



Final Report

Development and vibration analysis of an In-Wheel Electric Motor Drive system

Lucia Álvaro Álvarez

2017

3rd Year Individual Project

I certify that all material in this thesis that is not my own work has been identified and that no material has been included for which a degree has previously been conferred on me.

Signed.....Lucía Álvaro Álvarez.....

Final Report

[ECM3101]

Title: Development and vibration analysis of an In-Wheel
Electric Motor Drive system

Date of submission: Tuesday, 08 May 2018

Student Name: Lucia Alvaro Alvarez
Programme: Mechanical Engineering
Student number: 670058087
Candidate number: 055437

Supervisor: Julian Londono Monsalve

Abstract

The emerging production investment in Electric Vehicles is claiming to substitute the current automobile situation due to not just their multiple advantages but the increasing fossil sources depletion concern. Numerous studies have been working on the Electric Vehicles efficiency and driving experience improvement. One of the point of interest of these investigations was the setup of the motor and drive, introducing several proposals for the system implementation that included the In-Wheel Motor Drive structure.

This project aims to present the development of a novel In-Wheel Motor Drive design which claims to improve the vehicle response to a conventional road surface. The aims, process, outcomes and conclusions are included in this report. The project examines the response to a conventional road in different systems two stages. A first analysis of original structures, as Conventional Electric Vehicle, Fixed In-Wheel Motor and Suspended In-Wheel Motor, and a second one with the introduced new designs. Both analysis and simulation will be implemented in a frequency domain setting, with the purpose of showing the different response within the excitation frequency range. The mechanical parameters of the best-behaved systems will be contrasted in order to obtained an optimised system.

The final design presented is found to have an improved performance while being exposed to a conventional road surface spectrum, corroborating the project main objectives.

Keywords: *Electric Vehicle, In-Wheel Motor, Vibration, Frequency Analysis, Driving*

Table of Contents

1. Introduction and background	1
1.1. Aims and Objectives	1
2. Literature review	2
2.1. Concepts and conclusions	2
3. Methodology and theory	3
3.1. Activities and plan	3
3.2. Methods for evaluating results and outcomes	4
3.3. Road Surface modelling.....	4
3.4. Normal Modes Analysis.....	4
3.5. Dynamic Models	5
3.6. Frequency Spectrum	5
3.7. Bode Plot.....	6
4. Experimental work/analytical investigation/ design	6
4.1. Models.....	6
4.2. Testing.....	8
4.3. Analysis.....	11
4.4. Conclusions of first analysis	16
4.5. Bode Analysis	17
4.5.1. Initial Models	17
4.5.2. New Models.....	19
5. Presentation of analytical results/descriptions of final constructed product	22
5.1. Final Design Description	24
6. Discussion and conclusions	25
6.1. Further Research	25
7. Project management, consideration of sustainability and health and safety	26
7.1. Project Management	26
7.1. Health and Safety	26
7.2. Sustainability.....	28
References.....	29

1. Introduction and background

The development of Electric Vehicles (EVs) in the near future seems to be of great importance in relation to the environmental situation and the energy difficulties that today's society experience. Furthermore, EVs suffer less vibrations disturbances than combustion vehicles thanks to their motor characteristics, but their oscillatory performance in some unfavourable situation can be intensified [1].

In order to entirely diminish the potential adverse operation of EVs, various settings have been established, such as front-engine front-wheel drive, front-engine rear-wheel drive, mid-engine rear-wheel drive, and rear-engine rear-wheel drive [2].

Included within the possible setup options, the In-Wheel Motor (IWM) presents an outstanding performance. This engine proposal is based on placing the motor inside the wheel, displacing the drive mass and reducing the transmission elements. This novel setup improves energy efficiency and empowers an advantageous dynamical behaviour of the whole vehicle [2].

Despite the considerable advantages that IWM has, its structure brings an increase in the unsprung mass and, therefore, generates vibrations that can affect drive comfort and road holding [3].

This project aims to develop a novel design that diminishes the oscillation difficulties that are present in current EVs. The project analysis process is mainly divided in two stages. The first one includes the study of some existing setups that are represented by the conventional central motor, the Fixed In-Wheel Motor (FIWM) and the Suspended In-Wheel Motor (SIWM). This initial examination claims to determine the main performance of the EVs and to analyse the vibration phenomenon that is originated by a random road excitation. This examination will be evaluated by the wheel, vehicle body and motor displacements. The simulations will be repeated with the variation of the physical parameters with the aim of establishing a primary conclusion of their effect in the behaviour and apply the outcomes to the proposition of the new designs.

In the second stage, new mechanical systems will be established and tested in order to finally obtain the one with the best performance for the project aims.

1.1. Aims and Objectives

The main aim of this project is to implement a novel design of an In-Wheel Electric Motor Drive system for vehicles which operation is enhanced during oscillations in working conditions.

To achieve the primary purpose of the project, the founding of phased objectives has to be accomplished during the plan progress.

The development of this design is completed after settling basic knowledge of both electrical motors and dynamic vibrations in that sort of engine.

In order to compare the performance of the different setups and to validate the improved operation of the proposed system, the dynamic models of each structure will be simulated against a road surface roughness excitation, resembling the actual operation conditions.

As the dynamic functioning of the systems depends on its mechanical parameters, they will be optimized for the final design to be the most efficient one.

2. Literature review

The growth in development of Electric Vehicles (EVs) in the current energy situation is due to the decrease in the fossil sources used for running automobiles. However, the weight of EVs' batteries and the amount of transmission components cause several problems in relation to design and energy efficiency [4]. The main search of information in this project is based on papers that are focused in different proposals to solve these drawbacks.

The In-Wheel Motor (IWM) Drive is a very significant option for an improved development of the system, as the Electric Motor is set in the wheel hub to minimize the space and improve the power transmission efficiency.

