ACTIVE FORC LEARNING CONTROL
ALGORITHM FOR A VEHICLE SUSPENSION

ROSMAZI BIN ROSLI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Mechanical)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

OCTOBER 2013

ABSTRACT

The research focuses on the application of an active force control (AFC) strategy with iterative learning control (ILC) algorithms to compensate for the various introduced road profiles or 'disturbances' in a quarter car suspension system as an improvement to ride comfort performance. ILC algorithm is implemented into AFC-based control scheme to reduce its complexity and hence faster response, by replacing the use of artificial intelligence (AI) method as proposed by previous researcher. The new control scheme named active force control with iterative learning control algorithm (AFCIL) is complemented by the classic proportional-integral-derivative (PID) control incorporated and designed as the outermost control loop. The PID controller was first designed and tested prior to developing the AFC which was directly cascaded with the PID loop. A number of ILC algorithms were explicitly employed to compute the estimated mass in the AFC loop that is necessary to trigger the control action. The AFC with ILC (AFCIL) suspension system was experimented both through simulation and practical experimentation considering various ILC learning parameters, different operating conditions and a number of external disturbances to test and verify the system robustness. The simulation was conducted using MATLAB/Simulink software package whilst the experimental study utilized the existing experimental rig with a hardware-in-the-loop simulation (HILS) configuration with the proposed ILC algorithms incorporated as the new research contribution. The results obtained via various control schemes in the form of PID, AFCIL and passive systems were rigorously compared and analyzed to ascertain the system performance in terms of its ability to improve riding comfort characteristics. The results imply that the proposed AFC-based scheme produces the best response with an approximately 50% improvement in comparison to the PID and passive counterparts.

ABSTRAK

Kajian yang dilakukan dengan memfokus kepada aplikasi strategi kawalan daya aktif (AFC) yang disepadukan dengan algoritma kawalan pembelajaran berlelaran (ILC). Sistem ini bertujuan untuk menambahbaik keselesaan pemanduan dengan cara mengurangkan kesan gangguan ke atas sistem suspensi pada sebuah model kereta. Selain daripada menambahbaik keselesaaan pemanduan, kajian ini juga bertujuan untuk mengurangkan beban perkomputeran kaedah buatan pintar (AI) yang telah dijalankan oleh penyelidik sebelum ini terhadap sistem suspensi aktif. Sistem kawalan yang mampan dibantu oleh kawalan berkadaran-kamiran-terbitan (PID) digubah dan direkabentuk sebagai sistem kawalan di peringkat paling luaran. Sistem kawalan ini mula-mula sekali direkabentuk dan diuji sebelum digabungkan secara bersiri dengan sistem kawalan PID. Beberapa algoritma ILC digunakan untuk menganggar nilai jisim yang diperlukan untuk membolehkan sistem AFC bertindak dengan berkesan. Sistem kawalan yang menyepadukan AFC bersama ILC (AFCIL) ini akan diuji melalui simulasi dan juga secara praktik melalui eksperimen dengan mengambil kira pelbagai nilai parameter berlainan berkaitan dengan pembelajaran lelaran ILC, keadaan operasi dan gangguan untuk melihat kemampanan dan keberkesanan nsistem. Simulasi dilakukan menggunakan MATLAB/Simulink manakala eksperimen dilakukan menggunakan rig suspensi sedia ada secara simulasi perkakasan-di dalam-gelung (HILS) dengan mengambil kira algoritma ILC yang digabungkan ke dalam sistem ini sebagai sumbangan penyelidikan yang baharu. Hasil keputusan yang diperolehi dari sistem kawalan suspensi PID, AFCIL dan pasif dibandingkan dan dianalisis untuk melihat keberkesanan sistem cadangan dalam menambahbaik mutu keselesaan pemanduan kenderaan. Hasil kajian juga menunjukkan bahawa sistem berasaskan AFC yang dicadangkan berjaya menambahbaik mutu keselesaan pemanduan dalam sekitar 50% berbanding dengan sistem kawalan suspensi PID dan pasif.

