the process performance and tool life.

2.3 STRESS ANALYSIS

The stress analysis is very important step in designing any product or part in the automotive industry. By doing the stress analysis on the part we can get the data of the strength and life of the part that have been design. This is very important to determine the best material and the best shape have been use for part design. Seo et al. (2006) carried out a research about the Numerical integration design process to development of suspension parts by semi-solid die casting process. In the research, the authors focus on the practical use and lifetime guarantees for the suspension parts by predicting the stress distribution from the strength analysis and the lifetime from the fatigue analysis. The A356 aluminum alloy was used for the strength and fatigue analyses for the studied. The strength analysis results for the studied were presented with the Von Mises stress distributions and the strain distributions by using five ultimate load conditions and each constraint. From the studied result, the lower arm suspension to which homogeneous stress below the yield strength from the static and dynamic strength analyses was distributed from the analysis that have been done.

Conle and Chu (1998) carried out a study about the fatigue analysis and the local stress–strain approach in complex vehicular structures. The study focus on the observation of stress–strain hysteresis behavior, through the early development of computer versions of the stress–strain shape and memory models, to their evolution into routines that are closely linked to vehicle dynamics models that calculate loads in structures, finite element models that transform the loads into local stresses, and subsequent plasticity correction and damage evaluation routines which yield expected life color contour plots for vehicle body and chassis. The authors explained that in the early days of computerized analysis, this was achieved by scaling an appropriate load histogram with the worst case von Mises' equivalent stress, and then by applying the Neuber correction to each block of stress cycle in the history. In today's relatively complex FEA models similar techniques are still applied. After the complex load history is reduced to a uniaxial (elastic) stress history for each critical element, the Neuber correction is used to compute the local stress and strain. It should be noted here that this method only works well when the critical locations with plasticity are located within large zones of elasticity. When one reaches general yielding of the components, the process breaks down.

Prawoto et al. (2007) carried out a research about the design and failure modes of automotive suspension springs. In the research, a finite element analysis was performed to check the local stress distribution around a given defect using a typical coil spring. The overall stress distribution was checked without any defect in the material, and then at the location where the highest stress was found, each defect was added. Since the size of the defect is significantly smaller than the whole model, a sub modeling technique was used. The authors explained that this technique is used to study a local part of a model with refined meshing based on the FEA result of a global model with coarse meshing. Boundary conditions for the sub model will be automatically interpolated from the global model solution.

Seung (2008) was investigated about the fatigue analysis of an automotive steering link. Finite element method was employed by the authors to determine local stress and strain distributions of the link. The experimental strains at the critical locations in this study were measured by using strain-gages in order to verify the accuracy of the finite element analysis results. From the finite element stress analysis, the authors found that the cracking occurred at the curved region of the tubular steering link rod and propagated circumferentially to the opposite side of the link rod, resulting in the final fracture.

Zhoa et al**.** (2005) carried out a research about the analysis of damage in laminated automotive glazing subjected to simulated head impact. The author focused on occupant's head impacting on windshield or side window. The author explained that any attempt to design glazing that minimizes injury to and death of occupants during a vehicle accident requires a thorough understanding of the mechanical behavior of automotive glazing subjected to head impact loads. A continuum damage mechanics (CDM) based constitutive model is developed and implemented into an axisymmetric finite element model to study the failure and impact resistance of laminated automotive glazing subjected to simulated head impact. From the study, Damage due to normal principal stress and damage due to shear stress data are collected. Finite element analysis is used to simulate the damage pattern and zone size of a laminated glass panel subjected to normal impact of a featureless headform. The damage pattern and zone size are predicted from the stress analysis.

Kim et al. (2002) were studied a method for simulating vehicles dynamic loads, but they add durability assessment. For their multibody dynamic analysis they use DADS and a flexible body model. The model was for a transit bus. For their dynamic stress analysis , MSC. NASTRAN was used. The fatigue life was then calculated using a local strain approach. From the fatigue life, it was found that the majority of the fatigue damage occurred over a frequency range that depend on terrain traveled (service or accelerated test course). This showed that the actual service environment could be simulated instead of using an accelerated testing environment.

Rahman et al. (2007) were proposed about finite element based durability assessment in a two- stroke free piston linear engine component using variable amplitude loading. Authors discussed the finite element analysis to predict the fatigue life and identify the critical locations of the component. The effect of mean stress on the fatigue life also investigated. The linear static finite element analysis was performed using MSC. NASTRAN. The result was capable of showing the contour plots of the fatigue life histogram and damage histogram at the most critical location.

2.4 STOCHASTIC OPTIMIZATION METHOD

Zang et al. (2004) was studied about the review of robust optimal design and its application in dynamics. The author stated that the objective of stochastic optimization is to minimize the expectation of the sample performance as a function of the design parameters and the randomness in the system. The response surface methodology (RSM) is a set of statistical techniques used to construct an empirical model of the relationship between a response and the levels of some input variables, and to find the optimal responses. In the author's research stated that, Lucas (1994) and Myers et al. (1992) considered the RSM as an alternative to Taguchi's robust design method. Monte Carlo simulation generates instances of random variables according to their specified distribution types and characteristics, and although accurate response statistics may be obtained, the computation is expensive and time consuming. From the result of the author's studied, the author concluded that the robustness of the response due to uncertainty in the mass and stiffness of the main system, and the maximum mean displacement response and the variations caused by the mass and stiffness uncertainty were minimized simultaneously. Monte Carlo simulation demonstrated significant improvement in the mean response and variation compared with the traditional solution recommended from vibration textbooks. The results show that robust design methods have great potential for application in structural dynamics to deal with uncertain structures.

2.5 CONCLUSION

This chapter is about the summary of preview work that related to this project including the robust design, the stress analysis, and stochastic optimization method. The next chapter is about the methodology of the project.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter presents the overall methodology of the robust design method and the stochastic optimization which is be implemented into the design of lower arm suspension will be analyze in order to create a better functionality, better value, and longer lasting of a lower arm suspension.

3.2 ROBUST DESIGN METHOD

In this project, the lower arm design is analyzed using the MSC.Robust Design software.Robust Design is based on Monte Carlo simulation (MCS). MCS is the process that randomly generates the values for uncertain variables over and over again to simulate possible conditions a model might experience in reality. Simulation refers to any analytical method meant to imitate a real-life system, especially when other analyses are mathematically too complex or too difficult to model. The random behavior in games of chance is similar to how Monte Carlo simulation selects variable values at random to simulate a process. The variables are finite element characteristics, material properties, loads, and constraints. For each uncertain variable the possible values are defined by means of a probability distribution. During a single trial, MSC.Robust Design randomly selects a value for each uncertain variable, replaces the nominal values with the random ones, and submits the finite element analysis.

3.3 STOCHASTIC OPTIMIZATION METHOD

Optimization problems in practice depend mostly on several model parameters, noise factors, uncontrollable parameters, etc., which are not given fixed quantities at the planning stage. Due to several types of stochastic uncertainties (physical uncertainty, economic uncertainty, statistical uncertainty, and model uncertainty) these parameters are modeled by random variables having a certain probability distribution. In most cases at least certain moments of this distribution are known. Hence, instead of relying on ordinary deterministic parameter optimization methods – based on some nominal parameter values – and applying some correction actions, stochastic optimization methods should be applied: By incorporating the stochastic parameter variations into the optimization process, expensive and increasing online correction expenses can be avoided or at least reduced to a large extent.

Robust Design performs stochastic simulation using the Monte Carlo method. The salient characteristics of Monte Carlo techniques are that they:

- Are generic and independent of application type (linear, non-linear, etc.).
- Are independent of the number of variables (no “curse of dimension”).
- Cost-driven only by the required precision of the results.

