KINEMATICAL SUSPENSION OPTIMIZATION USING DESIGN OF EXPERIMENT METHOD

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ABSTRACT

This paper presents optimization of two suspension quarter car model using Design of Experiment Method. The aim is to determine suspension parameters to achieve the best comfort for human. Two models are used, which are 2 degree of freedom (2 DOF) and 3 degree of freedom (3 DOF). Sprung mass acceleration and also kinematic criteria chamber angle and toe angle had been used to validate both models. The optimization results are compared using step excitation base on the conditions from literature of optimal suspension system. In the case of 2 DOF suspension model at initial condition with optimized value from the literature, sprung mass acceleration did reduce by 32.36%, but suspension working space did increase by 18.71%. Dynamic tyre load did not show significant change which reduces by 0.02%. For 3 DOF suspension model at initial condition with optimize value from the literature, sprung mass acceleration did reduce by 32.28%, but suspension working space only increase by 0.09% and dynamic tyre load reduce only by 0.05% which did not shown significant change.

Keywords : *Optimization, Response Surface Method*

1.0   INTRODUCTION

Suspension is a road wheel guiding mechanism that can be considered as a multi-body system composed of rigid bodies and highly compliant links that interacting through some kinematic and compliant joints. Its primary functions are to determine the geometry of the wheel motion during jounce and rebound and to isolate the sprung mass from the road-induced vibration which improve car handling and can effectively attenuate the vehicle vibration resulting from various road conditions. Ideally, the suspension should allow the wheels to move with respect to the body of the vehicle in a direction perpendicular to the road, maintaining the plane of the wheel parallel to itself and constraining all motions in all directions.

This vertical motion must be managed through the suspension linkages in order to guarantee the tire's correct position with reference to the ground [1]. In theory, tires alone could isolate the vehicle body from forces coming from the road, but their elastic and damping properties are not sufficient to achieve suitable handling and comfort targets, unless at very low speed and on smooth roads. Suspensions are therefore essential for achieving adequate road holding behaviour (handling) and comfort [1].

Suspension parameter had been studied by comparing experimental data and simulations model [2]. In this study, it focussed on McPherson suspension hard point and optimization is carried out to get best kinematic characteristic. Studies on passengers comfort by optimizing suspension stiffness and damping is carried out by Abbas *et al.* [3]. Their study focussed on frequency transfer to passenger body and optimization ofsuspension stiffness and damping. From optimization study by Fallah *et al* [4], new nonlinear model of the McPherson strut suspension are developed to improve the ride quality and facilitate the evaluation of the suspension kinematic parameters. Procedure for optimal synthesis of three-dimensional

mechanisms and its application to the McPherson strut considering toe, caster and camber angle requirements are proposed by Kovacs [5]. Others studies using same parameters and using an axiomatic approach to the kinematic design of McPherson strut type are carried out by Bae *et al.* [6]. Even though a number of studies had been reported on suspension kinematics and passenger comfort, very little work has been reported on using optimize kinematic model to optimize passenger comfort. Gap that is recognized here is to find the relationship between suspension variable in optimize hard point model. The objective of this paper is to study the effect of suspension variable which are stiffness and damping on the suspension performance using optimized kinematic model. Design of Experiment response surface methods are used to examine the relationship between two suspension variables. Response surface methods are used to find best variable setting that will meet objective functions during optimization.

2.0   SIMULATION WORK

This study is structured as in Figure 1 which can be grouped into three main tasks. First is to develop model, second is to check model behaviour, and lastly is to optimize variable.
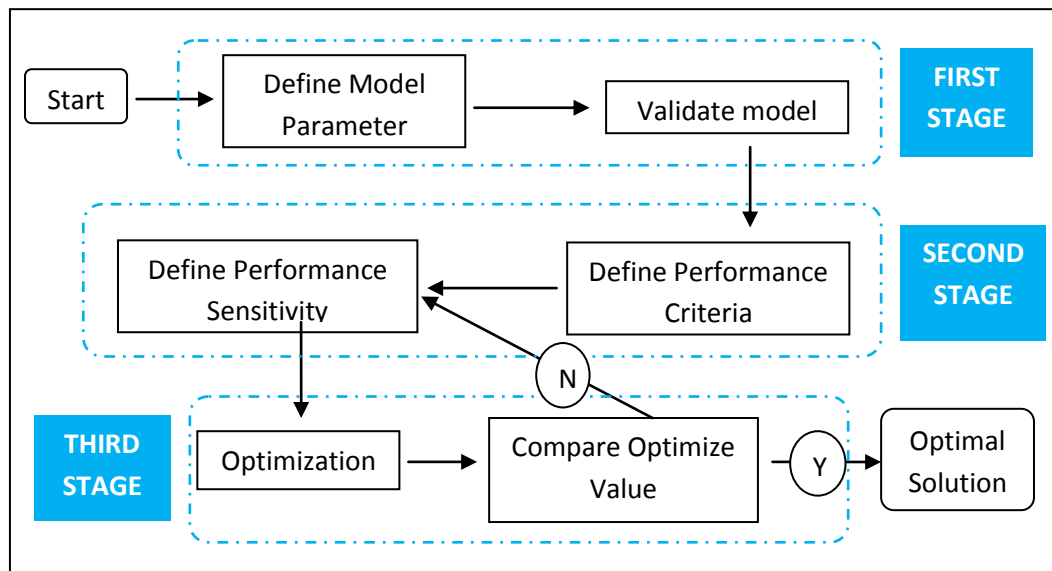

