SURROGATE-BASED MODELING STRATEGY FOR DESIGN OPTIMIZATION OF PASSENGER CAR SUSPENSION SYSTEM

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

School of Mechanical Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

DECEMBER 2021

DEDICATION

*“**M**erenung hasil usaha ku ini ...*
***J**erih perih ku menyiapkan ini...*

***G**aris masa 63 tahun mustahil memadai menukilkan **itu**...*
***K**u akui bahawa **itu** benarlah bukan karya manusia selayaknya...*

***Itu** terlalu sempurna...*
***D**emi masa...*
***T**iada kudrat berupaya mencari apa salah pada firman **itu**...*

***D**i dalam usahaku yang maha kerdil ini...*
***K**eagungan **Mu** jua yang ku temui...*

***S**esungguhnya aku bersaksi bahwa tiada tuhan selain **Mu**, **Allah**,*
*dan Nabi **Muhammad** saw itu adalah utusan dan kekasih **Mu**, ya **Allah**”*

جَزَاكَ اللهُ خَيْرًا

***E**makku Jammah dan Abahku Dzakaria... Asbabmu berdua aku kenal segala akan dunia ini...*
***J**asamu berdua tetap tidak akan dapatku balas ...*

***I**steriku Suriani ... Peneman setia diriku ...*
***B**ersama dengan anak-anakku Ariff, Amir, Adam, & Aariz ...*
***T**eramat sayang semuanya.*

ACKNOWLEDGEMENT

Alhamdulillah.
Praise be only to the Almighty Allah, the Most Merciful and Most Gracious, Who has granted me health and strength for the realization of this endeavour.

There are several people who made this thesis possible, and to whom I wish to express my gratitude. First and foremost, I wish to express my heartfelt thanks and appreciation to my supervisors at Universiti Teknologi Malaysia, Professor Ir. Dr. Shuhaimi Mansor and DDr. Saiful Abu Bakar. Also, to my previous supervisors at University of Leeds, United Kingdom, Professor Dr. Martin Levesley and Professor Dr. Vassili Toropov for their guidance, advise, criticisms, and comments throughout the preparation of this thesis. It is truly a privilege to have them all as my father for this study.

I am also indebted to Professor Dr. Roslan Abd. Rahman, Professor Dr. Mohamed Hussein, Associate Professor Dr. Zahir Hassan, Associate Professor Dr. Rahizar Ramli, Associate Professor Dr. Mohd Azman bin Zainul Abidin, Associate Professor Ir. Dr. Zarhamdy Md. Zin, Associate Professor Dr. Aminuddin Saat, Dr. Shuisma Ismail, Dr. Jamaluddin Taib, Tuan Haji Badri Abd. Ghani, Mr. Khidzir Zakaria, and also a staff from Proton Berhad, Mr. Marzuki Zakaria for their valuable assistance and suggestions.

Last but not least, I would like to thank Universiti Teknologi Malaysia and Malaysian Government for granting me the scholarship for this doctoral study, i.e., please kindly refer to official study leave letter of UTM.02.03/12.14/1/2/1652(23), UTM.02.02/12/14/1/2/1652(33) and Perjanjian Cuti Belajar (UTM.CB 9/97 (Pindaan 1/2000)). Also, to Proton Otomobil Sdn. Bhd. for the courtesy of sharing their experience and real vehicle data.