The result of a stochastic simulation is a meta-model, i.e. a matrix which has as many rows as the number of Monte Carlo samples + 1, and as many columns as the sum of input and output variables. Projections of the meta-model on two or three dimensions yield ant-hill plots, or 3 scatter plots. The first row of the meta-model corresponds to the nominal deterministic condition and is included in the corresponding matrix for convenience and reference. Meta-models can assume rich and complex forms. The topology of a multi-dimensional meta-model depends on the physics, which is carried in the FEM. The ability to relate these physics to the properties of a particular meta-model is directly proportional to the understanding of the product’s functioning. This is why it is so important to preserve the information contained in the meta-model and to extract it in a form that is directly usable by an engineer.

Robust Design provides the means to quickly sort through this information and indicate the variables that have the most significant correlations, and therefore most impact the product's performance. Correlation is a concept different from of sensitivity in that collective changes in variable values are considered. Correlation between two variables expresses the strength of the relationship between these variables by taking into account the scatter in all the other variables in a system. It is possible to compute correlations between any pair of variables (input-output, output-output, etc.). Knowledge of the correlations in a system is equivalent to the understanding of how that system works.
MSC. Robust Design uses two metrics for measuring the correlation between variables:

- Pearson's correlation coefficient (or linear correlation coefficient)
- The Spearman rank coefficient (or non-linear correlation coefficient)

The above correlations are used in Robust Design for results interpretation and are labeled as linear and non-linear correlations on output plots. Pearson's correlation coefficient measures the linear correlation between variables. For two stochastic variables, *x* and *y*, their Pearson, or linear correlation is expressed as equation (3.1).

$$= \frac{\Sigma\ (\qquad)}{\sqrt{\Sigma\ (\qquad)}\ \sqrt{\Sigma}} \tag{3.1}$$

where *u* is the mean value
The values of the Pearson correlation range from –1 to 1. A value close to either 1 or –1 indicates a strong linear correlation. Values close to zero indicate the variables are uncorrelated.

The Spearman rank correlation compensates for this, and is a more reliable means for determining if a significant relationship exists between stochastic variables. The computation of the Spearman's rank correlation is done by ranking the variables from highest to lowest assigning ranks from 1 to N. The variable value is then replaced with its corresponding rank. The Spearman rank correlation coefficient r_s, is then computed as the linear correlation coefficient between the ranks R_i of the $x_i s$ and the ranks S_i of the $y_i s$, the r_s is expressed as equation (3.2)

$$= \frac{\sum (\qquad)(\qquad)}{\sqrt{\sum (\qquad)}\sqrt{\sum (\qquad)}} \tag{3.2}$$

As with the Pearson correlation, the values of the Spearman coefficient range from –1 to 1. A value close to either 1 or –1 indicates a strong correlation. The Spearman ranking is used to create pie charts to show the relative influence of tolerances in input variables on the scatter (quality) in a particular functionality (output).

For the design of the lower arm suspension, the application of Stochastic Design Improvement (SDI) will be use which is in the MSC.Robust Design software. SDI is a fast and efficient capability to improve a system design so that its most probable behavior coincides with specified target values. Variables that can be controlled are selected as design variables, while those that cannot be controlled are established as randomized noise variables. The tolerances on the design variables are opened up to include the full range of physically possible values. A target output behavior is selected from the output variables available in the FEM. The values of the design variables in this first set of 15 runs scatter around the nominal values for those variables contained in the input FEM. Another set of 15 runs is performed using the result from the first set of runs that is closest to the target value as the new nominal value. This process continues until either the target value or a physical limit for the design variable is reached. This is normally accomplished with 4 to 6 sets of 15 analysis runs. The key feature of SDI is that it operates on a full FE model, which incorporates tolerances, and not on a simplified surrogate. SDI surpasses classical optimization techniques in terms of performance and computational cost. Figure 3.1 shows the flows of steps that will be done in the SDI for the lower arm suspension design.

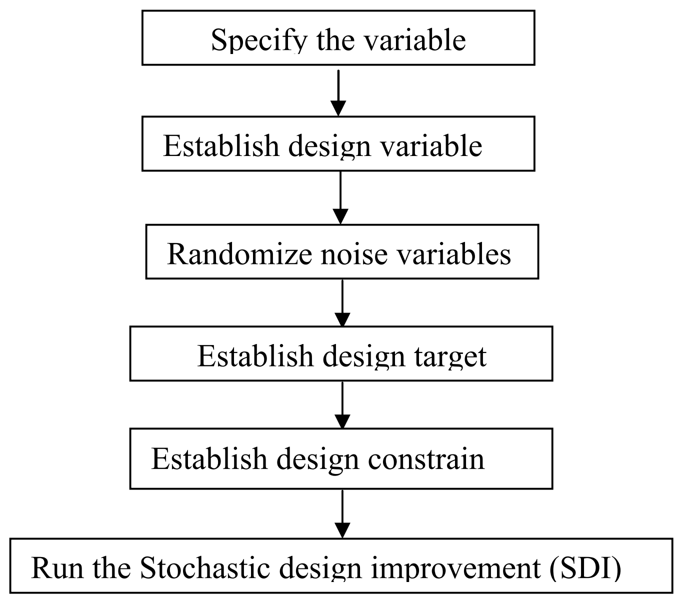

Figure 3.1: Flow chart of steps in SDI

3.4 CONCLUSION

This chapter is about methodology of the robust design method and the stochastic optimization which was implemented into the design that have been made. The next chapter will be describe about the result of structural modeling, finite element modeling (FEM), analysis and the optimization.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter is represents about the results of the finite element (FE) analysis, stochastic simulation, and stochastic design improvement (SDI).

4.2 FINITE ELEMENT MODELING

The lower arm suspension is one of the important parts in the suspension system. A specific area of constraint has been set into the design in order to get a precise result. A structural modeling of the lower arm suspension was developed using SolidWorks software as shown in Figure 4.1. Overall dimensios of the suspension arm is shown in Figure 4.2. Two types of nodes, 4 nodes tetrahedral (TET4) and 10 nodes tetrahedral (TET10) has been used in the finite element modeling using MSC. PATRAN. These analyses were preformed iteratively at different mesh global length until the appropriate accuracy obtained. The convergence of the stresses was studied as the mesh global length was refined in the analysis. The mesh global length of 0.1 mm was chosen and the pressure of 8 MPa was applied at the end of the bushing that connected to the tyre. The other two bushing that connected to the body of the car are constraint.The pressure that has been applied is based on Al-Asady,et al. (2008). The three-dimensional FE model, loading and constraints of suspension arm is shown in Figure 4.3.