However, one of the main disadvantages of IWM is the presence of a higher unsprung mass that could disturb the engine operation, causing stability and vibration complications. Therefore, there has to be an offset between the dimensions, power and mass of the machine [5].

The study of the vehicle stability is based on the yaw-moment control. This is highly influenced by the reaction speed of the system torque, being faster in Electric Vehicles than in Combustion Vehicles. Moreover, the IWM Electric Vehicle allows each wheel motor to be controlled separately, improving the general performance [4], and that control can be achieved in different ways. In [1], the vibrations originated on the drive shaft during velocity and gear changing are suppressed with a low-pass filter. In [6], a study of the velocity fluctuation in low frequencies and controller design is composed changing the system poles to reduce vibrations but preserving the dynamic performance of the system.

However, the dynamic quality is associated to the longitudinal movement, the stability corresponds to the lateral dynamics and the comfort of the vehicle consists in vertical dynamics [7]. In relation to the dynamical behaviour of the system, some damping systems have been developed to solve the possible complications.

In [8], a feedback control system that resemble a virtual mechanical damping system is introduced. A physical dynamic-damper mechanism for reducing the violent vibrations that fixed IWM cause is presented in [3] as a suspended IWM, which also improves the tire contact force and, therefore, the road holding. In [9], the suspended IWM performance is improved by a multiple optimization of the engine parameters that dismisses the resonant peak of the design. In [10], the insertion of three pairs of rubber bushings is proposed. The bushings are allocated between the stator and the hub knighthead, between the stator and the suspension bracket and between the ring and the rotor, separating the motor mass from the source of the vibrations and reducing them by the absorption function of the bushings. By that, the Motor Gap Deformation is improved more than 90%.

2.1. Concepts and conclusions

To summarise, one of the main concepts obtained from the literature review is that the elimination of the power train reduces costs and space, raising energy efficiency, but generates an inconvenience by increasing the unsprung mass and, therefore, worsening the vehicle vibration.

The prior studies of the IWM vehicle determined that, by providing the structure with a damper and spring system, the IWM becomes isolated and the vibration energy is absorbed by the bushings.

A series of different models is presented in each study, but the focus of this project will be the suspended motor concept as it has been proved to improve the driving quality experience and is presented as an innovative proposal with an option for further research. The outcomes of these studies also show that the motor suspension parameters affect the performance, resolving that the optimization of these parameters will facilitate the development of the upgraded proposition.

The following process will use these basic conclusions in order to obtain and develop a proper design that will promote the performance of the system and reduce the vibrations that could affect the driving experience and the motor efficiency.

3. Methodology and theory

The primary approach for the completion of this project was to follow a methodical and iterative process during the course of the different stages.

The development of the project started by reducing the working field, examining the existing problems related to the subject of interest, Electric Vehicles. The taken approach included an extensive research of current literature that helped to resolve the project background. All the information was condensed and systematised until finally obtaining a more concrete subject for the project.

When the previous knowledge was settled, the design process commenced. Based on a series of theoretical concepts and hypotheses, the analysis of the proposed initial models was fulfilled. The outcome data was used to advance in the process and to introduce several new systems. The models of these novel systems passed through the analysis scheme and where evaluated.

The results obtained from the different analysis were interpreted and used to evolve and, finally, accomplish the project aims. This report includes all the information that resulted from the testing and the different activities accomplishment and is presented organised in a way that pretends to guide the reader into each step taken and aims to be helpful with the understanding of the reasons of the final design resolution.

3.1. *Activities and plan*

The project has been implemented from a mechanical and analytical point of view and is evaluated by the implementation of different activities that include the development of block diagram models, the procurement of their dynamic equations, the incorporation of the models to the MATLAB/Simulink environment and the implementation of the simulations.

This course will be followed and repeated for each of the presented systems, starting with the original ones and finishing with the improved novel design. The results obtained from the simulations will provide the information that should be used for the comparison of the different setups and the accomplishment of the project aims.

The whole project planning is based in a Gantt Chart more detailed in chapter 7.

During the fulfilment of the project, the initial activity plan has been modified in order to adapt it to the unexpected setbacks.

One of the main problems that caused the modification of the initial project structure was that the outcomes, in time domain, obtained from the Simulink models were not sufficiently complete to be considered functional for the project development. This issue was solved by considering the possible reasons of that behaviour, and this consideration was tested by examining the frequency peaks of the road excitation, that means, those frequencies in which the excitation has more power. After that, a new analysis point of view was proposed: the frequency domain.

3.2. Methods for evaluating results and outcomes

The results obtained from the analysis were mainly evaluated using graphical techniques.

Firstly, the correct operation of the initial models was tested using a normal modes analysis, comparing the theoretical result with the one obtained with the simulations.

The primary evaluating method was based on the time domain. The models built in Simulink were compared by overlapping their operation while changing some parameters.

Due to the results achieved, more extensively commented in the analysis paragraph, the following examinations were taking into the frequency domain, using the Laplace transformation and plotting the outcomes in a Bode Diagram. There, the results were contrasted by their magnitude amplitude, looking for the model with the best performance.

3.3. Road Surface modelling

The road surface model is expressed as

$$\dot{x}_0(t) = -2\pi f_0 x_0(t) + 2\pi\sqrt{G_0}uw(t)$$

where f_0 value is 0.0628 Hz; u is the velocity and will be considered of 60 km/h; G_0 is the roughness coefficient of the road and is presumed of 0.02 m^{1/2}/s; $w(t)$ represents the white noise. The road model expression and the selected parameters values have been taken by considering [10] and in order to guarantee the similarity with an actual road spectrum.

The tests carried out with this model prove its appropriate performance and suggest its correct utilisation for the project development.

3.4. Normal Modes Analysis

Every dynamic system can be expressed in a matrix form that depends on its mass, stiffness and damping parameters as:

$$[M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = \{F(t)\}$$

With, [M] as mass matrix, [C] as damping matrix, [K] as stiffness matrix and {F(t)} as the external forces applied to the system.