ABSTRACT

The dynamic response of a Low-Fidelity (LoFi) vehicle model exhibits a discrepancy when compared to a High-Fidelity (HiFi) vehicle model. HiFi model construction involves complex state-space equations, a high degree of freedom, and requires a huge quantity of early data to completely define this model. This causes a delay and makes the computation process less efficient. On the other hand, the LoFi model developed using simpler state-space equations is faster and computationally cheaper. However, the response accuracy of this model is lower than that of HiFi. Due to this competence mismatch, it constrains the ability and integration of LoFi model or HiFi model applications in vehicle dynamics research. In previous researches, the proposed surrogate model has been completely replaced any physics-based model for subsequent engineering applications once it has been generated. However, this model has limitation to perform fine tuning either on LoFi or HiFi models. The primary aim of this research was to formulate a surrogate-based modeling strategy by tuning LoFi model for optimizing the design of the passenger car suspension system. The study began with the development of HiFi and LoFi models in Matlab, and their performances were verified by comparing the results produced by MSC Adams software. The LoFi model was used to determine the overall relationship between the suspension system's main elements, namely spring stiffness (K_s) and damper rate (C_s), and the design criteria, namely Body Acceleration (BAcc), Dynamic Tire Load (DTL), and Suspension Workspace (SWS). Based on the Design Criteria Space (DCS) map and recommendations from the literature, the Design Objective Space (DOS) map for a passenger car suspension system was established. Following that, three approaches to formulating surrogate models were introduced, namely the Response-Based Approach (RBA), the Variable-Based Approach (VBA), and the Parameter-Based Approach (PBA). The VBA for the Quadratic Transformation Scheme (QTS) was found to be the most suitable for the proposed newly surrogate model. Next, the surrogate model was linked to an optimization strategy to tune the suspension elements. Finally, a single optimal solution was obtained using the Min-Max method. The optimal tuning for the suspension elements of the chosen passenger car was K_s = 12535.6 N/m and C_s= 1416.7 Ns/m which increased the BAcc by 12.6% but at the expense of DTL performance by 6.4%, and keeping the SWS below the 7 mm restriction. In conclusion, the proposed surrogate-based modeling strategy could be a potential tool for optimizing the design of a passenger car suspension system.

ABSTRAK

Gerak balas dinamik bagi model kenderaan fideliti rendah (LoFi) menunjukkan percanggahan jika dibandingkan dengan model kenderaan fideliti tinggi (HiFi). Pembinaan model HiFi melibatkan persamaan keadaan ruang yang kompleks, darjah kebebasan yang tinggi, dan ia memerlukan kuantiti data awal yang banyak untuk mentakrifkan model ini sepenuhnya. Hal ini menyebabkan kelewatan dan proses pengiraan menjadi kurang cekap. Sebaliknya, model LoFi yang dibangunkan menggunakan persamaan ruang keadaan yang lebih mudah, lebih pantas dan pengiraannya adalah lebih murah. Namun demikian, ketepatan gerak balas bagi model ini adalah lebih rendah berbanding dengan model HiFi. Disebabkan oleh ketidakpadanan kebolehan ini, ia mengekang keupayaan dan penyepaduan untuk aplikasi model LoFi atau model HiFi di dalam penyelidikan dinamik kenderaan. Dalam penyelidikan terdahulu, model *surrogate* yang dibangunkan menggantikan sepenuhnya sebarang model berasaskan fizik untuk aplikasi kejuruteraan sejurus setelah ia dihasilkan. Walau bagaimanapun, model ini mempunyai kelemahan untuk melaksanakan penalaan halus sama ada ke atas model LoFi atau pun HiFi. Matlamat utama penyelidikan ini adalah untuk merumuskan strategi pemodelan berasaskan *surrogate* dengan penalaan model LoFi untuk mengoptimumkan rekabentuk sistem gantungan kereta penumpang. Kajian bermula dengan membangunkan model HiFi dan LoFi dengan menggunakan Matlab dan prestasinya disahkan dengan membandingkan keputusan yang dihasilkan oleh perisian MSC Adams. Model LoFi telah digunakan untuk menentukan hubungan keseluruhan di antara elemen-elemen utama sistem gantungan iaitu kekakuan pegas (K_s) dan kadar redaman (C_s) dengan kriteria-kriteria rekabentuk iaitu Pecutan Badan (BAcc), Beban Tayar Dinamik (DTL) dan Ruang Kerja Suspensi (SWS). Berdasarkan peta Ruang Kriteria Rekabentuk (DCS) dan saranan-saranan dari literatur, peta Ruang Objektif Rekabentuk (DOS) untuk sistem gantungan kereta penumpang telah diwujudkan. Berikutnya, tiga pendekatan untuk merumus model *surrogate* diperkenalkan iaitu Pendekatan Berasaskan Gerak Balas (RBA), Pendekatan Berasaskan Pembolehubah (VBA) dan Pendekatan Berasaskan Parameter (PBA). VBA untuk Skim Transformasi Kuadratik (QTS) didapati paling sesuai sebagai model *surrogate*. Seterusnya, model *surrogate* ini dipautkan kepada strategi pengoptimuman untuk menala elemen-elemen suspensi. Akhir sekali, satu penyelesaian optimum diperolehi melalui kaedah Min-Mak. Penalaan optima untuk elemen-elemen gantungan kereta penumpang yang dipilih ialah K_s = 12535.6 N/m dan C_s = 1416.7 Ns/m yang dapat meningkatkan prestasi BAcc sebanyak 12.6%, tetapi mengorbankan prestasi DTL sebanyak 6.4%, dan mengekalkan SWS di bawah had 7 mm. Kesimpulannya, strategi pemodelan berasaskan *surrogate* boleh menjadi satu alat yang berpotensi untuk mengoptimumkan rekabentuk sistem gantungan kereta penumpang.