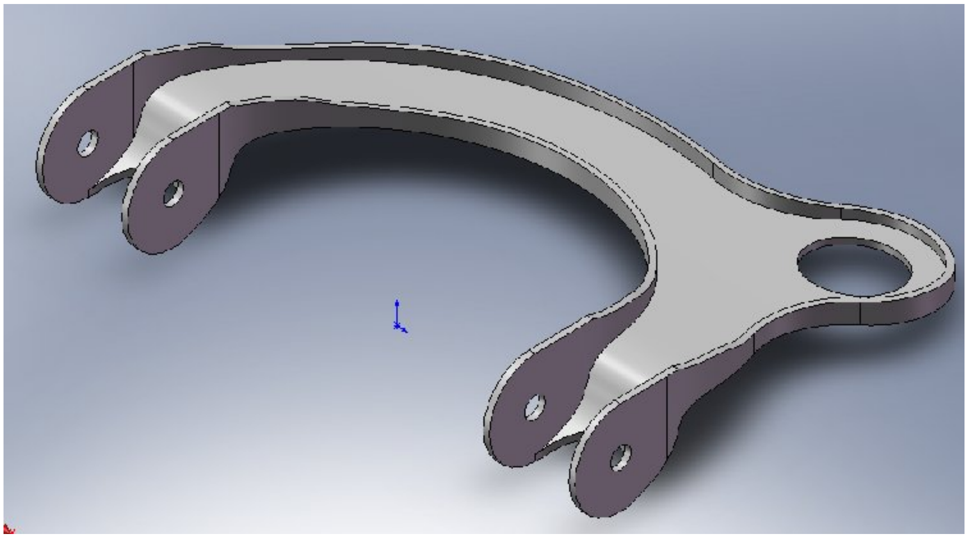

Figure 4.1: Structural model of suspension arm

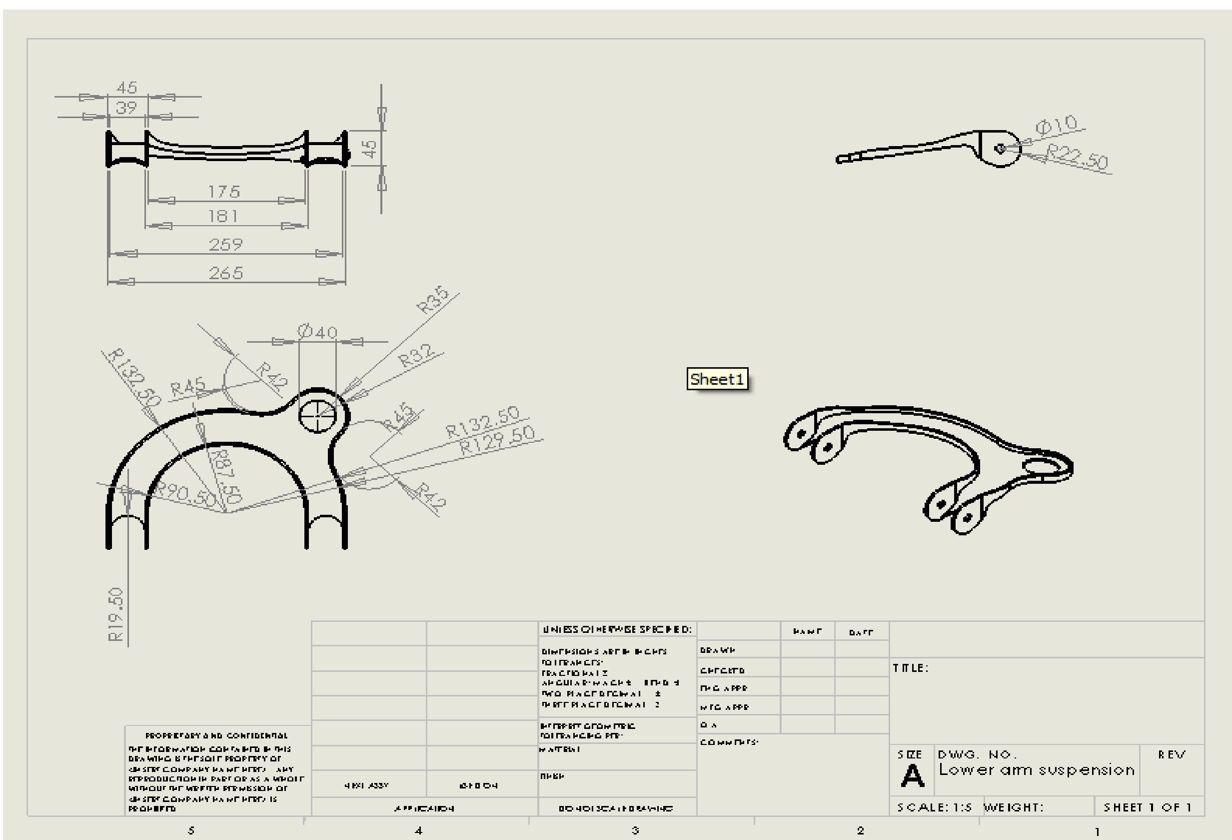

Figure 4.2: Overall dimensions of lower arm suspension

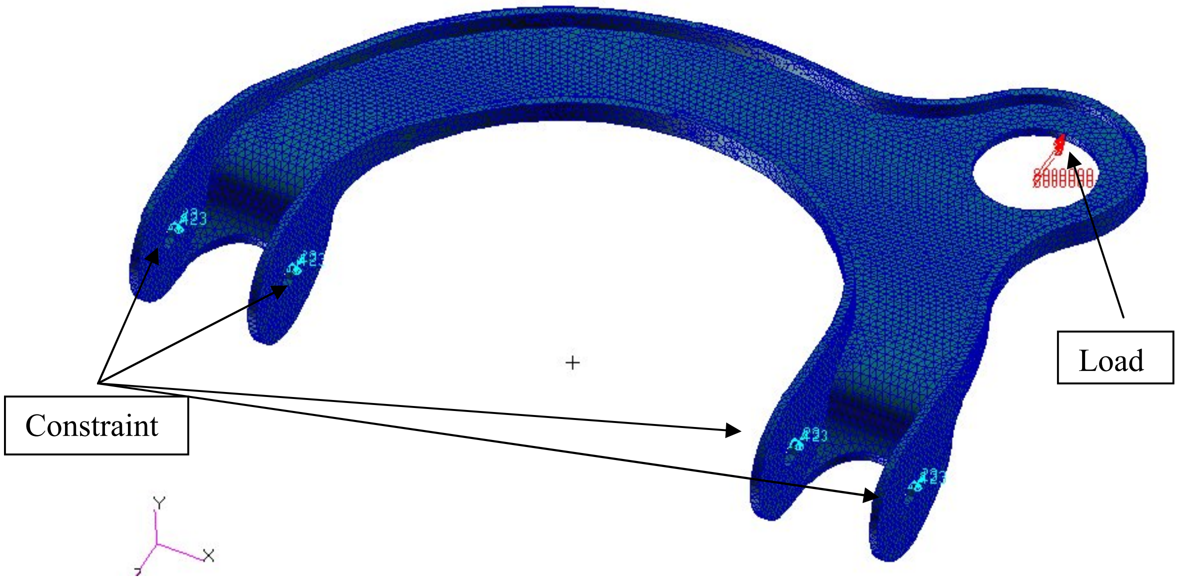

Figure 4.3: Three-dimensional FE model, loading and constraints.

4.3 EFFECTS OF THE MESH TYPES

In the finite element modeling and analysis, a mesh study has been constructed by refining the mesh in order to obtain the accuracy of the calculated result which depends on the competitive cost (CPU time). During the analysis, the specific variable of mesh global length and the mesh convergence was monitored and evaluated. The mesh convergence is based on the geometry, model topology and analysis objectives. For this analysis, the auto tetrahedral meshing approach is employed for the meshing of the solid region geometry. By using the tetrahedral meshing, a high quality meshing for boundary representation can be obtained from the solid model that is imported into the analysis. The tetrahedral elements (TET10) and tetrahedral elements (TET4) are used for the mesh analysis. From the mesh analysis, TET10 gives a higher value of nodes compare to the TET4 type of mesh (Figure 4.4 and 4.5). By setting the pressure and the constraint on the lower arm design, the first analysis result shown that TET10 mesh predicted higher von Mises stress than the TET4 mesh (Figures 4.6 and 4.7) various mesh global length. Then, the comparison was made between these two elements based on stresses concentration such as von Mises, Tresca, maximum principal stress and displacement as shown in Figure 4.8. The overall results show that the TET10 mesh give a higher stresses concentration compared to TET4 for the same mesh global length. Thus, TET10 is used for overall analysis.

From the stress analysis, the result shows that the white area of the design is the lowest predicted stress acted on the lower arm suspension design. Therefore, the area can be made as a guide in the future process of modifying or optimizing the design. It is also important to make sure that the critical points on the design which have the highest predicted stress should be look carefully in the process of modifying and optimizing the design in order to avoid any failure in the future usage of the lower arm design.