The normal modes analysis evaluates the system when it is in a free vibration situation, that means, when the damping and the applying forces are zero.

$$[M]\{\ddot{x}(t)\} + [K]\{x(t)\} = 0$$

To simplify, the displacement will be considered sinusoidal considering Euler's Formula, as expressed below, so the acceleration will be,

$$\{x(t)\} = \{\phi\}e^{i\omega t} \quad \{\ddot{x}(t)\} = -\omega^2\{\phi\}e^{i\omega t}$$

The dynamic equation will look as,

$$(-\omega^2[M] + [K])[\phi]e^{i\omega t} = 0$$

Taking into consideration that $e^{i\omega t}$ can never be equal to zero, the equation is rearranged as,

$$([K] - \omega^2[M])[\phi] = 0$$

One of the solutions ($[\phi]=0$) is trivial, that is why the analysis is focused on the other one.

Renaming ω^2_i as λ_i , called eigenvalues, the solution of the equation $|[K] - \lambda[M]| = 0$ will provide the natural frequencies of the system.

3.5. Dynamic Models

The systems presented in this project have been modelled using block diagrams that notably simplify the mechanical structure and performance analysis of the setups.

The dynamic equations obtained from the models are based in Newton's Second law, being stated as follows [13]:

‘The net force of an object is equal to its mass times its acceleration and points in the same direction of the acceleration’

$$\sum F = m \cdot a$$

Where, F is the net force, m is the object mass and a is the acceleration.

The equations work in a force equilibrium basis, taking into consideration that the damping force is expressed as $c \cdot v$, with v as velocity, and the stiffness force as $k \cdot x$, where x is the displacement.

3.6. Frequency Spectrum

The frequency spectrum is used in this project with the intention of demonstrating the amplitude distribution of each frequency.

This representation shows the frequency range in which an excitation is working, which signifies the frequency rate in which the system will receive the excitation influence in its utmost. As the road excitation is presented in the time domain, the Fourier Transformation scheme is used to change it to the frequency domain.

$$S(f) = \int_{-\infty}^{\infty} s(t) \cdot e^{-2i\pi f t} dt$$

In this project, the transformation and spectrum representation will be implemented with MATLAB interface.

3.7. Bode Plot

It is the representation of the frequency response of a system. Mainly composed by magnitude (dB) and phase (°) response. To achieve the Bode diagram representation, the functions have to be transformed to the frequency domain using the Laplace Transformation scheme.

$$F(s) = \int_0^{\infty} f(t) \cdot e^{-st} dt$$

In this project, the transformation and Bode representation will be implemented with MATLAB interface.

4. Experimental work/analytical investigation/ design

4.1. Models

A dynamic model will be presented to introduce a clearer image of the initial systems and to simplify the vertical vibration study by use of their dynamic equations obtained with the Newton's second law.

The models of the Conventional EV and the Fixed IWM are described by a 2 degrees of freedom systems, while the Suspended IWM is defined by a 3 degrees of freedom system. In the three models, m_1 represents the unsprung mass (that includes tire, wheel, motor mass in the cases of Conventional EV and Fixed IWM, etc), m_2 is the vehicle body mass and m_3 is the motor mass in the SIWM case.

In the following figures the block diagrams of the three original systems and their corresponding dynamic equations are presented.