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BAcc	-	Body Acceleration (in z-direction)
BBD	-	Box-Behnken Design
CCD	-	Central Composite Design
CG	-	Centre of Gravity
DAE	-	Differential Algebraic Equations
DCS	-	Design Criteria Space
DFM	-	Data-Fitting Modeling
DoE	-	Design of Experiment
DoF	-	Degree of Freedom
DOS	-	Design Objective Space
DTL	-	Dynamics Tire Load
Eq.	-	Equation
EVHSC	-	Etman, Vermeulen, Heck, Schoofs, and Campen
FFD	-	Full Factorial Design or Fractional Factorial Design
FRF	-	Frequency Response Function
FCM	-	Full Car Model
GA	-	Genetic Algorithms
GAM	-	Global Approximation Modeling
GDD	-	Gap Distribution Diagram
GPM	-	Gradient Projection Method
GSA	-	Global Sensitivity Analysis
HiFi	-	High-Fidelity
KPI	-	Key Performance Indicator
LHD	-	Latin Hypercube Design
LoFi	-	Low-Fidelity
LTC	-	Longridge Teaching Center
LTS	-	Linear Transformation Scheme
MAE	-	Maximum Absolute Error
MBS	-	Multi-Body Simulation
MOGA	-	Multi Objective Genetic Algorithms

MOPBA	-	Multi-Objective Population-Based Algorithm
MOO	-	Multi-Objective Optimization
MSC	-	MacNeal-Schwendler Corporation
MTS	-	Multiplicative Transformation Scheme
NSGA-II	-	Non-dominated Sorting Genetic Algorithm version two
OAD	-	Orthogonal Array Design
OLHD	-	Optimal Latin Hypercube Design
OLHS	-	Optimal Latin Hypercube Sampling
PBA	-	Parameter-Based Approach
PBSM	-	Physics-Based Surrogate Models
PSD	-	Power Spectral Density
PSO	-	Particle Swarm Optimization
QTS	-	Quadratic Transformation Scheme
QCM	-	Quarter Car Model
RBA	-	Response-Based Approach
RBF	-	Radial Basis Function
RMS	-	Root Mean Squared
RMSE	-	Root Mean Squared Error
RTE	-	Relative True Error
SA	-	Simulated Annealing
SMTS	-	Sprung Mass Transformation Scheme
SNR	-	Signal to Noise Ratio
SOO	-	Single Objective Optimization
SQP	-	Sequential Quadratic Programming
STM	-	Space Transformation Method
SuMo	-	Surrogate Model
SUMT	-	Sequential Unconstrained Minimization Technique
SWS	-	Suspension Working Space
TD	-	Triplex Diagram
TS	-	Tabu Search
UMTS	-	Unsprung Mass Transformation Scheme
VBA	-	Variable-Based Approach
VDAS	-	Vehicle Dynamics Analysis Software