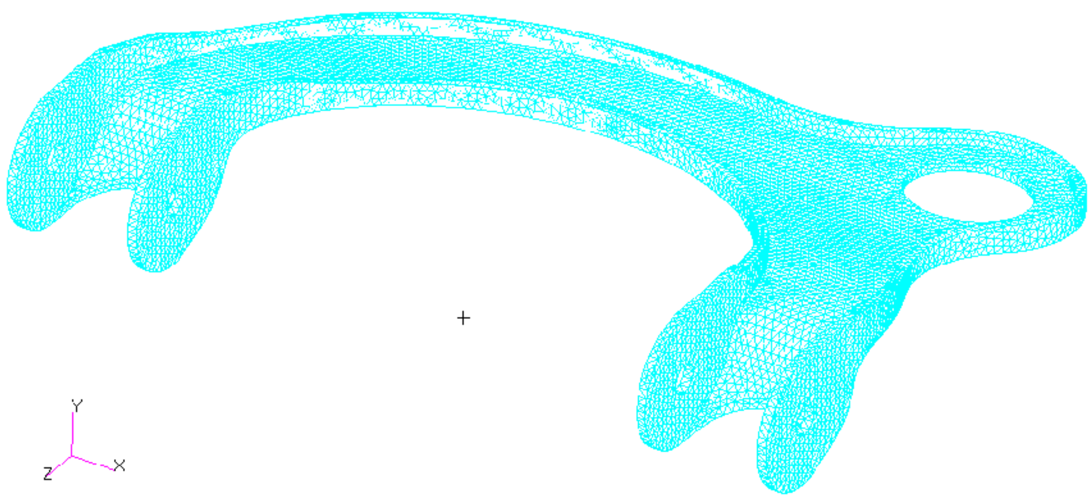

Figure 4.4: TET4, 54 141 elements and 15 098 nodes

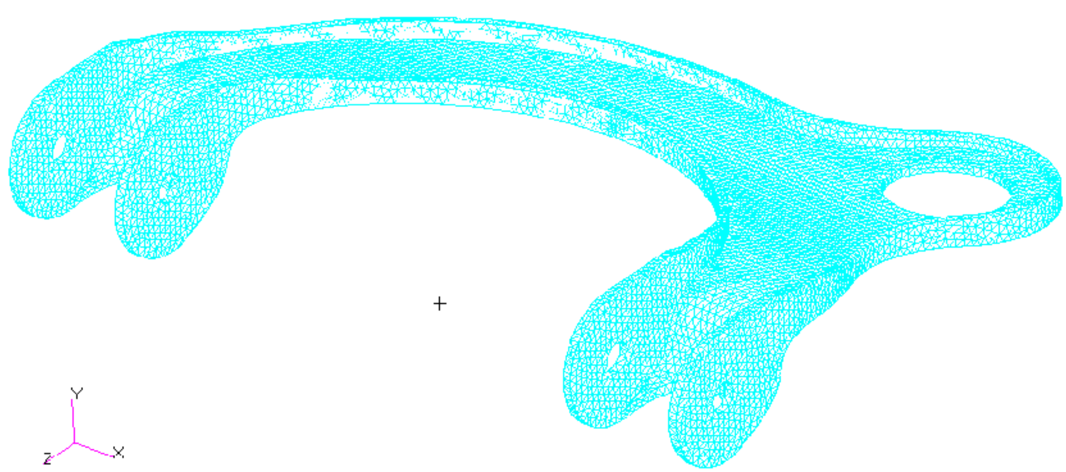

Figure 4.5: TET10, 54 178 elements and 96 080 nodes

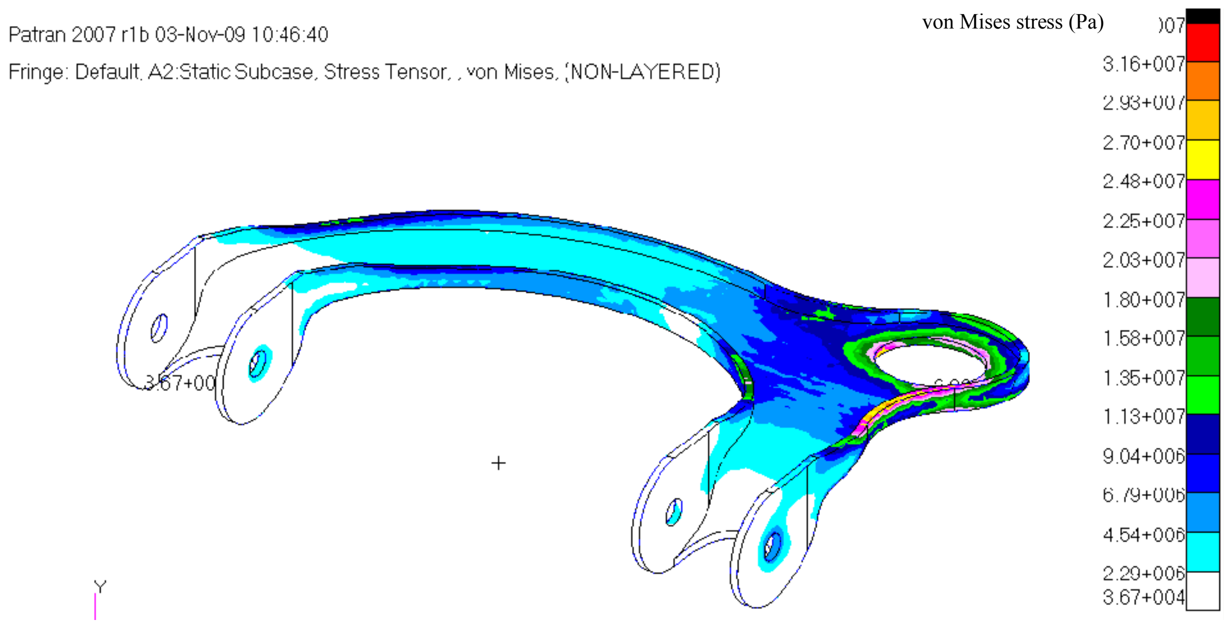

Figure 4.6: von Mises stresses contour for TET4

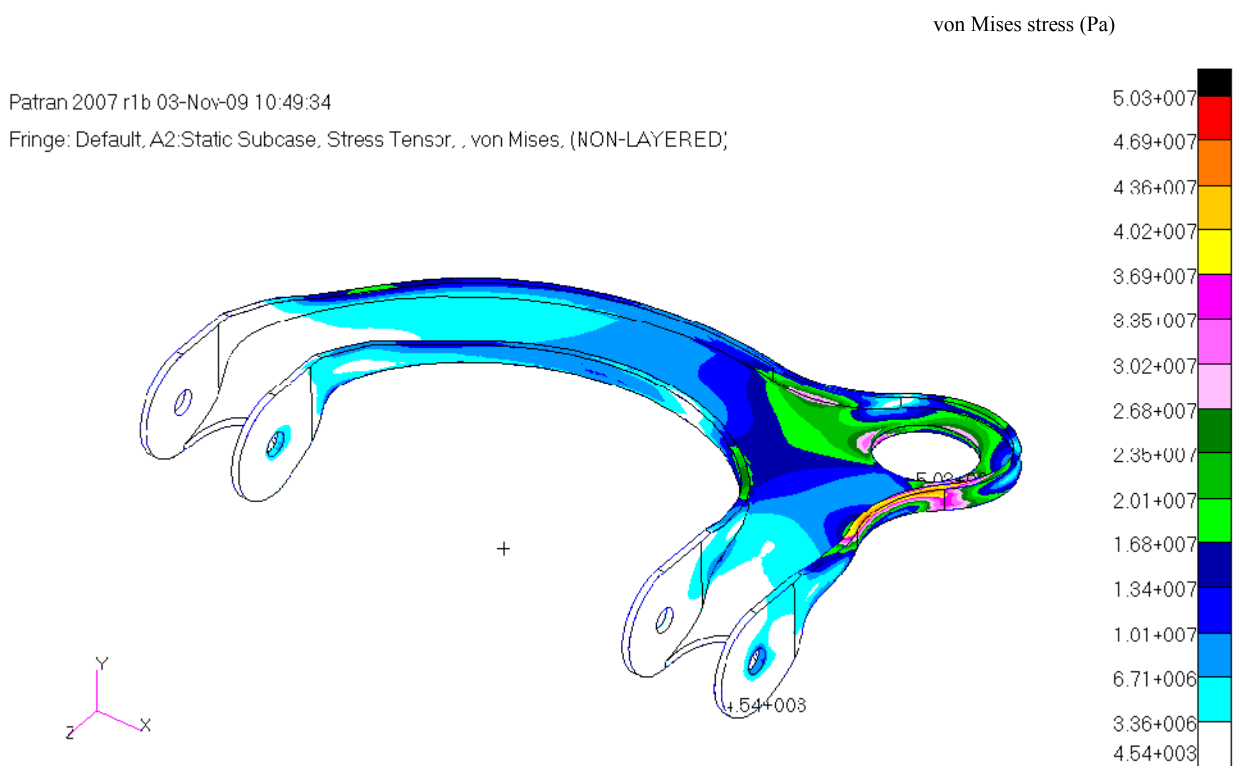

Figure 4.7: von Mises stresses contour for TET10

Mesh size (mm)	Total nodes	Total Elements	Von Mises (MPa)	Tresca (MPa)	Max Principal Stress (MPa)
0.1	96 080	54 178	50.3	56.3	45.2
0.3	10 041	4676	50.2	54.2	42.3
0.6	5889	2665	48.9	52.2	35.6
1.0	5436	2465	47.4	50.7	35.2
1.5	3186	1409	45.3	49.9	25.7

Table 4.1: Variation of stresses concentration at the critical location of the suspension arm for TET10 mesh.

Mesh size (mm)	Total nodes	Total Elements	Von Mises (MPa)	Tresca (MPa)	Max Principal Stress(MPa)
0.1	15 098	54 141	31.6	36.4	28.1
0.3	1775	4643	21.0	23.4	15.9
0.6	1055	2621	16.4	18.4	13.2
1.0	977	2429	15.8	17.5	12.7
1.5	561	1320	14.1	15.6	11.3

Table 4.2: Variation of stresses concentration at the critical location of the suspension arm for TET4 mesh.

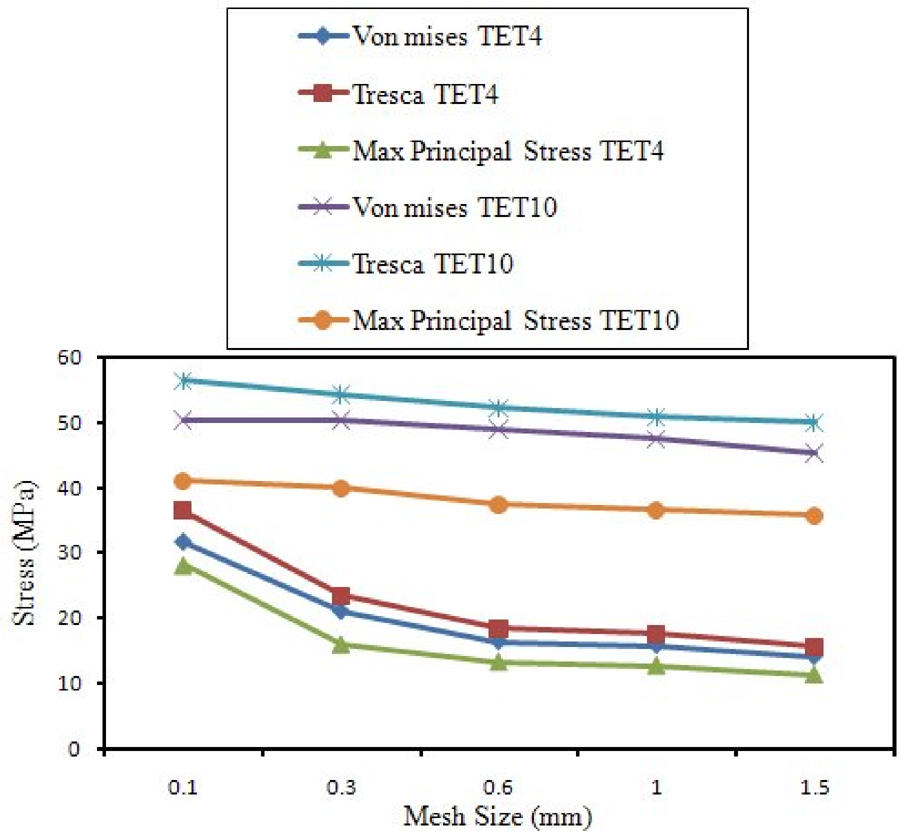

Figure 4.8: Stress results comparison between TET4 and TET10

4.4 IMPORTANCE OF THE MESH CONVERGENCE