Figure 1: Studies flowchart.

In this study, two quarter suspension models as in Figure 2 will be used. The first one is using simple suspension model with 2 degree of freedoms (2 DOF) and the other model is complex suspension model with 3 degree of freedoms (3 DOF). These two suspension models are built using MSC ADAMS VIEW platform. Parameter requires in building model taken from the studies done by Tey *et al.* [2] and Abbas *et al.* [3].

It is important to make sure 2 DOF and 3 DOF suspension models are constrained correctly. Using published literature experimental and simulations result as benchmark, 2 DOF and 3 DOF suspension models can be verified. 2 DOF and 3 DOF suspension models should produce similar result as benchmark to put it as valid models for next task. Benchmark that had been used to validate both models are sprung mass vertical acceleration, chamber angle and toe angle.
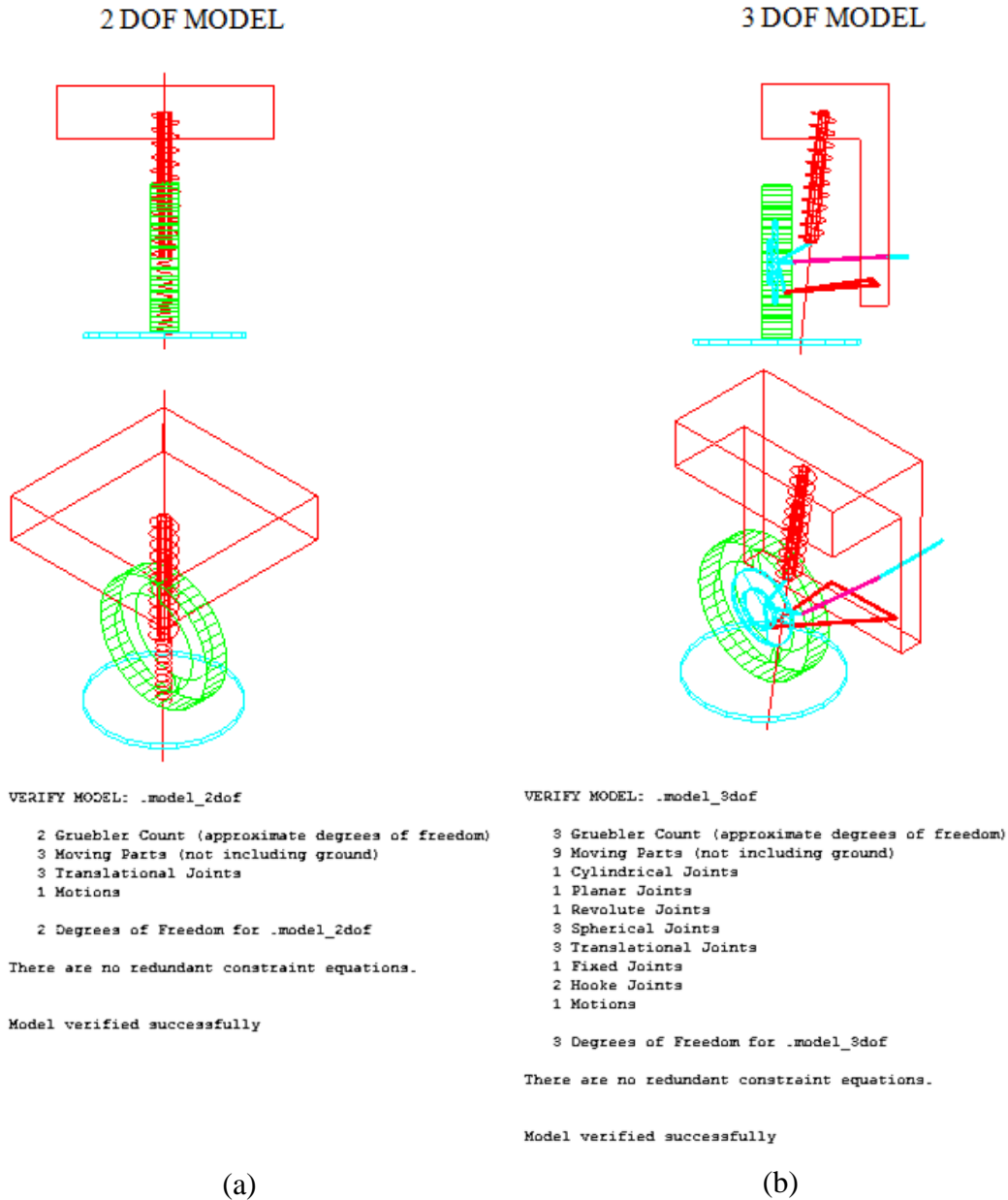
2 DOF MODEL   3 DOF MODEL