LIST OF SYMBOLS

$\boldsymbol{a}$ - Tuning parameters

a - Distance of front wheel center to center of gravity

A - System matrix

b - Distance of rear wheel center to center of gravity

B - Input matrix

c - Half-track width

C - Output matrix

C_s - Damping rate or damping coefficient

C_{s1} - Damping rate (front right corner)

C_{s2} - Damping rate (front left corner)

C_{s3} - Damping rate (rear right corner)

C_{s4} - Damping rate (rear left corner)

C_{cr} - Critical damping coefficient

C_{sr} - Damping coefficients of rebound

C_{sb} - Damping coefficients of bump

C_{sm} - Mean damper coefficient

d - Difference between HiFi response and Surrogate response

D - Direct transmission matrix

E - Potential energy

e_d - Asymmetric coefficient

f_n - Natural frequency

$f(x)$ - known approximation function

$F(\boldsymbol{x})$ - Multi-variable objective function

$\boldsymbol{F}(\boldsymbol{x})$ - Multi-variable multi-objective function

$\tilde{f}(\boldsymbol{x})$ - Low-Fidelity responses

$\tilde{F}(\boldsymbol{x})$ - High-Fidelity responses

$g(\boldsymbol{x})$ - Inequality functions

H_z - Response gain or transfer function or transmissibility *in general

H_{bacc} - Response gain of BAcc

H_{dtl} - Response gain of DTL

H_{sws} - Response gain of SWS
I_{xx} - Moment of inertia about x-axis
I_{yy} - Moment of inertia about y-axis
I_{zz} - Moment of inertia about z-axis
K_s - Spring stiffness or spring coefficient
K_{s1} - Spring stiffness (front right corner)
K_{s2} - Spring stiffness (front left corner)
K_{s3} - Spring stiffness (rear right corner)
K_{s4} - Spring stiffness (rear left corner)
K_t - Tire stiffness
K_{t1} - Tire stiffness (front right corner)
K_{t2} - Tire stiffness (front left corner)
K_{t3} - Tire stiffness (rear right corner)
K_{t4} - Tire stiffness (rear left corner)
K_w - Wheel rate
L_{ij} - Euclidean gap
M_u - Unsprung mass
M_s - Sprung mass
M_b - Unsprung mass
N - Number of the design variables or dimensionality number
p - Roll rate
P_z - Power spectral density *in general
P_{bacc} - Power spectral density of BAcc
P_{dtl} - Power spectral density of DTL
P_{sws} - Power spectral density of SWS
q - Pitch rate
r - Yaw rate
$\tilde{S}(\boldsymbol{x}, \boldsymbol{a})$ - Surrogate responses
t - time
v - Longitudinal vehicle speed
$\boldsymbol{w}$ - Weights of the radial basis function
$\boldsymbol{x}$ - Design variables or state variables
x_c - basis function center