The convergence of the stress was considered as the main criteria to select the mesh type. The finite element mesh was generated using the TET10 for various mesh global length as showed in Table 4.3. Figure 4.9 shows the predicted result of stresses concentration at the critical location of the lower arm suspension. It is seen that the smaller the mesh size the higher the stresses concentration predicted. The result of higher stress predicted is because of smaller and more complex mesh is use, the analysis can calculate more sharp edges and complex area in the design, thus the value of predicted stress is higher and more precise. From Figure 4.9, it can be seen that mesh size of 0.1 mm (54 178 elements) has the largest stresses predicted be seen. The smaller mesh size than 0.1 mm did not implemented due the limitation of the computational time

(CPU time) and storage capacity of the computer. Hence, the maximum Von Mises based on TET10 at 0.1 mm mesh size is used in the stochastic optimization analysis.

Table 4.3: Variation of mesh size related to number of element and node for TET10.

Mesh size (mm)	Number of nodes	Number of elements
0.1	96 080	54 178
0.3	10 041	4676
0.6	5889	2665
1.0	5435	2465
1.5	3185	1409

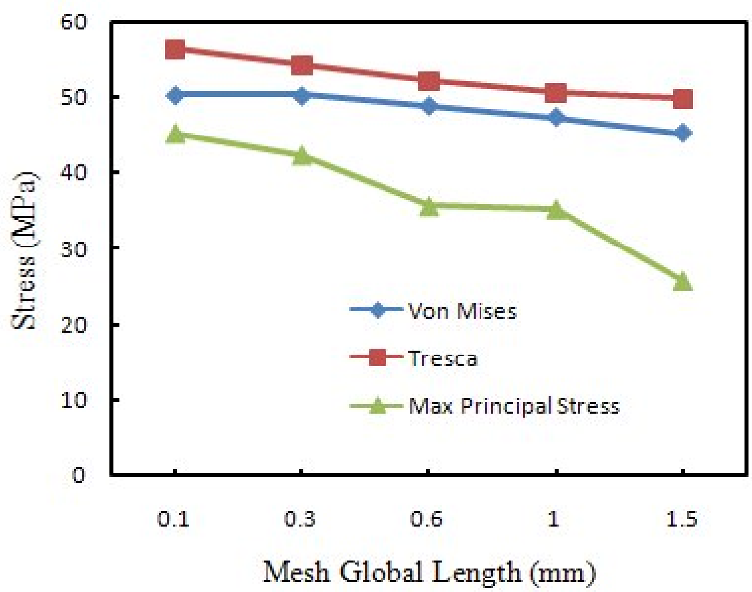

Figure 4.9: Stresses concentration versus mesh size at critical location of suspension arm for TET10 to check mesh convergence.