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VERIFY MODEL: .model_2dof

    2 Gruebler Count (approximate degrees of freedom)
    3 Moving Parts (not including ground)
    3 Translational Joints
    1 Motions

    2 Degrees of Freedom for .model_2dof

There are no redundant constraint equations.


Model verified successfully
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VERIFY MODEL: .model_3dof

    3 Gruebler Count (approximate degrees of freedom)
    9 Moving Parts (not including ground)
    1 Cylindrical Joints
    1 Planar Joints
    1 Revolute Joints
    3 Spherical Joints
    3 Translational Joints
    1 Fixed Joints
    2 Hooke Joints
    1 Motions

    3 Degrees of Freedom for .model_3dof

There are no redundant constraint equations.


Model verified successfully
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(a)   (b)

Figure 2: (a) 2 DOF and (b) 3 DOF Suspension Model.

        2 DOF suspension model will be validated using sprung mass vertical acceleration. Result from Abbas *et al.* [3] is used to validate 2 DOF suspension model as shown in Figure 3. For 3 DOF suspension model, Abbas *et al.* [3] result can be used to check sprung mass vertical acceleration (Figure 4) and result from Tey *et al.* [2] is used to validate toe angle (Figure 5) and chamber angle (Figure 6). From these validations, both models are validated and can be used in the next step.

        In Design of Experiment study, only two variables will be used to study suspension performances that are suspension stiffness and damping. For this study suspension stiffness range from 10 N/mm to 50 N/mm and 0.5 N.s/mm to 3.5 N.s/mm for damping will be used to study the suspension performance such as sprung mass accelerations, suspension working space and dynamic tyre load. Response surface methods are used to generate response surface for each suspension performance. Response surface generated from each models then be used to find best variable setting that will meet objective functions during optimization for each variable that has been studied.
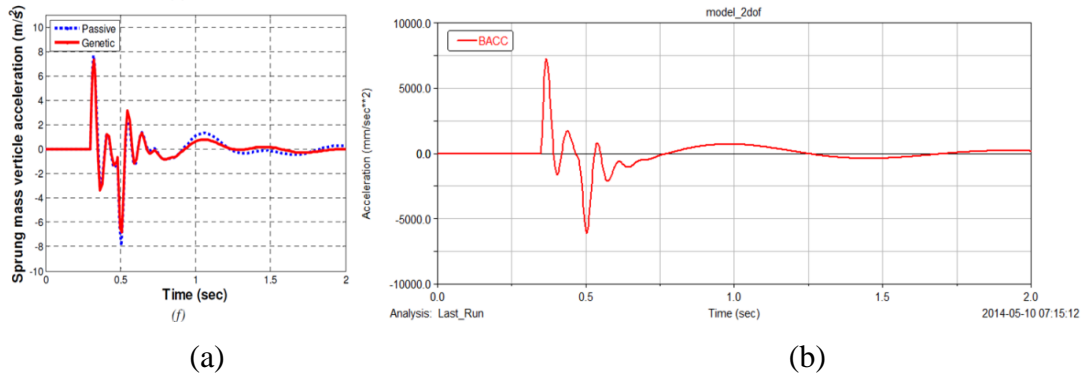
(a)	(b)

Figure 3: Verification: sprung mass accelerations of (a) abbas *et al.* [3], (b) 2 dof suspension model.