TABLE OF CONTENTS

5 COMPARATIVE STUDY BETWEEN SIMULATION AND EXPERIMENTAL RESULTS

6 CONCLUSION AND RECOMMENDATION

APPENDICES

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

A/D	: Analogue to digital converter
AFC	: Active force control
AI	: Artificial intelligence
AFCIL	: Active force control with iterative learning
DOF	: Degree of freedom
D/A	: Digital to analogue converter
DAS	: Data acquisition system
DC	: Direct current
EISA	: Extended industrial system association
HILS	: Hardware-in-the-loop simulation
I/O	: Input/output
ILC	: Iterative learning control
LVDT	: Linear variable differential transformer
MR	: Magneto-rheological
PID	: Proportional-integral-derivative
PLC	: Programmable logic controller
RAM	: Read access memory
RMS	: Root mean square
RTW	: Real time workshop

LIST OF SYMBOLS

b_s : Suspension damping coefficient
D_f' : Estimated disturbance force
e_k : ILC error
F : Actuating force from force sensor
f_a : Actuator force
g : Gravitational acceleration
K_d : Derivative gain
K_i : Integral Gain
K_p : Proportional gain
k_s : Spring stiffness
k_t : Tyre stiffness
m_s : Sprung mass
m_u : Unsprung mass
y_k : Current iteration value
y_{k+1} : Next iteration value
z_s : Sprung mass displacement
z_u : Unprung mass displacement
z_r : Road profile
$\dot{z}_s$: Sprung mass velocity
$\dot{z}_u$: Unsprung mass velocity
$\ddot{z}_s$: Sprung mass acceleration
$\ddot{z}_u$: Unsprung mass acceleration
ϕ : ILC proportional learning parameter

ψ : ILC integral learning parameter

Γ : ILC derivative learning parameter

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Ride comfort has become one of the essential criteria in determining the quality of a passenger car. The more comfortable a vehicle could be designed, manufactured and tested, the better quality it will be classified as a passenger vehicle. It is highly desirable for passengers that the vehicle will give them a very comfortable riding while travelling on various types of road surfaces and conditions. Suspension system has contributed greatly to the ride comfort in passenger vehicle as it serves to ensure the main body of the vehicle (sprung mass) is relatively 'free' from the external and internal source of vibrations and other related disturbances. In other words, the vehicle suspension system is the system constructed in a vehicle to primarily isolate or reduce the effect of oscillation from a vibration source to the body compartment. In addition, the vehicle suspension system is also expected to improve the stability of the vehicle during cornering as it helps to keep the tyre in constant contact with the road surface. This primary function of a suspension system is the main concern of this research in which the proposed research shall focus on improving the ride comfort aspect of a vehicle model, taking into account the implementation of a specific intelligent control algorithm on a selected suspension system investigated both through simulation and experimental study.

Vehicle suspension system appears in market nowadays in many types and classification according to their properties, functions, and adaptability typically known as the passive suspension. In the current market, it may be in the form of leaf spring type, double wishbone and *McPherson* strut. *McPherson* strut which consists of a coil spring and a shock absorber is the most popular type of suspension system for a passenger vehicle due to its simplicity in construction, suitably located in small and confined space and most important of all, low cost. Passive suspension is usually constructed with a fixed dynamic properties and non-controlled disturbance isolation ability. The setting or tuning of the suspension can be either soft for ride comfort or stiff for stability. More often than not, it could not compromise both circumstances for ideal situation if the riding conditions are varied. This leads to the innovation of semi-active suspension system with some control mechanisms applied to control the damping force of the suspension such as using the magneto rheological (MR) fluid in the damper like the one carried out by Chooi and Oyadiji, (2009).

The development of electronic sensors contributes to the implementation of a practical robust control strategy using active suspension. The sensor attached in the system could vary the output of the suspension system and create a feedback control strategy, thereby giving more adaptability to the suspension system considering various road surfaces (Appleyard and Wellstead, 1995). Active force control (AFC) is one of the approaches in controlling dynamical system subject to various forms of excitations (Hewit and Burdess, 1981). In their work, they managed to show that AFC is a simple but yet a robust control scheme that could compensate for disturbances in a system with a very acceptable delay due to the simplicity of its control algorithm. Priyandoko *et al.,* (2009), first implemented AFC on the vehicle suspension and came out with a significant improvement in the ride comfort of the vehicle model considering the AFC with artificial intelligence (AI) technique and a number of road input profiles as the disturbances (Priyandoko *et al.*, 2009). The main burden of the AFC scheme is the estimated mass parameter which needs to be appropriately determined before the scheme could be effectively executed.

Iterative learning control (ILC) algorithm may yet be another intelligent method to control dynamical systems (Arimoto *et al.*, 1984). ILC is developed to produce the output of a system that is largely based on a repetitive process that considers trajectory errors as the typical inputs to the system. It was successfully implemented by a number of researchers in both simulation and experimental works. In AFC scheme, ILC can be used to determine the best value for estimated mass parameter. By tuning the learning parameters to get the appropriate learning parameters, ILC can predict the value for estimated mass after a few iterations. It is very important though to make sure the convergence of the value and it is desired to speed up the convergence to as minimum iteration as possible.