z - Basis functions
$Z(x)$ - Random function with zero mean
Z_b - Body displacement
$\dot{Z}_b$ - Body velocity
$\ddot{Z}_b$ - Body acceleration
Z_r - Road input
Z_s - Sprung displacement
$\dot{Z}_s$ - Sprung velocity
$\ddot{Z}_s$ - Sprung acceleration
Z_{s1} - Sprung displacement (front right corner)
$\dot{Z}_{s1}$ - Sprung velocity (front right corner)
$\ddot{Z}_{s1}$ - Sprung acceleration (front right corner)
Z_{s2} - Sprung displacement (front left corner)
$\dot{Z}_{s2}$ - Sprung velocity (front left corner)
$\ddot{Z}_{s2}$ - Sprung acceleration (front left corner)
Z_{s3} - Sprung displacement (rear right corner)
$\dot{Z}_{s3}$ - Sprung velocity (rear right corner)
$\ddot{Z}_{s3}$ - Sprung acceleration (rear right corner)
Z_{s4} - Sprung displacement (rear left corner)
$\dot{Z}_{s4}$ - Sprung velocity (rear left corner)
$\ddot{Z}_{s4}$ - Sprung acceleration (rear left corner)
Z_u - Unsprung displacement
$\dot{Z}_u$ - Unsprung velocity
$\ddot{Z}_u$ - Unsprung acceleration
Z_{u1} - Unsprung displacement (front right corner)
$\dot{Z}_{u1}$ - Unsprung velocity (front right corner)
$\ddot{Z}_{u1}$ - Unsprung acceleration (front right corner)
Z_{u2} - Unsprung displacement (front left corner)
$\dot{Z}_{u2}$ - Unsprung velocity (front left corner)
$\ddot{Z}_{u2}$ - Unsprung acceleration (front left corner)
Z_{u3} - Unsprung displacement (rear right corner)
$\dot{Z}_{u3}$ - Unsprung velocity (rear right corner)
$\ddot{Z}_{u3}$ - Unsprung acceleration (rear right corner)

Z_{u4} - Unsprung displacement (rear left corner)

$\dot{Z}_{u4}$ - Unsprung velocity (rear left corner)

$\ddot{Z}_{u4}$ - Unsprung acceleration (rear left corner)

α - Roll angle

$\dot{\alpha}$ - Roll velocity

$\ddot{\alpha}$ - Roll acceleration

β - Pitch angle

$\dot{\beta}$ - Pitch velocity

$\ddot{\beta}$ - Pitch acceleration

Γ - Normalize

δ - Damping ratio

ζ - Vandermonde matrix

ζ^+ - Moose-Penrose pseudo-inverse

σ - Standard Deviation

σ^2 - Variance

$\tau(\boldsymbol{x}, \boldsymbol{a})$ - Tuning function

$\boldsymbol{\psi}$ - Gram matrix

$\psi(r)$ - Radial basis functions

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Passenger car is a complex system. It consists of many systems, and the suspension system is one of the essential systems in a car. A suspension system can enhance or degrade the behaviours of ride and handling and it can be divided into two types, i.e., passive suspension and active suspension systems. The technology of the active suspension system is more advanced than the passive system. However, the advancement has no effect on the passive suspension system, which is still found on the majority passenger car brands today, particularly for upper mid-range class and below. This is due to the feature offered by its lighter weight, lower energy consumption, easier maintenance, and lower price compared to active suspension or semi-active suspension systems. Automakers have been searching for any new technology that will help them remain ahead of the competition due to strong competition in the automotive sector. An excellent passive suspension system design always offers a strong alibi in promoting car sales. Therefore, this research that focuses on the passive suspension system design is still necessary and relevant.

The primary purpose of the suspension system is to provide a flexible mediator between the wheel system and the body car system. This flexible mediator system must be able to satisfy two basic needs, which are (i) isolating the road inputs from the body, and (ii) reducing the vertical wheel load variations. Spring and damper are two essential elements in a flexible mediator system for achieving good performance in ride and handling (Nunney, 2007).

The design of a complex system such as a suspension system requires a lot of calculations, often repeated for various combinations of the design variables. This makes modelling a necessity, as it allows the prediction of the system behaviour before it is built and tested. In this research context, modeling refers to the process of formulating mathematical representations of real-world suspension systems.