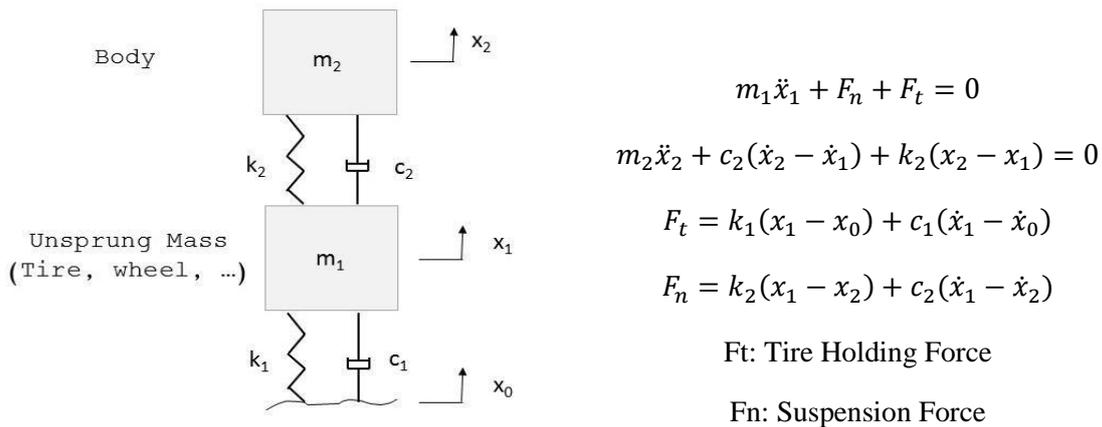


Figure 1. Conventional EV model

$$(m_1 + m_3)\ddot{x}_1 + F_n + F_t = 0$$

$$m_2\ddot{x}_2 + c_2(\dot{x}_2 - \dot{x}_1) + k_2(x_2 - x_1) = 0$$

$$F_t = k_1(x_1 - x_0) + c_1(\dot{x}_1 - \dot{x}_0)$$

$$F_n = k_2(x_1 - x_2) + c_2(\dot{x}_1 - \dot{x}_2)$$

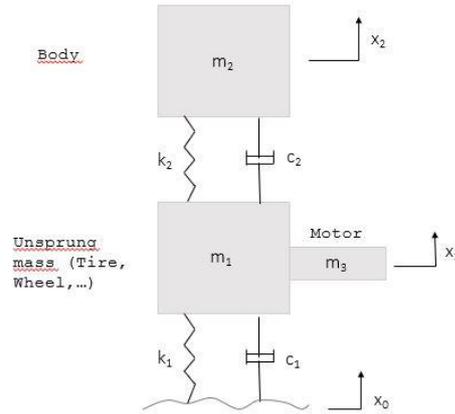


Figure 2. IWM Fixed motor

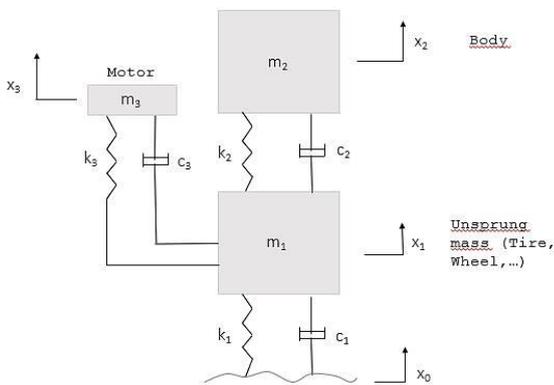


Figure 3. IWM Suspended Motor

$$m_1\ddot{x}_1 + F_n + F_t + F_d = 0$$

$$m_2\ddot{x}_2 + c_2(\dot{x}_2 - \dot{x}_1) + k_2(x_2 - x_1) = 0$$

$$m_3\ddot{x}_3 + c_3(\dot{x}_3 - \dot{x}_1) + k_3(x_3 - x_1) = 0$$

$$F_t = k_1(x_1 - x_0) + c_1(\dot{x}_1 - \dot{x}_0)$$

$$F_n = k_2(x_1 - x_2) + c_2(\dot{x}_1 - \dot{x}_2)$$

$$F_d = k_3(x_1 - x_3) + c_3(\dot{x}_1 - \dot{x}_3)$$

Fd: Damping Force

Through the matrix dynamic equations of each system, the models will be implemented using the Simulink environment. The aim of these representations is to implement the analysis that will evaluate the driving quality, by the displacements of tire, vehicle body and motor.

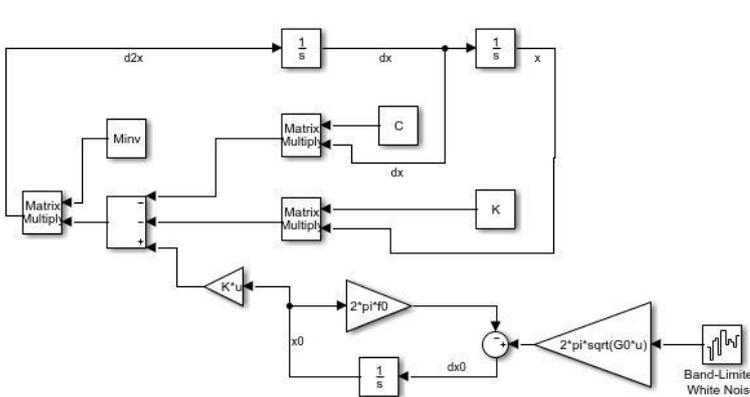


Figure 4. EV and Suspended IWM Simulink model

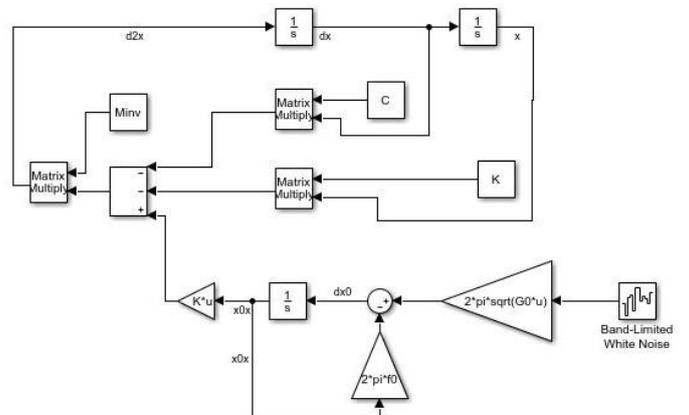


Figure 5. Suspended IWM Simulink model

4.2. Testing

To examine the proper operation of the systems' models, a normal modes analysis will be developed. The natural frequencies of each system will be mathematically obtained and then experimentally tested by simulating the models.

As it has been explained in chapter 3, firstly, the matrix movement expression in free vibration will be obtained. It is understood by free vibration the nonexistence of both damping and external forces applied to the body.

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix}$$

To simplify, the matrices will be renamed as,

$$M = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}$$
$$K = \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix}$$

Then, knowing that with a sinusoidal displacement the previous expression is $[[K] - w^2[M]]\{\varphi\} = \{0\}$ the term $\det([K] - w^2[M]) = 0$ should be solved in order to obtain the natural frequencies of the system

$$\left| \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} - w^2 \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \right| = 0 \rightarrow \left| \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} - \begin{bmatrix} w^2 m_1 & 0 \\ 0 & w^2 m_2 \end{bmatrix} \right| = 0$$
$$\left| \begin{bmatrix} k_1 + k_2 - w^2 m_1 & -k_2 \\ -k_2 & k_2 - w^2 m_2 \end{bmatrix} \right| = 0$$

After the analysis, using MATLAB to solve the determinant, the obtained frequencies of the Conventional EV model were

$$w_1 = 8.4807 \text{ rad/s}$$

$$w_2 = 96.7667 \text{ rad/s}$$

To prove the results and the efficiency of the models, the different systems will be exposed to a frequency analysis. They will be simulated for a range of frequencies from 0.1 to 100 rad/s and a sinusoidal excitation. For every frequency the maximum value of the displacements and of the excitation will be recorded. Then, the result of the first one divided by the second will be plotted against the frequencies, resulting the representation of the system reception. The frequencies in which the representation show reception peaks should be considered as the natural frequencies and must coincide with the mathematically obtained values in order to prove the correct operation of the models.