4.5 STOCHASTIC SIMULATION

A stochastic simulation generates multiple scenarios of a model by repeatedly sampling values from the probability distributions for the uncertain variables. The stochastic simulation takes the uncertainty of variables into account to determine the level of uncertainty in the outputs. The more stochastic variables a model contains, the more realistic it is. From the figure 4.10, the relative influence of tolerances in input variables on the scatter in a particular functionality (output) can be obtained. The pressure gives the largest influence on the stress value followed by the Poisson ratio, modulus of elasticity, and density respectively. This result is very logical and showed that the design is functioning correctly. The specific results of the influence of the variables can be seen in the ant hill scatter plots as shown in figure 4.11.

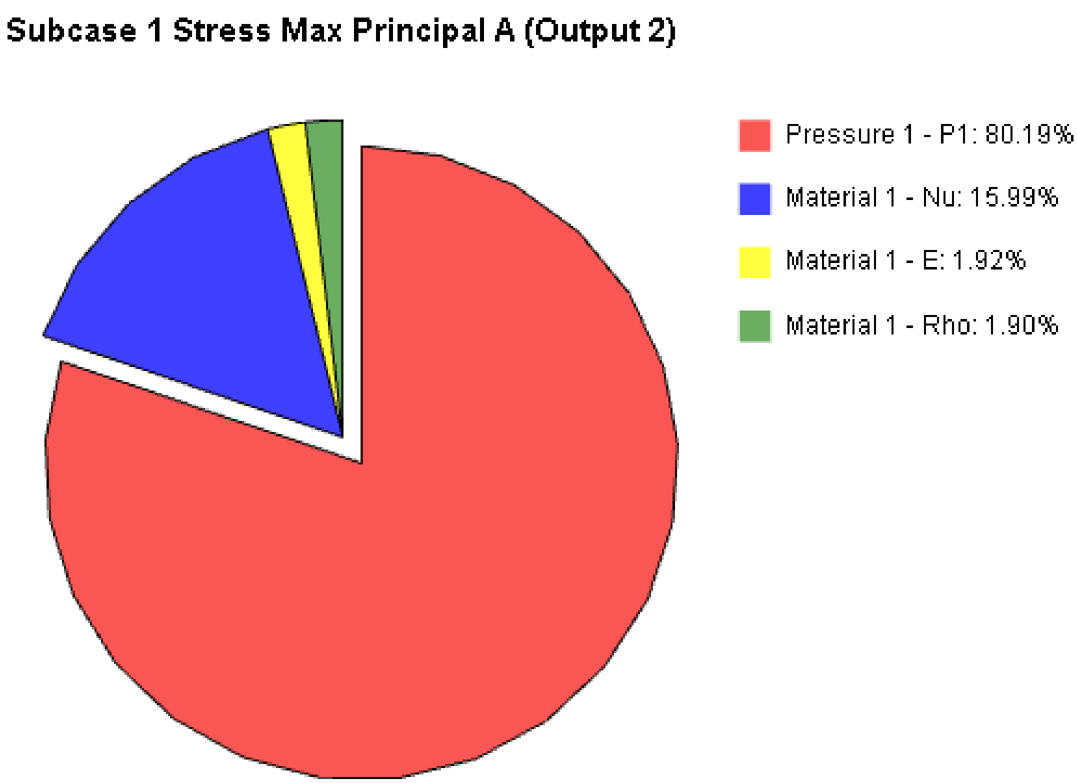

Figure 4.10: Pie chart of factors that influence to the stress value in the design.

From the ant hill plot in Figure 4.11, essentially no clear correlation can be seen between the stress and the Poisson ratio. This confirms the pie chart result that the Poisson ratio is a small factor in the stress value. The clearer relation between the pressure and the stress can be seen in the Figure 4.12 and Figure 4.13 below. It can be seen that the pressure have a high correlation value in the ant hill plot scatter plot. This also confirms the result in the pie chart that the pressure is the highest factor for the value of the stress acted on the design. From all the results obtained from the stochastic simulation all the variables that drive the response on the design can be identify such as pressure, Poisson ratio, Modulus of elasticity, and density. The simulation results also provides a general understanding of how the design works. All this information and parameters are very important in order to proceed with the design optimization process.