(a)	(b)
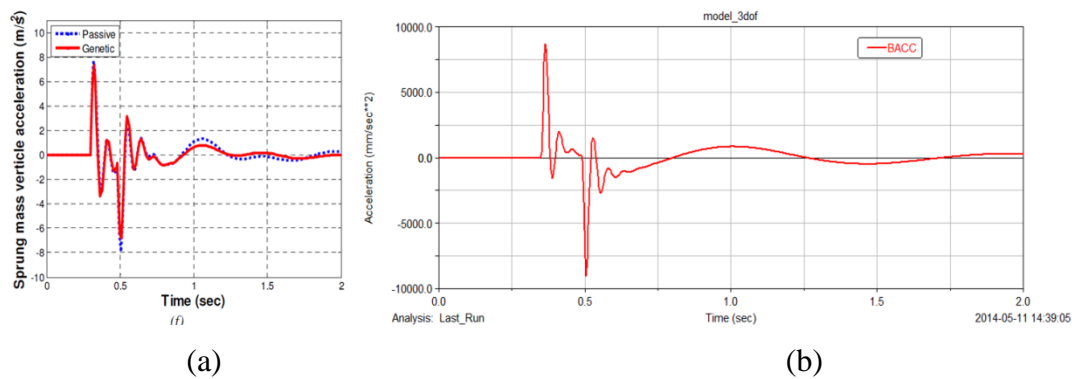
Figure 4: Verification: Sprung Mass Accelerations of (a) Abbas *et al.* [3], (b) 3 DOF Suspension Model.

(a)	(b)
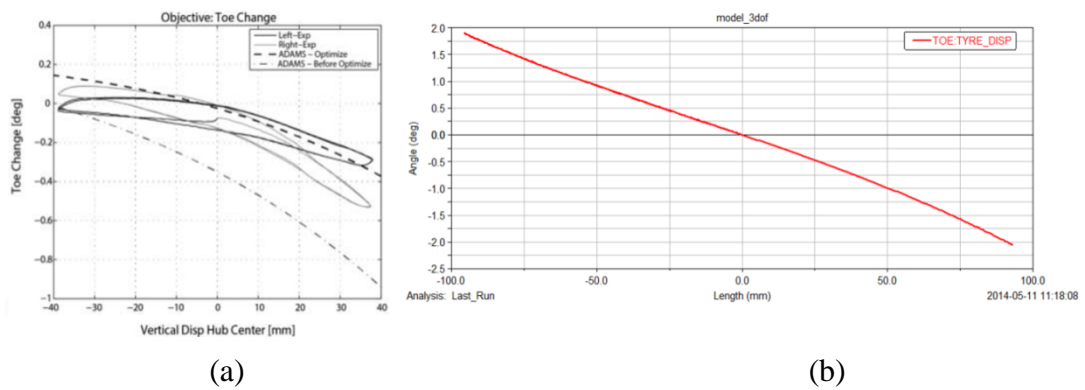
Figure 5: Verification: toe angle of (a) tey *et al.* [2]. (b) 3 dof suspension model.
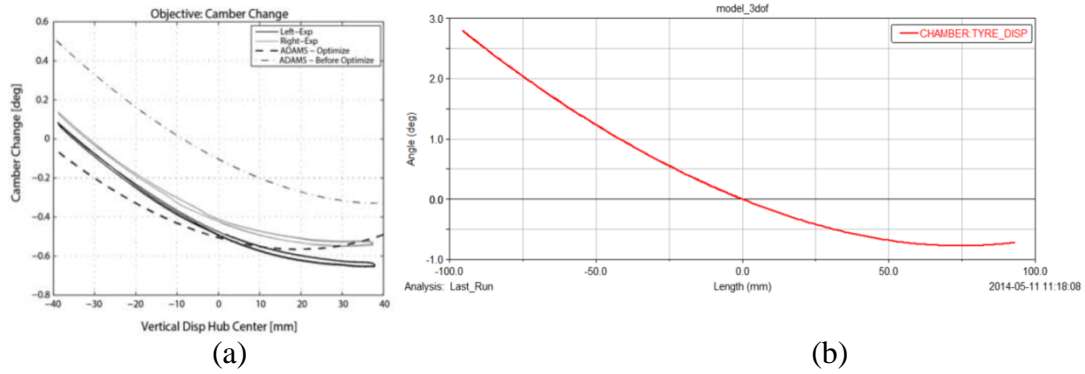
Figure 6: Verification: chamber angle of (a) tey *et al.* [2]. (b) 3 dof suspension model.