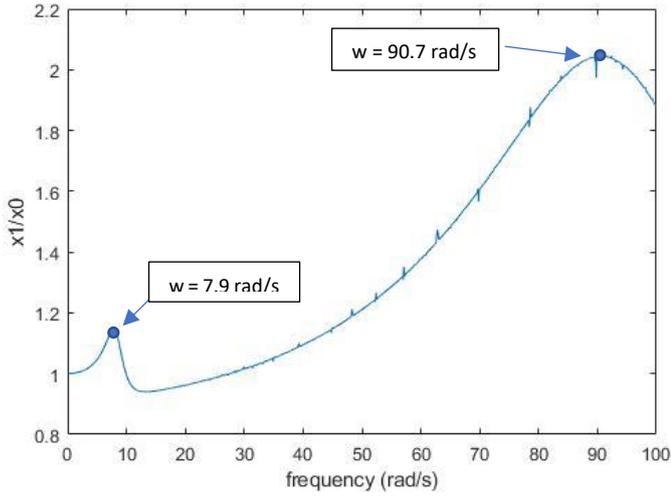


Figure 6. Tire Displacement Frequency Spectrum

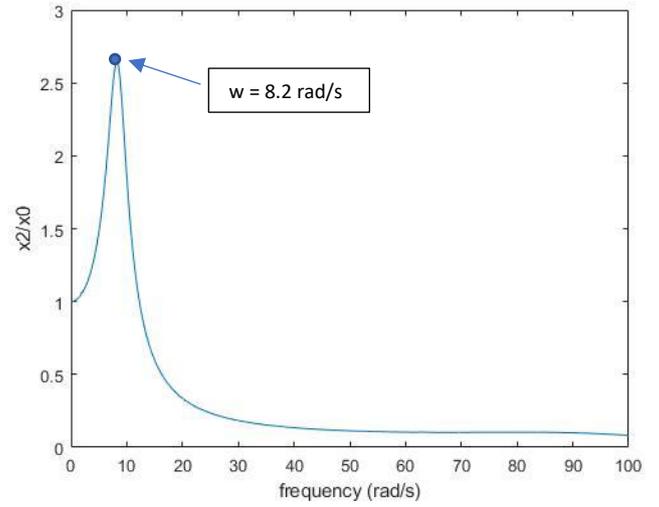


Figure 7. Body Displacement Frequency Spectrum

Repeating with the other two models, the Fixed IWM model matrix expression will be expressed as

$$\begin{bmatrix} m_1 + m_3 & 0 \\ 0 & m_2 \end{bmatrix} \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} c_1 + c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix} \begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} + \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix}$$

With,

$$M = \begin{bmatrix} m_1 + m_3 & 0 \\ 0 & m_2 \end{bmatrix}$$

$$K = \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix}$$

And its natural frequencies will be

$$w_1 = 8.7992 \text{ rad/s}$$

$$w_2 = 80.9765 \text{ rad/s}$$

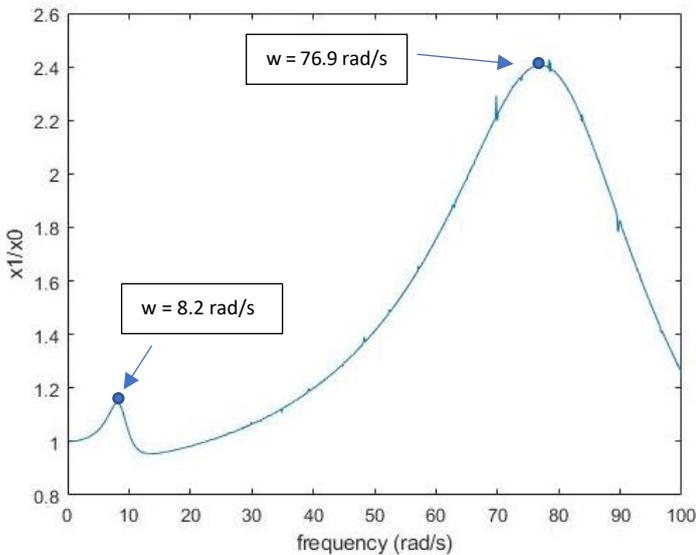


Figure 8. Tire Displacement Frequency Spectrum

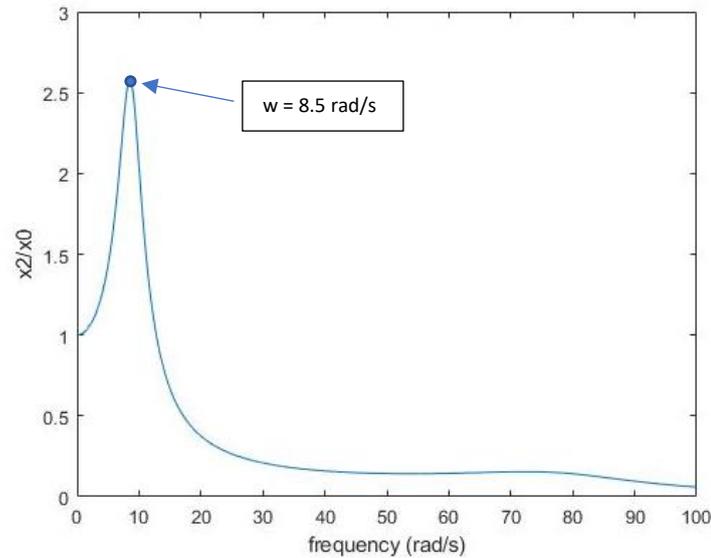


Figure 9. Body Displacement Frequency Spectrum

And for the Suspended IWM model,

$$\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix} \begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{Bmatrix} + \begin{bmatrix} c_1 + c_2 + c_3 & -c_2 & -c_3 \\ -c_2 & c_2 & 0 \\ 0 & -c_3 & c_3 \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \end{Bmatrix} + \begin{bmatrix} k_1 + k_2 + k_3 & -k_2 & -k_3 \\ -k_2 & k_2 & 0 \\ -k_3 & 0 & k_3 \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \end{Bmatrix}$$