British Engineer Maurice Olley (1946) began to establish the behaviour of a suspension system by using a simple model or lumped mass model. During the last forty years, there have been massive improvements in computers and computations. Consequently, this rapid progress has led to enormous efforts to increase the complexity of the model so that the model resembles the actual physical system as close as possible. However, a complex model always requires more data and funding, besides consuming more time. It is common to be hindered from continuing the analysis until it is accurately defined to match the actual car behaviour at the early design cycle. When there are demands to compress the engineering timetable or difficulty installing the measurement instruments to the test car, modeling becomes more prominent in vehicle engineering.

The complex model and the simple model are also known as High-Fidelity (HiFi) model and Low-Fidelity (HiFi) model respectively. The advantage of the HiFi model is the response is more accurate than LoFi Model. On the other hand, the LoFi model has the advantage of being computationally faster and cheaper. The responses between the LoFi model and the HiFi model are incompatible with one another (Markine and Toropov, 2002). This incompatible response exists ‘as is’ since both models are correct, each has its purpose and advantage. The mismatch response performance proves that modeling is a challenging engineering decision process.

1.2 Problem Statement

Based on the literature review, previous researchers had only studied whether to use the LoFi model or HiFi model in their research. Thus, this research intends to formulate a generic strategy to tune the LoFi model so that the tuned-LoFi model has similar accuracy as the HiFi model. In other words, this tuned-LoFi model or the surrogate model will have the advantages of both the LoFi and the HiFi models.

The optimization process involves gigantic iteration steps when searching for optimal solutions in a broad design objective space. Reliance on the HiFi model causes the process of searching for optimal solutions to become slower and inefficient. The simplicity and computationally faster features inherited by the surrogate model can speed up the optimizing operation of the passenger car suspension system.

1.3 Research Aim and Objectives

This research aims to formulate a surrogate-based modeling strategy for the design optimization of the passenger car suspension system. In order to attain this aim, three objectives had been underlined as follows:

(i) Developing a strategy to devise two design maps: design criteria space and design objective space for passenger car suspension system through LoFi and HiFi models.

(ii) Formulating a robust strategy to tune the LoFi model to match the same level of accuracy as the HiFi model. The tuned-LoFi model is known as a surrogate model.

(iii) Optimizing the suspension element settings through the integration of the surrogate model.

In brief, the details of research work to satisfy the first, second, and third objectives will be sequentially explained in Chapter 3, Chapter 4 and Chapter 5.

1.4 Scope of Research

The scope of this research is bounded as follows:

(i) This research gives full attention on the ride dynamics aspect only. In other words, the research will not consider the subjective part of ride segment.

(ii) The suspension system is used for passenger car application.

(iii) The suspension system is used to support the front-end corner.

(iv) The type of suspension system is passive suspension system or McPherson suspension system.

(v) The tuning of suspension elements is focused on the spring and damper. In other words, the tuning involves two key suspension properties which are spring stiffness and damper rate.

(vi) Two types of fidelity model should be developed. The first fidelity model is a quarter car model with two degrees of freedom. The second fidelity model is a full car model with seven degrees of freedom. The first and the second models are defined as the LoFi and the HiFi models respectively.

(vii) The surrogate model is created by tuning the LoFi model to be like the HiFi model.

(viii) The surrogate model must be integrated to the optimization process for suspension system tuning.

1.5 Research Methodology

Figure 1.1 shows the research methodology for this research. Fundamentally, there are three primary phases in this research. In the first phase, four models of vehicle suspension system, namely multi-fidelity model will be formulated and analysed subjected to a random road input. The random road input, suspension, and damper models are obtained from published work. In general, these models will be constructed using two different architectures. The first and second architectures implement mathematical code in Matlab/Simulink environment and multi-body approach in MSC Adams respectively. The purpose of multi-body models (in MSC Adams) is mainly for verifying the model in mathematical code one. The vehicle models will be constructed in two scales, i.e., (i) quarter car scale and (ii) full car scale. Quarter car scale and full car scale are classified as LoFi model and HiFi model respectively. The design objective spaces for addressing ride dynamics are expected to be produced at the end of this phase. This primary phase will be discussed in more detailed in Chapter 3.