3.0   RESULTS AND DISCUSSION

Sprung mass vertical acceleration of simple 2 DOF suspension model has similar characteristics with results from Abbas *et al.* [3]. Main characteristics of sprung mass vertical acceleration appears in 2 DOF suspension model. The only difference is the magnitude of peaks and valleys. As Abbas *et al.* [3] studies using Matlab and 2 DOF suspension model develop in MSC ADAMS, this differences causing magnitude to be different. Both programming expose to error during simulations in solving mathematical modelling. Comparison of sprung mass vertical acceleration of complex 3 DOF suspension model and Abbas *et al.* [3] also shows similar characteristics with closer magnitude. Chamber angle and toe angle slop is similar to Tey *et al.* [2] studies. From these comparisons, both 2 DOF and 3 DOF suspension model is valid model to do studies.

Response surface generated from both models are shown in Figure 7. Basically both models generate similar profile on each suspension performance. From all three performance response surfaces, it can be concluded that the damping coefficient is the main variable that shapes response surface profile. Stiffness coefficient does not influence much on the response surface profile. Sprung mass acceleration and dynamic tyre load reduce as damping coefficient reduces. For suspension working space, it behaves the other way. models require more space as damping coefficient reduces.

The other aspect that can be discussed here are the sensitivity of each suspension performance to the suspension variable. Simple calculations can be done by comparing range maximum and minimum of each suspension performance with the maximum value to get percentage. For 2 DOF suspension model, sprung mass acceleration can vary up to 63.29%, dynamic tyre load can vary maximum of 0.10% and suspension working space can vary maximum of 56.78%. Here, it can be seen that the dynamic tyre load does not experience significant change due to variable change. For 3 DOF suspension model, sprung mass acceleration can vary maximum of 61.46%, dynamic tyre load can vary maximum of 0.30% and suspension working space can vary maximum of 0.36%. These show that dynamic tyre load and suspension working space do not experience significant change due to variable change.
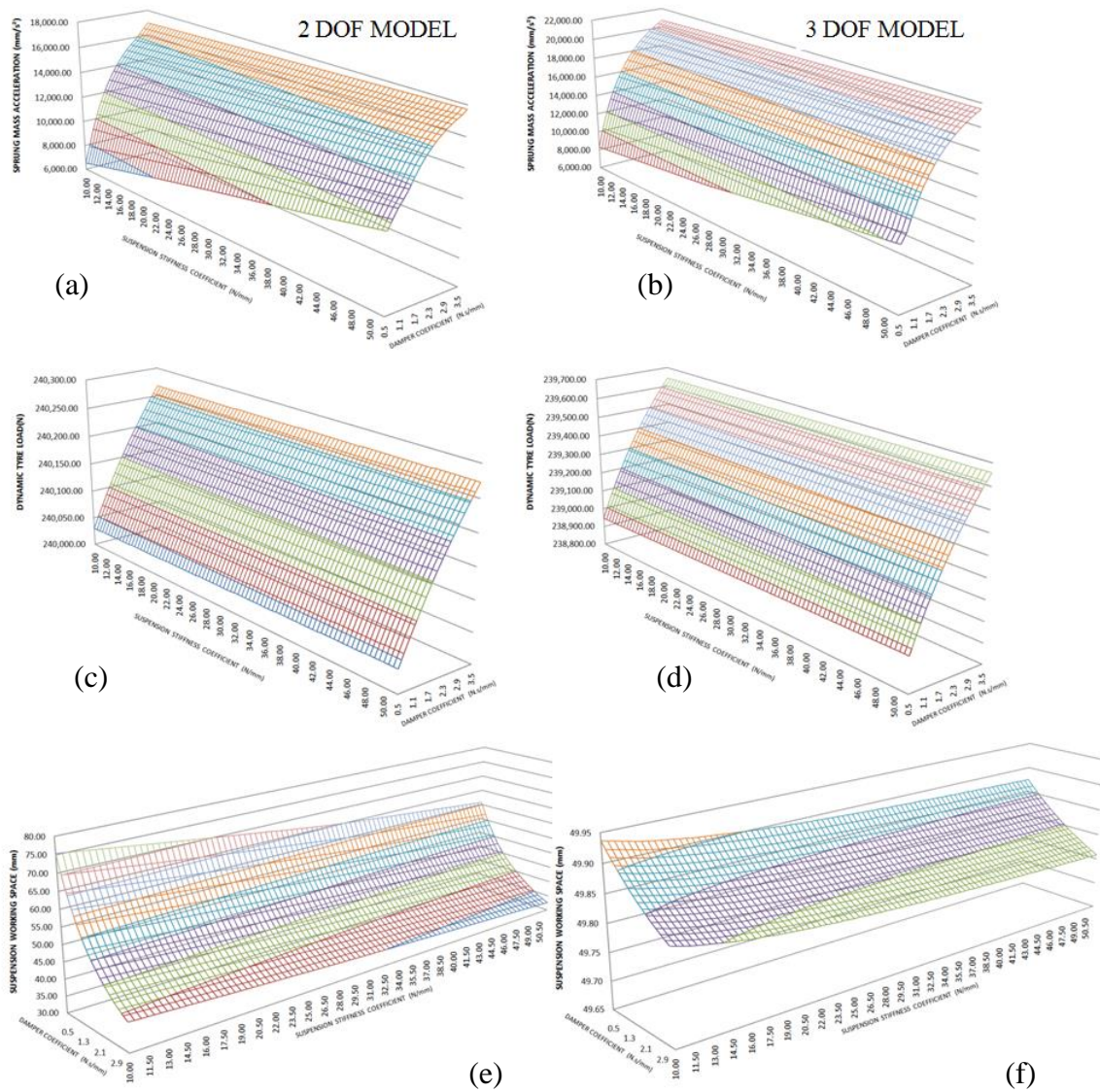
Figure 7: Response surface plot on (a) sprung mass acceleration 2 dof suspension model, (b) sprung mass acceleration 3 dof suspension model, (c) dynamic tyre load 2 dof suspension model, (d) dynamic tyre load 3 dof suspension model (e) suspension working space 2 dof suspension model and (f) suspension working space 3 dof suspension model.