Being,

$$M = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix}$$

$$K = \begin{bmatrix} k_1 + k_2 + k_3 & -k_2 & -k_3 \\ -k_2 & k_2 & 0 \\ -k_3 & 0 & k_3 \end{bmatrix}$$

Giving the natural frequencies of

$$w_1 = 8.7971 \frac{rad}{s} \quad w_2 = 37.7291 \frac{rad}{s} \quad w_3 = 85.8705 \frac{rad}{s}$$

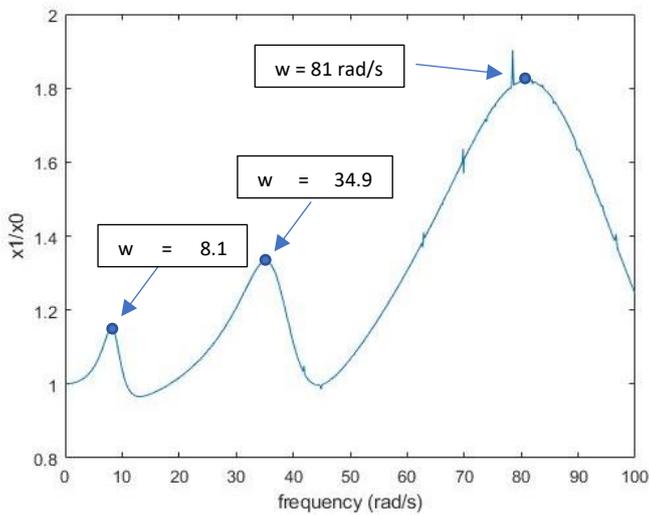


Figure 10. Tire Displacement Frequency Spectrum

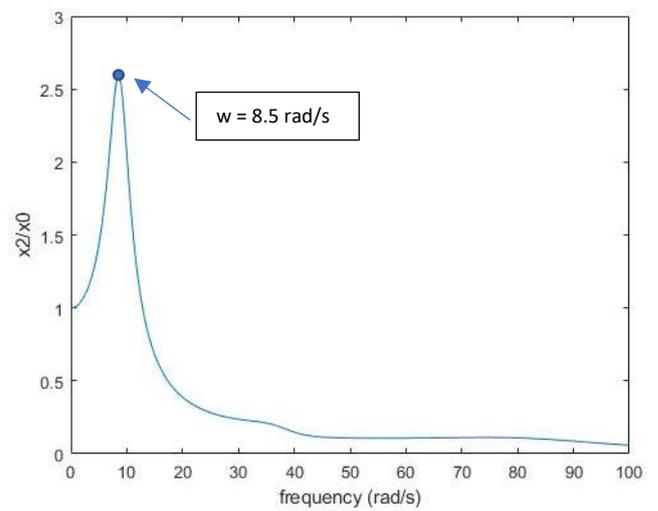


Figure 11. Body Displacement

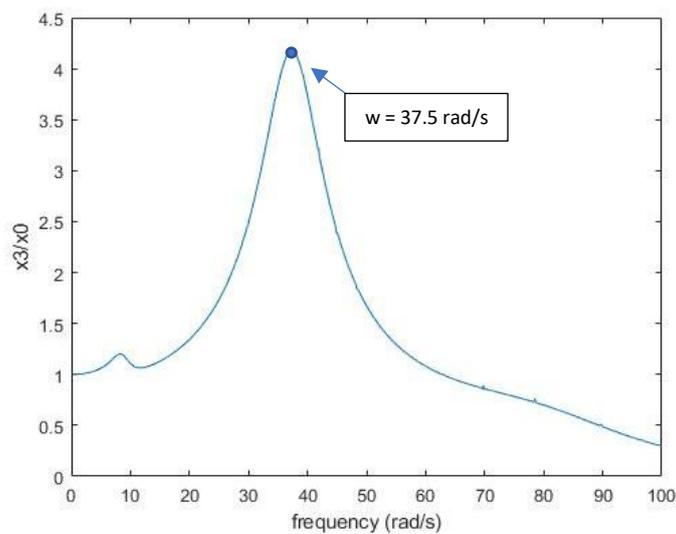


Figure 12. Motor Displacement Frequency Spectrum

The similarity between the numerical and the experimental values proves that the dynamical equations and, therefore, the developed Simulink models have a well-behaved performance and its utilisation for the design analysis will be appropriate and should show the required results.

4.3. Analysis

The analysis was performed in time domain running the different system models while changing the parameters (mass m , stiffness coefficient k and damping coefficient c) and plotting the displacements values of the tire, x_1 , the vehicle body, x_2 , and suspended motor, x_3 .

That representation will provide the information needed to analyse how the systems' behaviour changes with the variation of their physical values.

The simulations were repeated 7 times for each system, being the first one the one with the original parameters, and the increasing and decreasing each of the values separately. The values of the original parameters were selected by analysing the previous papers studies and in order to make the models as similar as an actual EV.