1.2 Background Study

Ride comfort has thus become the main business in automotive sector in the present day situation. Manufacturers are seen chasing each other to produce very comfortable suspension system but at the same time very stable during cornering and braking. Passive suspension however could only offer one of those characteristic or compromise between ride comfort and handling or stability. Manufacturer then offers the adjustable suspension system which can be adjusted to be very comfort or very stable according to the drivers needs but it cannot be changed instantly during driving. Researchers then proposed and implemented various semi-active and active vehicle suspension systems both theoretically as well experimentally (Appleyard and Wellstead, 1995). A semi-active suspension has the ability to change the damping characteristics of the shock absorbers as in an electro-rheological or MR damper and also some of them have the ability of changing the spring rate by using an air spring system. In active suspension system however, an actuator is typically attached in parallel with both a spring and a shock absorber in between the sprung and unsprung masses or sometime replacing them. The actuator then will inject energy into the suspension system according to the disturbance created by the road profile in real-time during driving without having the driver to set them manually (Cherry and Jones, 1995).

Suspension system in a vehicle has the main purpose of isolating the passenger from the external disturbances from the road roughness and also from the internal disturbances caused by the engine bay, and act of dive during decelerations and squat during accelerations. To achieve an acceptable ride comfort, suspension system works by minimizing the vertical sprung acceleration. A number of parameters need to be control in order to observe the suspension system could achieve this goal as described by Miller (1988) and Gaoa *et al.* (2006). These parameters are explained as follows:

a. Body acceleration

Body acceleration is the parameter that directly connected to passenger since it is the passenger who is in the compartment of a vehicle. This parameter will be sensed by the passenger most and will contribute to how comfort the vehicle is. In fact the level of comfort for a car is typically evaluated by the body acceleration in the vertical direction. This would be the most important parameter to be controlled so that the ride comfort could be improved.

b. Tyre deflection

Tyre deflection contributes most in terms of vehicle stability and usually did not give significant effect to the ride comfort. The main idea to control this parameter is only to ensure that it's always in contact with road surface. Since the main concern of this project is ride comfort, this parameter will not be focused in discussion.

c. Suspension deflection

Suspension deflection is crucial since it determines the safety of the car and also the ride comfort. This parameter must be controlled so that its value is always within the range of the absorber and spring rate. Hazardous consequences can arise if the suspension deflection exceeds any of its maximum or minimum rates. It is also needed to be settled down to its origin level as soon as possible or else the suspension will be considered to be too bumpy.

d. Actuator saturation

The ability of the actuator to inject energy into the suspension system is also an important thing to be observed since it relates the controller to the real world suspension system. No matter how good a controller scheme is, without a sufficient actuator power, the controller means nothing to the real world application.

Based on the above, the focus of the study will be on the first and second influential parameters, i.e., the vertical body acceleration and suspension deflection (body displacement) that are deemed to contribute most of the riding comfort aspect. Thus it is the main aim of the study to show good improvement in the riding comfort by reducing the parameter to a certain level. This project will try to contribute a new robust control strategy of a suspension system based on the active force control, AFC. AFC had been known as a very robust yet very simple and effective controller both in theory and practice (Mailah and Rahim, 2000; Hussein *et al.*, 2000; Kwek *et al.*, 2003; Mailah *et al.*, 2005). This research will apply AFC to improve suspension dynamic performance and tested using artificial intelligent method, and a number of disturbance profile to show its robustness. Simulation will be carried out to see the controller ability and then a hardware-in-the-loop simulation (HILS) will be done to investigate the effectiveness of the controller in real world taking into account various weakness of real-time hardware. A simple quarter car model is used in this research as it is simple but yet can give most of the important characteristic of the suspension system (Fischer and Isermann, 2004).

1.3 Problem Statements

AFC has been first introduced by Hewit and Burdess (1981). The basic idea of AFC is to estimate and measure some identified parameters to predict its compensation action. The main problem arised is the computation of the estimated mass or inertial parameter that will be in turn multiplied with the body acceleration (from accelerometer) to produce the estimated disturbance force or torque on the dynamical system; in the study, it is the sprung mass and hence the estimated disturbance force is used . The other burden is to compute the inverse dynamics of the actuator which is needed to convert the estimated disturbance force calculated by the controller into an appropriate electrical signal required by the physical actuator. Priyandoko *et al.* (2009) have come up with some intelligent methods to obtain the appropriate estimated mass of the unsprung mass and the inverse dynamics of the actuator using fuzzy and neural network strategies. However, the problem with the implementation of the proposed intelligent methods is the computational burden, since it usually involves complicated algorithm, thus require longer time to resolve and execute the algorithms. The nonlinearity of the pneumatic actuator also gives a problem in order to give significant and accurate signal into the actuator so that it will generate sufficient energy into the suspension system to match the disturbance forces. Using the approach used by Priyandoko *et al.* (2009) ensured that the actuator will act as accurate as possible to match the desired force trajectory and hence it is also used in the proposed study.