The main difference between these two models is suspension working space performance. In 2 DOF suspension model sprung mass movement, it is restricted only by suspension variable and geometry, but in 3 DOF suspension model, sprung mass movement is restricted by additional constrains which is suspension linkage. In 3 DOF suspension model, there is Lower Control Arm that restrict tyre and body movement. These arms limits the suspension working space when suspension variable is changed.

Due to this, in optimization of 2 DOF suspension model, dynamic tyre load can be eliminated from objective functions and for 3 DOF suspension model both dynamic tyre load and suspension working space can be eliminated from objective function.

The objective of the optimization problem are to determine suspension parameters to achieve the best comfort for human in these studies should be divided into two which is 2 DOF suspension model case and 3 DOF suspension model case. As in sensitivity study, 2 DOF suspension model will be optimized only based on sprung mass acceleration and suspension working space and 3 DOF suspension model will be optimized based on sprung

mass acceleration. Mathematically, the general optimization problem is formulated as minimization of the cost function subject to variable, which can be expressed as:

2 DOF suspension model minimize

$$\text{Sprung Mass Acceleration} = f(k, c)$$
$$\text{Suspension Working Space} = f(k, c)$$

(1)

3 DOF suspension model minimize

$$\text{Sprung Mass Acceleration} = f(k, c)$$

(2)

and both objective functions

$$\text{subjected to} \begin{cases} 10\text{N/mm} \leq k \leq 50\text{N/mm}, \\ 0.5\text{N.s/mm} \leq c \leq 3.5\text{N.s/mm} \end{cases}$$

(3)

With MSC ADAMS INSIGHT capability to run optimization, the final result proposed by ADAMS are 10 N/mm for suspension stiffness coefficient and 0.5 N.s/mm for suspension damping coefficient.

In Figure 8, sprung mass acceleration for 2 DOF suspension model reduces by 32.36% after optimized. In Figure 9, optimized suspension working space for 2 DOF suspension model increases by 18.71%. Dynamic tyre load do not show any significant changes which reduce only by 0.02% in Figure 10.
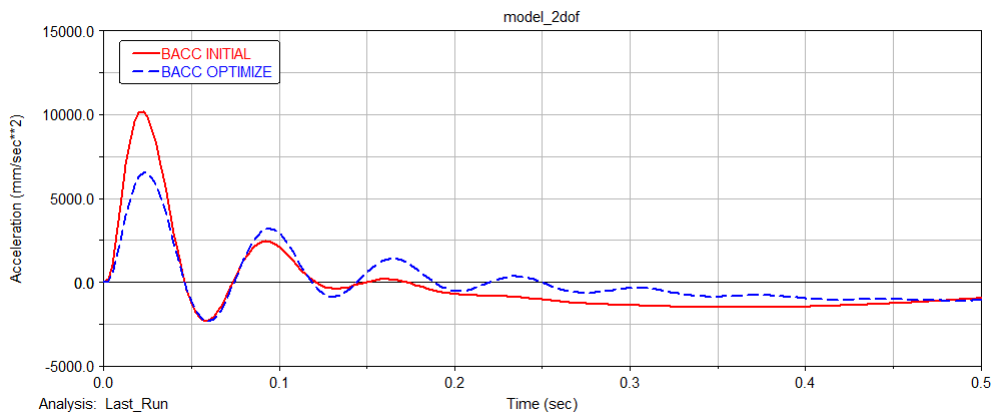