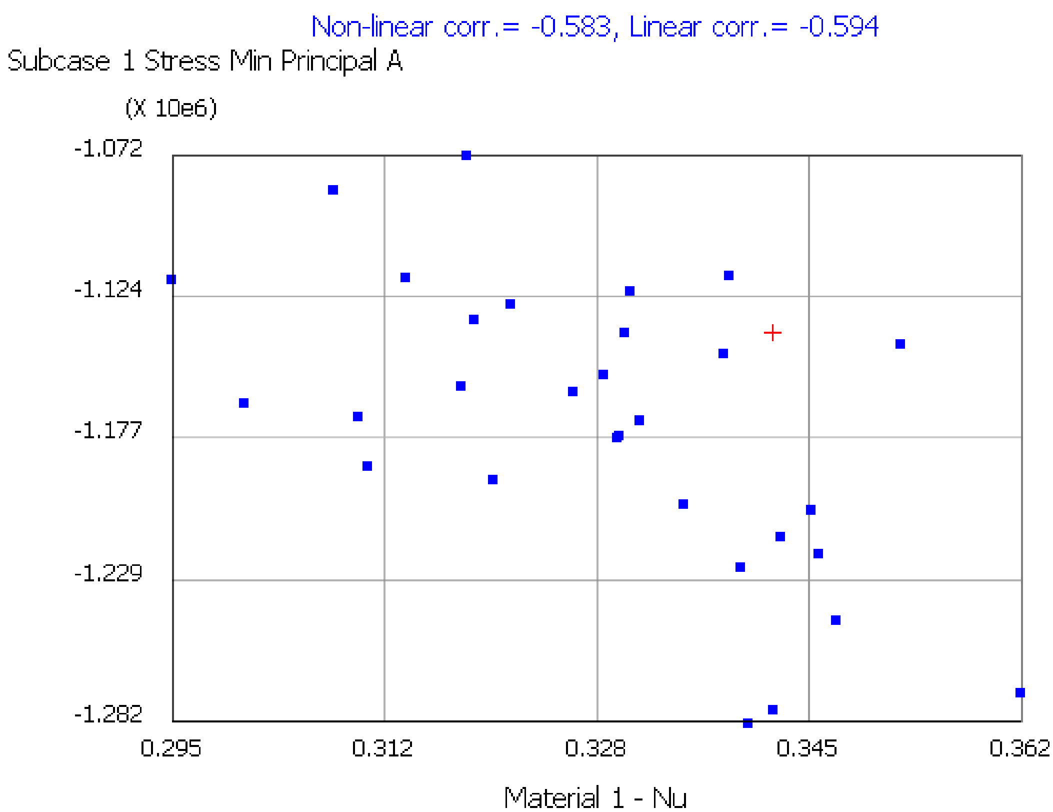

Figure 4.11: Ant hill scatter plot for stress VS Poisson ratio

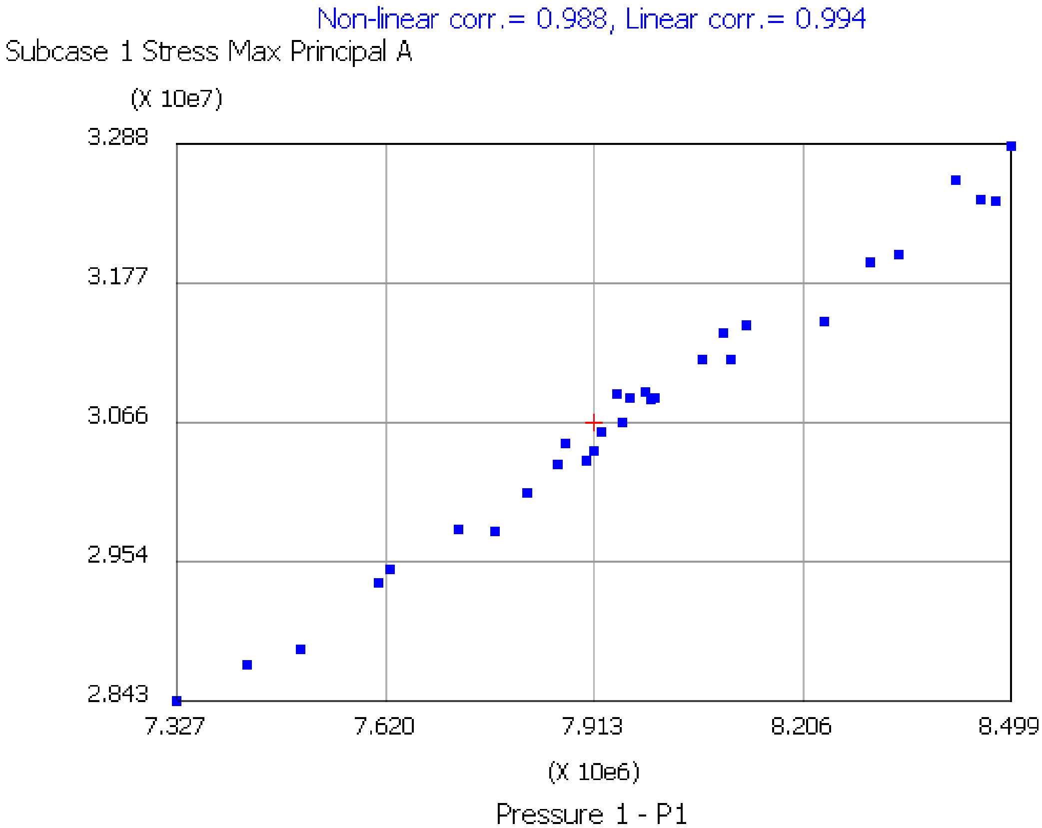

Figure 4.12: Ant hill scatter plot for stress VS pressure

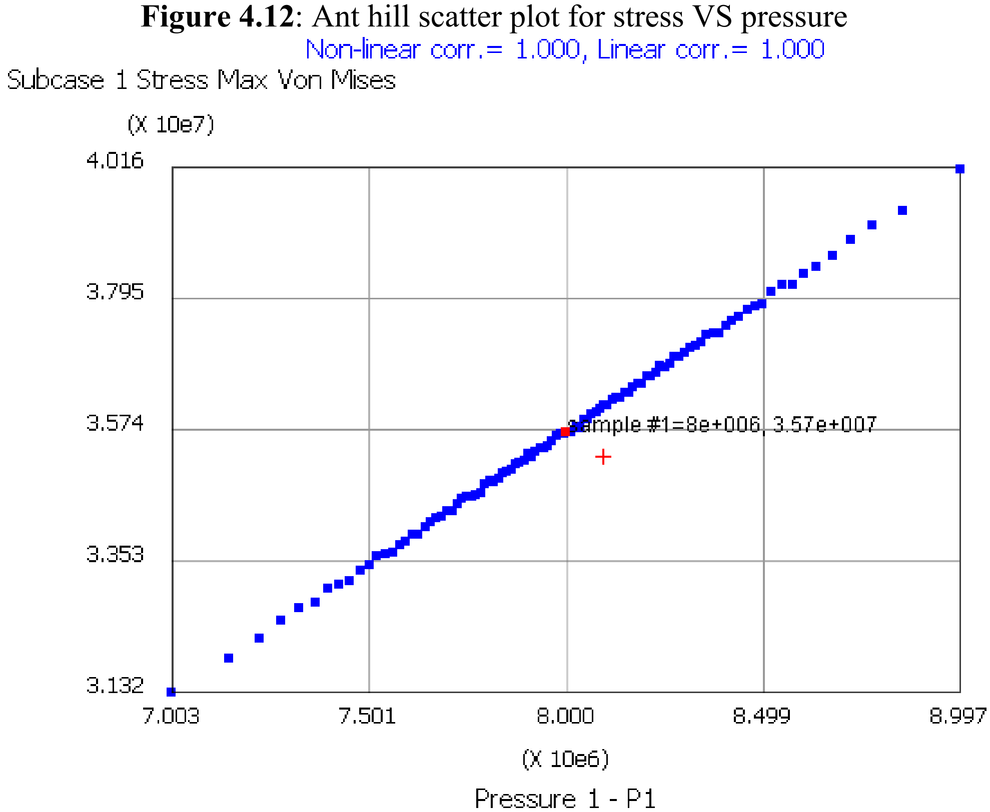

Figure 4.13: Ant hill scatter plot for stress VS pressure

4.6 STOCHASTIC DESIGN IMPROVEMENT

In the optimization process, stochastic design improvement (SDI) has been performed to the design using MSC. Robust Design. SDI is a fast and efficient capability to improve a system design so that its most probable behavior coincides with specified target values. Variables that can be controlled are selected as design variables, while those that cannot be controlled are established as randomized noise variables. The tolerances on the design variables are opened up to include the full range of physically possible values. A target output behavior is selected from the output variables available in the FEM. In the optimization process for the design all the parameters have been set as follows.

i. Hard target : Von Mises Stress , 50.3 MPa
ii. Design Variable : Modulus of Elasticity
: Poisson Ratio
: Density
: Pressure

The SDI process has been perform in 5 iterations, thus the scatter plot have 5 colors in the result of the SDI. Each color represents for each iterations. The blue color was the first run and the purple was the last iteration. From the data of the scatter plot, the best sample of the result is chose for the optimization parameters. The results of SDI shows that there are multiple samples from the ant hill scatter plot that give the value of the parameter to use in the optimization process. The best sample from the ant hill scatter plot is selected. All the parameter values are as shown in table 4.3.

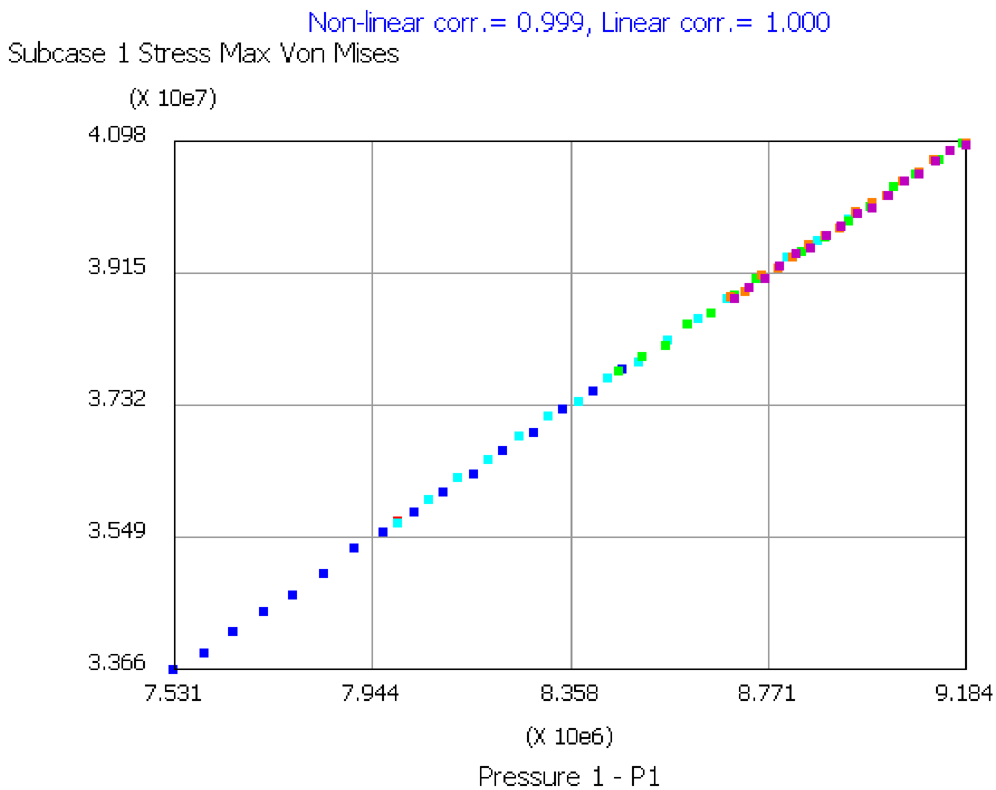

Figure 4.14: Ant hill scatter plot for stress VS pressure (After SDI)