NOTATION

x_1 : x_1 : Unsprung mass vertical displacement

x_2 : x_2 : Vehicle Body vertical displacement

x_3 : x_3 : Suspended Motor vertical displacement

Table 1. EV

EV	1	2	3	4	5	6	7	
m_1 (Kg)	35	50	20	35	35	35	35	1- Original State
m_2 (Kg)	350	350	350	350	350	350	350	2- Unsprung Mass m_1 increase
k_1 (kN/m)	300	300	300	450	160	300	300	3- Unsprung Mass m_1 decrease
k_2 (kN/m)	27.5	27.5	27.5	27.5	27.5	27.5	27.5	4- Unsprung Mass Rigid coefficient k_1 increase
c_1 (Ns/m)	50	50	50	50	50	100	30	5- Unsprung Mass Rigid coefficient k_1 decrease
c_2 (Ns/m)	1500	1500	1500	1500	1500	1500	1500	6- Unsprung Mass Damping coefficient c_1 increase
								7- Unsprung Mass Damping coefficient c_1 decrease

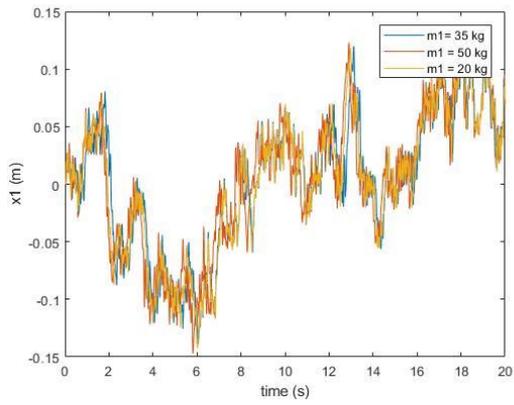


Figure 1. x_1 - mass variation

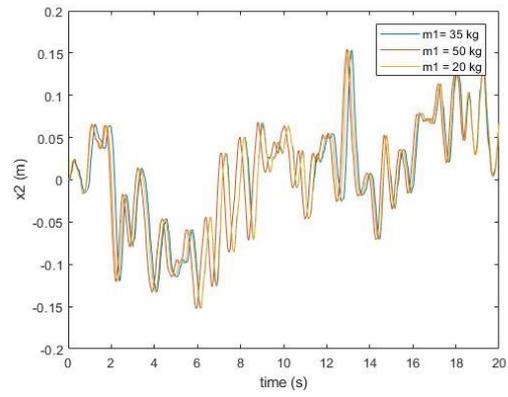


Figure 2. x_2 - mass variation

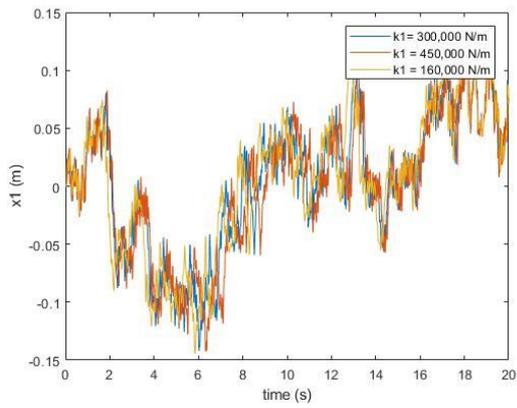


Figure 15. x_1 - k variation

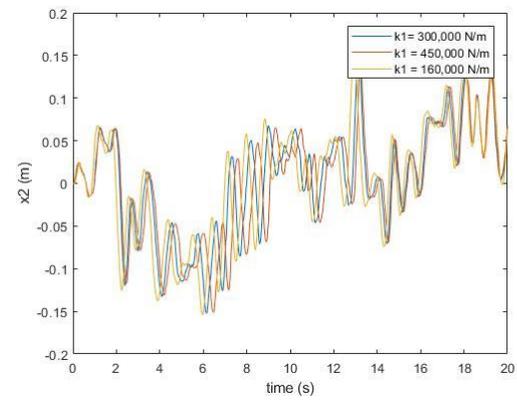


Figure 16. x_2 - k variation

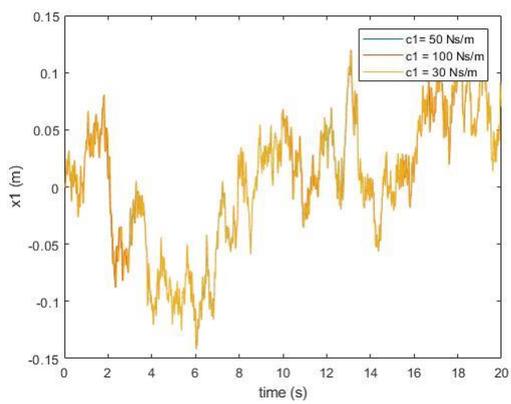


Figure 17. x_1 - c variation

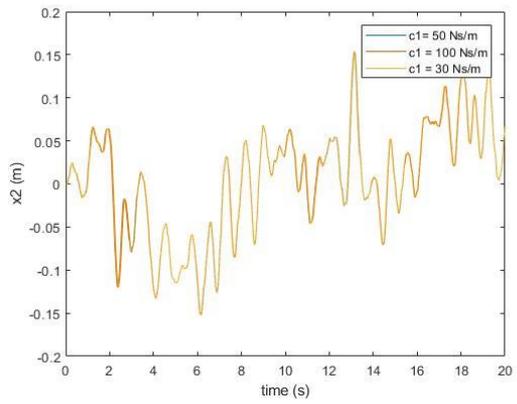


Figure 18. x_2 - c variation

Table 2. Fixed IWM

FIWM	1	2	3	4	5	6	7	
m_1 (Kg)	50	70	30	50	50	50	50	1- Original State
m_2 (Kg)	350	350	350	350	350	350	350	2- Unsprung Mass m_1 increase
k_1 (kN/m)	300	300	300	450	160	300	300	3- Unsprung Mass m_1 decrease
k_2 (kN/m)	27.5	27.5	27.5	27.5	27.5	27.5	27.5	4- Unsprung Mass Rigid coefficient k_1 increase
c_1 (Ns/m)	50	50	50	50	50	100	30	5- Unsprung Mass Rigid coefficient k_1 decrease
c_2 (Ns/m)	1500	1500	1500	1500	1500	1500	1500	6- Unsprung Mass Damping coefficient c_1 increase
								7- Unsprung Mass Damping coefficient c_1 decrease