Figure 8: Sprung mass acceleration 2 dof suspension model plot initial condition and after optimize.
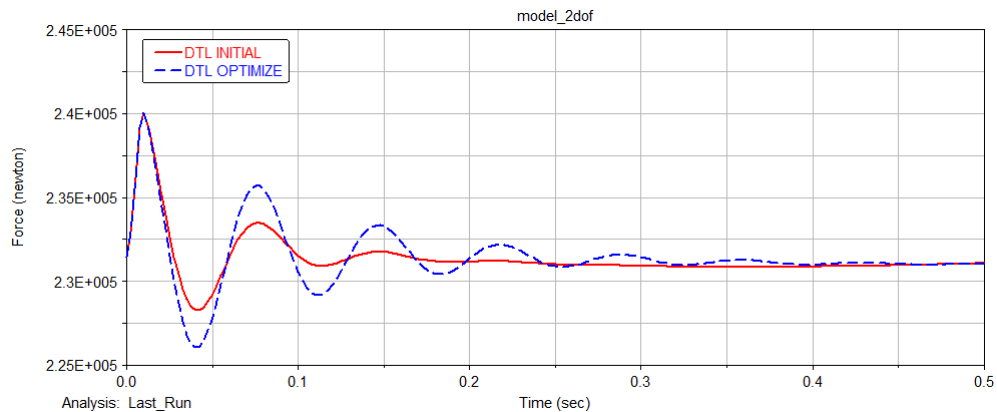

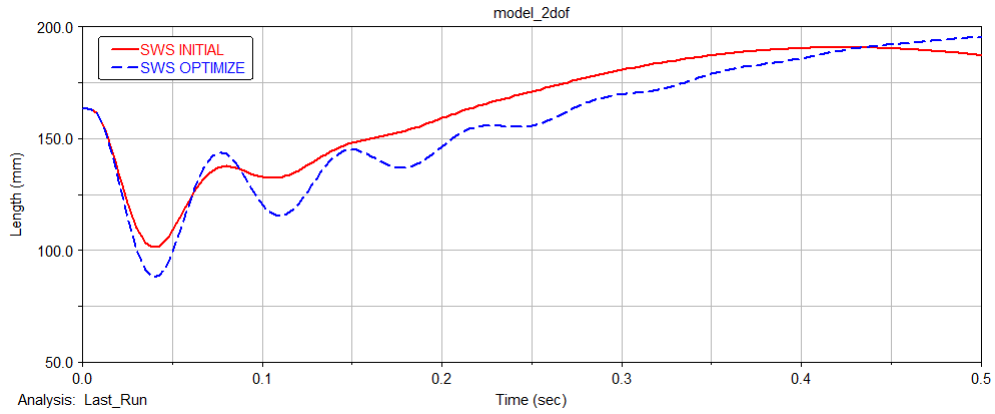Figure 9: Dynamic tyre load 2 dof suspension model plot initial condition and after optimize.

Figure 10: Suspension working space 2 dof suspension model plot initial condition and after optimize.

In Figure 11, sprung mass acceleration for 3 DOF suspension model did reduce by 32.28% after optimized. In Figure 12, optimized suspension working space only increase by 0.09%. Dynamic tyre load only reduce by 0.05% which did not shown significant change in Figure 13.
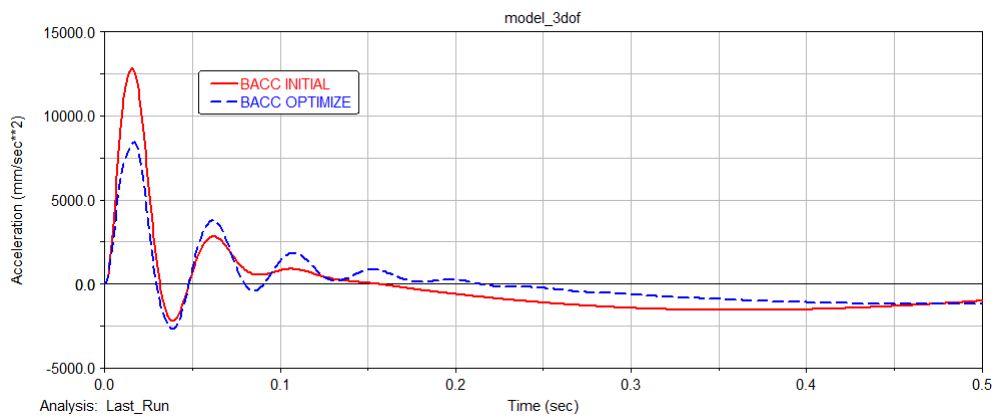