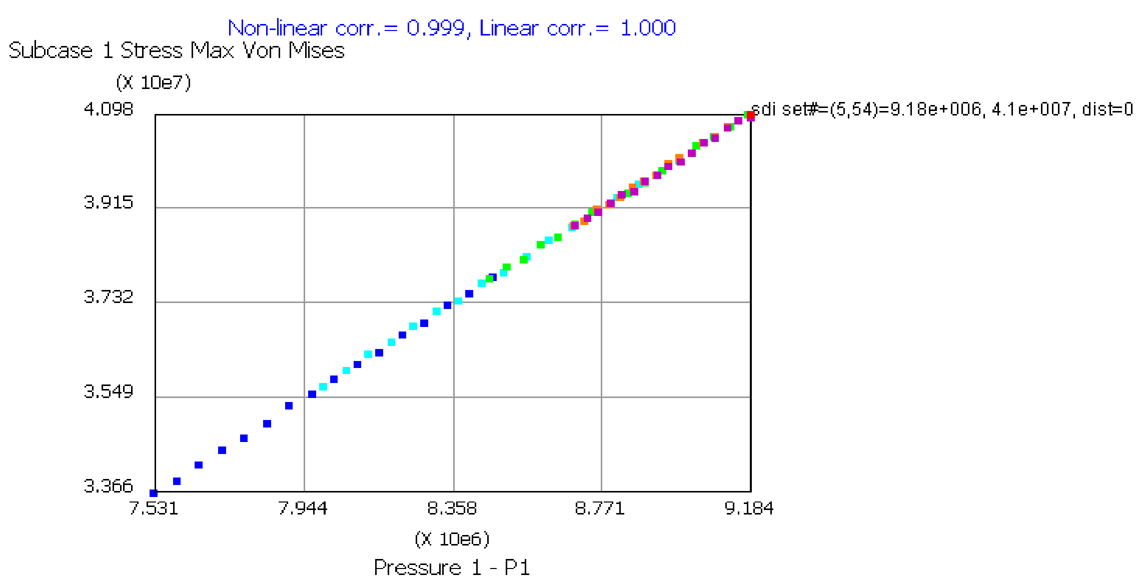

Figure 4.15: Best SDI sample result selection in Ant hill scatter plot

From table 4.4, improvement to the design can be done by using the design parameter which is obtained from the stochastic design improvement. The result shows that the lower arm design has a higher capability to stand higher pressure as 9.18 MPa with the stress acted on lower arm is 41 MPa. The Modulus of Elasticity and density also decrease, so a lighter material can be chose for the lower arm design.

Table 4.4: Comparison of the design parameter before and after optimization

Parameter	Initial Design	After SDI
Modulus Of Elasticity	71.7 GPa	69.1GPa
Density	2.7 g/cc	2.489 g/cc
Poisson Ratio	0.33	0.3428
Pressure acted on the design	8 MPa	9.18 MPa
Predicted stress acted on the design	50.3MPa	41.0 MPa

4.7 CONCLUSIONS

The results of optimization on the lower arm suspension are well presented in this chapter. The finite element modeling and analysis of lower arm suspension has also been presented. The stress analysis has been investigated for the lower arm suspension. The result of stochastic design improvement has been presented. The summary of the finding and recommendations will be present in the next chapter.

CHAPTER 5

CONCLUSION

5.1 INTRODUCTION

This chapter summarized the conclusion and recommendations for the overall objective of the project based on finite element analysis.

5.2 CONCLUSIONS

A robust design of lower arm suspension using stochastic optimization is presented. From the analysis, several conclusions can be drawn as follows.

i. The design capability to endure more pressure with lower predicted stress is identified through the optimization process.
ii. A lower density and modulus of elasticity of material can be reconsidered in order to optimize the design.
iii. The area of the design that can be altered for the optimization and modification is identified through the stress analysis result.

5.3 RECCOMMENDATIONS

For further research, the experimental works under controlled laboratory conditions should be done to determine the validation of the result from the software analysis. All the parameter of optimization that has been obtained from the study should be make as a range and guidelines during the experimental works of modifying and optimizing the lower arm suspension.

REFERENCES:

Al-Asady, N.A., Abdullah, S., Arrifin, A.K., Rahmman, M.M. and Beden, S.M. 2008. Improving the automotive lower suspension arm durability using finite element analysis, *Seminar on Engineering Mathematics*. Universiti Malaysia Pahang of Department of Mechanical and Materials Engineering.

Bharatendra, R., Nanua, S. and Mustafa, A. 2004. Robust design of an interior hard trim to improve occupant safety in a vehicle crash, *Reliability Engineering & System Safety*, **89**(3): 296-304

Conle, F.A., and Chu, C. C. 1998. Fatigue analysis and the local stress–strain approach in complex vehicular structures, *International Journal of Fatigue,* **19**(93): 317-323

Kim, H.S, Yim, H.J. and Kim, C.M. 2002. Computational durability prediction of body structure in prototype vehicles. *International Journal of Automotive Technology*, **3** (4): 129-136

Kopac, J. and Krajni, P. 2007. Robust design of flank milling parameters based on grey-Taguchi method, *Journal of Materials Processing Technology,* **191**(1-3): 400-403

Lucor , D., Enaux, C., Jourdren, H. and Sagaut, P. 2007. Computer Methods in applied mechanics and engineering, **196**(49-52): 5047-5062

Lucas, J.M. 1994. How to achieve a robust process using response surface methodology, *J Quality Technol*, **26** :248–260.

Myers, R.H., Khuri, A.I. and Vining, G. 1992. Response surface alternative to the Taguchi robust parameter design approach, *J Am Stat,* **46**: 131–139.

Prawoto, Y., Ikeda, M., Manville, S.K. and Nishikawa A. 2007**.** Design and failure modes of automotive suspension springs, *Engineering Failure Analysis*, **15**(8): 1155-1174

Rahman, M.M., Ariffin, A.K., Abdullah, S. and Jamaludin, N. 2007. Finite element based durability assessment of a free piston linear engine component. *SDHM*, **3** (1): 1-13

Rakesh, M., Tong, L.H., Zhijie, L. and Ibrahim, Y.2002. Robust design of a spindle motor: a case study, **75**(3): 313-319

Riley, R.Q. 2003. Alternative Cars in the 21st Century: A New Personal Transportation paradigm Second Edition.

Sreeram, P. 1994. Robust Design of an Automotive Suspension System. M.S. Thesis. Michigan Technological University, USA .http://www.mfg.mtu.edu/docs/thesis.html

Seo, P.K., Kim, H.C. and Kang, C.G. 2006**.** Numerical integration design process to development of suspension parts by semi-solid die casting process, *Journal of Materials Processing Technology,* **183**(1): 18-32

Seung, K.K. 2008. Fatigue analysis of an automotive steering link, *Engineering Failure Analysis*, **16**(3): 914-922

Zhao, S., Dharani, L.R., Chai, L. and Barbat, S.D. 2005. Analysis of damage in laminated automotive glazing subjected to simulated head impact, *Engineering Failure Analysis,* **13**(4): 582-597

Zang, C., Friswell, M.I. and Mottershead, J.E. 2004. A review of robust optimal design and its application in dynamics, *Computers & Structures*, **83**(4-5): 315-326