The findings from previous phase will be used for the second phase. In order to increase the efficiency of the dynamic simulation, Audze-Eglais method is utilized. The design spaces are discretized into two, three, four, five, and ten sampling nodes. Furthermore, these sampling results will be validated against the twenty sampling nodes. Several formulations of surrogate model are going to be introduced in this thesis, later. Each surrogate model is designed such that it can be easily attached and detached from the main strategy's framework. Statistical measurements such as R^2 (read as r-square), root mean squared error (RMSE), and maximum absolute error (MAE) are employed to check the quality of surrogate model. Additionally, the advantages and limitation of the surrogate model are addressed. Eventually, the best surrogate model can be identified with respect to the suspension system design. This secondary phase will be discussed in more detailed in Chapter 4.

In the final phase, the finding (i.e., the best surrogate model) from phase two is assimilated into the framework of design optimization scheme. In the beginning, the tuning of suspension elements is compromised using Space Transformation method (STM). Following that, the surrogate model is linked to a population-based optimization algorithm. Both methods will produce a Pareto front or set compromise solution. The Pareto front obtained using a population-based optimization method is compared to the Pareto front obtained using STM. Furthermore, one datum car is selected and the Pareto front is normalized against that car. Through application of min-max method, a single compromise solution is eventually ascertained. Finally, a complete strategy of surrogate-based design optimization of vehicle suspension system is proposed in this thesis. This tertiary phase is discussed in more detailed in Chapter 5.