Figure 11: Sprung Mass Acceleration 3 DOF Suspension Model Plot Initial Condition and After Optimize.
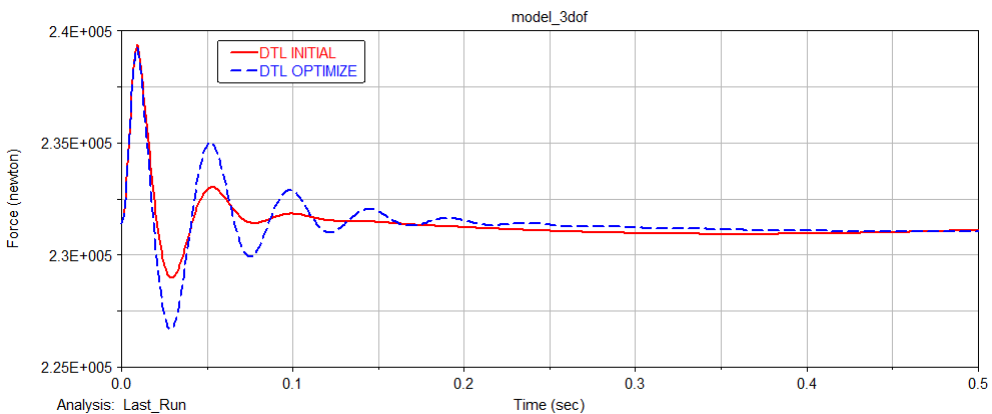

Figure 12: Dynamic Tyre Load 3 DOF Suspension Model Plot Initial Condition and After Optimize.
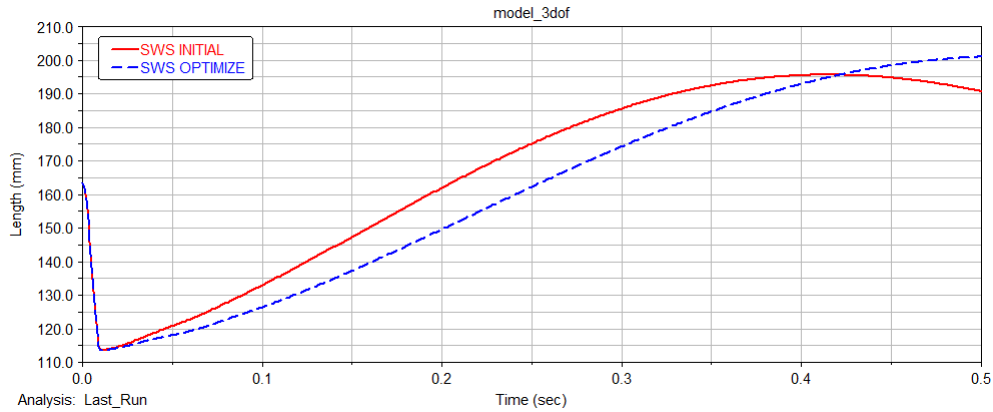
Figure 13: Suspension Working Space 3 DOF Suspension Model Plot Initial Condition and After Optimize.

4.0   CONCLUSSION

The proposed method has demonstrated by using optimize kinematics model in 2 DOF and 3 DOF suspension model to determine suspension parameters to achieve the best comfort for human. This method is capable to correlate between simple and complex suspension model. Response surface model on each suspension performance manages to show behaviour of each suspension performance within desired suspension variable limit in both 2 DOF and 3 DOF suspension model. Sensitivity study manages to identify important suspension performance before optimization. Then it is followed with execution of the design of experiments to explore the design space and analysing the correlation between the parameter and objectives measured. The result of response surface method is used in the optimization. This shows that the optimized variable value manages to improve suspension performance on sprung mass acceleration both models. By reducing the sprung mass acceleration, human comfort do improve.

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