1.4 Research Contribution

The research produces a new practical intelligent AFC based scheme applied to a suspension system already developed by a previous researcher in the Systems and Control Laboratory, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia (UTM) to improve the ride comfort aspect. The scheme is embedded with iterative learning control (ILC) algorithms in conjunction with the AFC method to compute the estimated mass parameter for the overall control implementation. This new proposed scheme named as AFCIL applied to a quarter car model suspension test rig is tested both in simulation and experimental environments. It contributes yet an effective and robust disturbance compensation scheme in improving the ride comfort for a passenger vehicle. It will also show some study on learning parameters that affect the performance of the proposed system.

1.5 Research Objectives

The main objectives of this research are:

2. To model and simulate AFC model with ILC algorithm (AFCIL) controller scheme as a disturbance compensator in a quarter car suspension model.
3. To perform experiments on the test rig based on the proposed control model for validation.

1.6 Research Scope

The scope covered the frame work in this research is as follows:

1. Mathematical modelling of the proposed system considering a quarter car suspension system, ILC algorithm, PID controller, AFC compensation system including selected road profiles as disturbance. The main proposed control scheme is known as AFCIL.
2. Simulation of the proposed system is performed using MATLAB/Simulink to take into account various operating and loading conditions.
3. Consider a two degree of freedom (DOF) quarter car model. The spring constant and damping coefficient are assumed to be from a *Kelisa* car model.
4. The analysis is performed on the ride comfort characteristics only related to the body acceleration and suspension deflection parameters.
5. A hardware-in-the-loop simulation (HILS) will be done to observe the system (AFCIL scheme) performance and validate the theoretical results via experiments. The experiment is performed on an existing quarter car vehicle suspension in the laboratory. The experiments were run under free friction assumption and the tyre is always in contact with the test rig platform surface. The road surface signal is a sinusoidal wave as disturbance.
6. The actuator used in the test rig to control the damping force is a nonlinear pneumatic type.

1.7 Research Methodology

The research project involves the modelling and simulation of an active suspension control of quarter car model to observe and predict some preliminary results of the proposed AFCIL scheme. The controller parameters related to PID controller and ILC are appropriately tuned using the typical standard heuristic methods while those for the AFC, the necessary estimated mass parameter is acquired using the ILC algorithm. MATLAB/Simulink software package is the simulation platform used to perform this procedure considering various operating and loading conditions. Some passive system responses of the suspension when subjected to disturbances were obtained as a reference data. The simulation parameters of the suspension system and the pneumatic actuator were gathered from previous researcher as a reference (Priyandoko *et al.,* 2009).

It was followed by a validation of the proposed control method (i.e., AFCIL) in the form of a HILS that was carried out in real-time considering physical limitations of the test rig. The experimental works were performed on the existing quarter car suspension test rig with slight modification (embedding the ILC algorithm). The main stages of the project are shown in Figure 1.1.

A proportional-integral-derivative, PID controller was first implemented as the outermost positioning controller. The best tuning were obtained by using heuristics tuning method before some fine tuning is done to produce the best results. Note that this controller gains were fixed and directly used without further tuning in the AFC implementation at a later stage. The results from this conventional PID controller were used as a basis for comparison of the effectiveness of the new proposed scheme in improving the ride comfort.

The AFC loop was later added in series with the PID controller to compensate disturbance that cannot be fully rejected by the conventional PID controller. As the objective of this study to only concentrate on the estimated mass that is needed by the AFC control loop, the inverse dynamic of the actuator was obtained from the previous research by Priyandoko *et al.* (2009) was taken. The body acceleration from the suspension model is used as the input which is then multiplied with the estimated mass obtained from the ILC algorithm. This multiplication will give estimated resultant (disturbance) force for the AFC loop. The actuated force generated from the pneumatic actuator block diagram will be subtracted from the resultant force mentioned above leaving only the remaining disturbance forces. The signal then goes through the inverse dynamic of the actuator generating an appropriate signal which then will be recognized by the actuator as an additional signal to overcome the disturbance generated from the road profile. Road profile which becomes the main disturbance sources in this study was represented by some input signals generated in Simulink environment.

Iterative learning algorithm is used to estimate the mass that is required by the AFC loop. The algorithm proposed by Saguru Arimoto was used in this project for both simulation and experiment works. The learning parameters in the *Arimoto*-type algorithm were studied to see how they affect the estimated mass values. The tuning process has been done via the ILC algorithms to produce the best estimated mass values which contribute to the effectiveness of AFC in compensating disturbances.