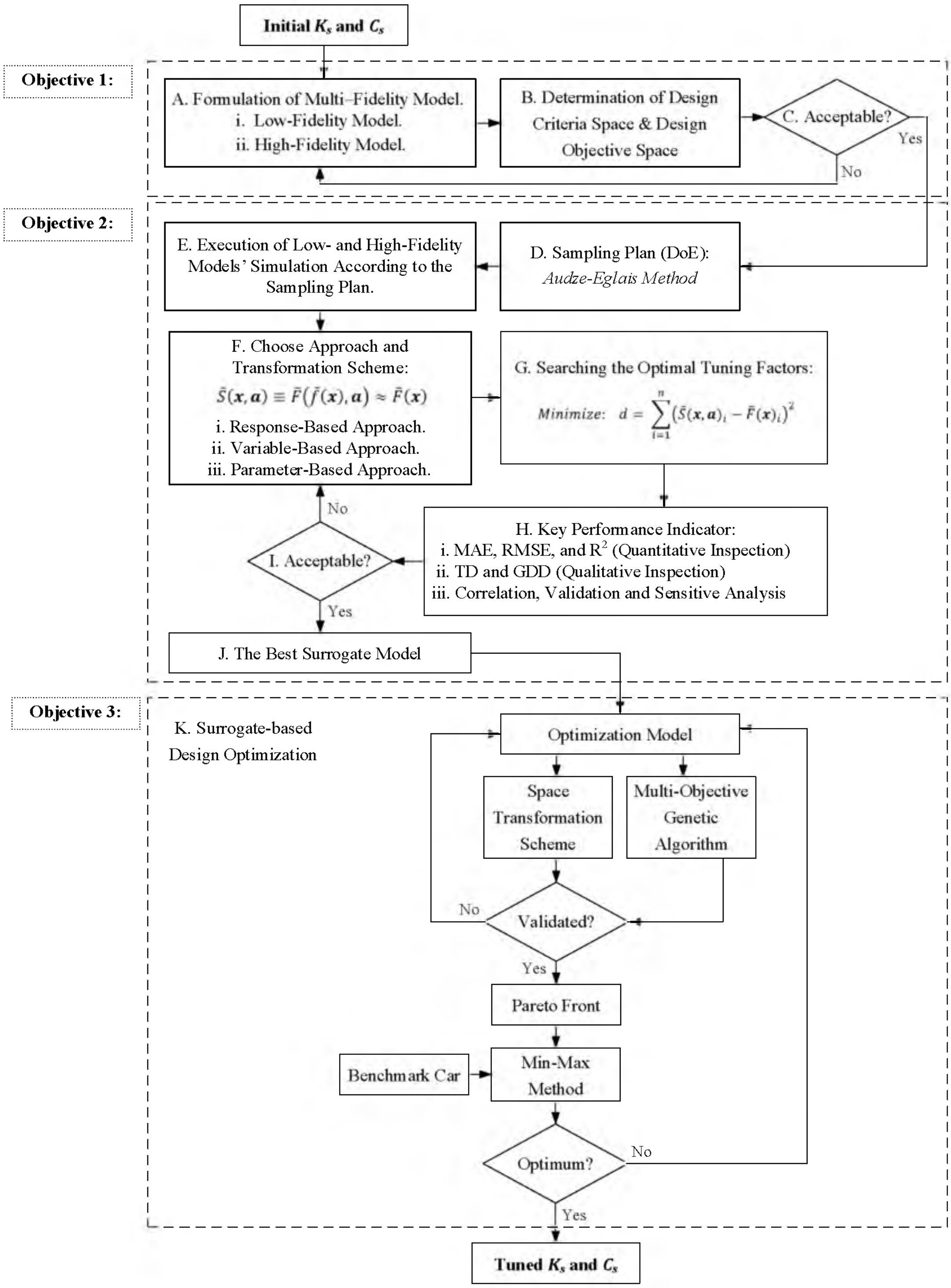

Figure 1.1 Flowchart of overall research methodology.

1.6 Thesis Structure

This thesis is structured into six chapters. Chapter 3, Chapter 4 and Chapter 5 are the three specific chapters explaining the study that had been conducted to achieve the research objectives.

Chapter 1 sets the scene for the thesis. It describes the research background, problem statement, research aim and objectives, scope of the project, and research methodology. At the end of the chapter, thesis structure is set out.

Chapter 2 provides literature review on the three main parts which determine the knowledge gap and competence for assisting these doctoral thesis works. Modeling issues in passive suspension system of passenger car is elaborated in the first part of the review. In the second part, numerous attempts to optimize the passive suspension system through various computational optimization strategies were reviewed. The last part of this chapter provides reviews on the surrogate modeling strategies.

Chapter 3 explains the development of two mismatch fidelity models, namely low- and high-fidelity models in the Matlab environment. A multi-body simulation approach is used to verify the model's correctness. The LoFi model is then used to determine the relationship between the suspension system's main elements, namely spring stiffness and damping ratio, and the design criteria, namely Body Acceleration (BAcc), Dynamic Tire Load (DTL), and Suspension Workspace (SWS). This relationship is clarified by the Design Criteria Space (DCS) map. The design objective for a passenger car suspension system is established using DCS and a few recommendations from the literature.

Chapter 4 proposes three formulation variations for tuning the LoFi model so that the tuned-LoFi model inherits two key features required for an analytical model, namely (i) the model is as simple as the LoFi model and (ii) the model can generate responses as good as the HiFi model. The variants are the Response-Based Approach (RBA), Variable-Based Approach (VBA), and Parameter-Based Approach (PBA). The tuned-LoFi model is called a surrogate model.

Chapter 5 discusses the use of a surrogate model to optimise the design of a passenger car suspension system. The optimal solution candidates for suspension element setting are determined using a proposed method known as the Space Transformation Method (STM). STM performance was validated by comparing the results to the Genetic Algorithm, a well-known population-based method. The Min-Max method is used to arrive at a single compromised design solution. Finally, a comparison of the suspension before and after tuning is performed.

Chapter 6 concludes the work and explains how the objectives are met. Besides, the novelty contribution of this study to the current field of knowledge is also explained. This chapter also provides several recommendations as the continuation of the proposed formulation for future research.

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