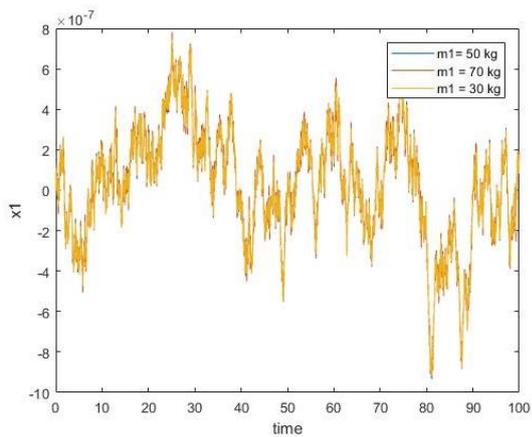


Figure 19. x_1 - mass variation

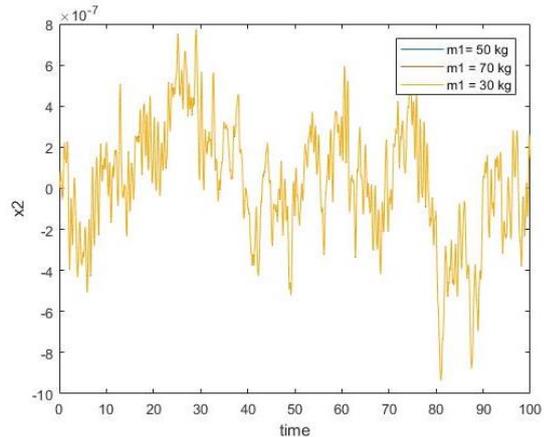


Figure 20. x_2 - mass variation

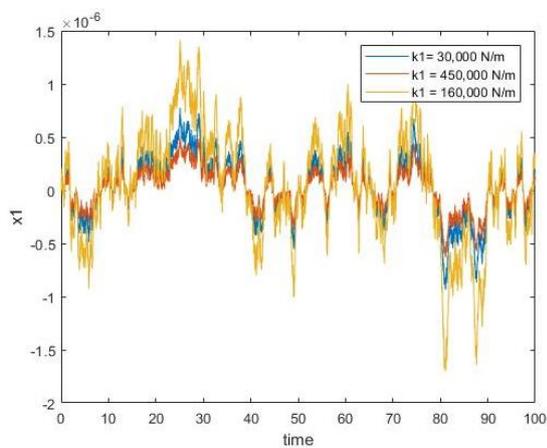


Figure 21. x_1 - k variation

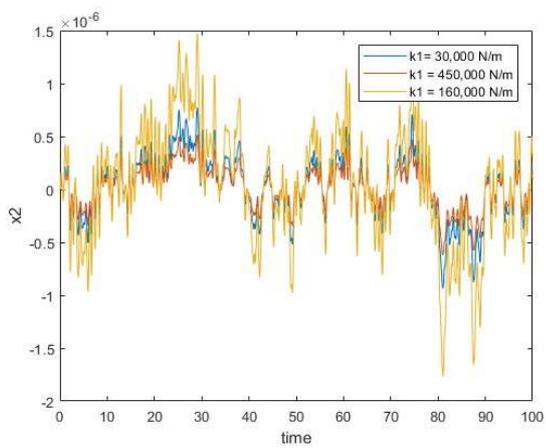


Figure 22. x_2 - k variation

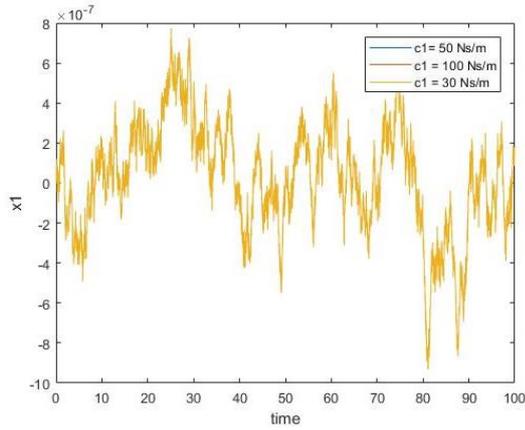


Figure 23. x_1 - c variation

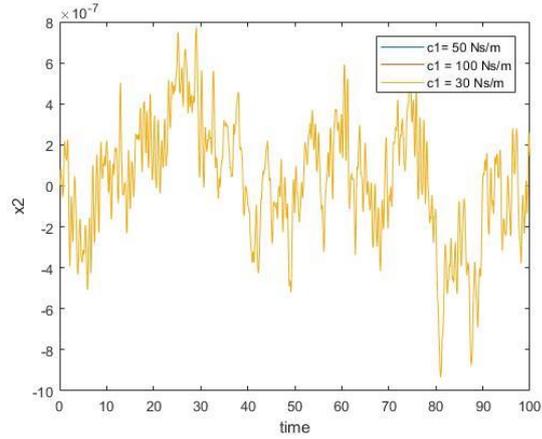


Figure 24- x_2 - c variation

Table 3. Suspended IWM

SIWM	1	2	3	4	5	6	7	
m_1 (Kg)	50	50	50	50	50	50	50	1- Original State
m_2 (Kg)	325	325	325	325	325	325	325	2- Unsprung Mass m_3 increase
m_3 (Kg)	20	40	12	20	20	20	20	3- Unsprung Mass m_3 decrease
k_1 (kN/m)	300	300	300	300	300	300	300	4- Unsprung Mass Rigid coefficient k_3 increase
k_2 (kN/m)	27.5	27.5	27.5	27.5	27.5	27.5	27.5	5- Unsprung Mass Rigid coefficient k_3 decrease
k_3 (kN/m)	32	32	32	50	13	32	32	6- Unsprung Mass Damping coefficient c_3 increase
c_1 (Ns/m)	50	50	50	50	50	50	50	7- Unsprung Mass Damping coefficient c_3 decrease
c_2 (Ns/m)	1500	1500	1500	1500	1500	1500	1500	
c_3 (Ns/m)	250	250	250	250	250	600	90	

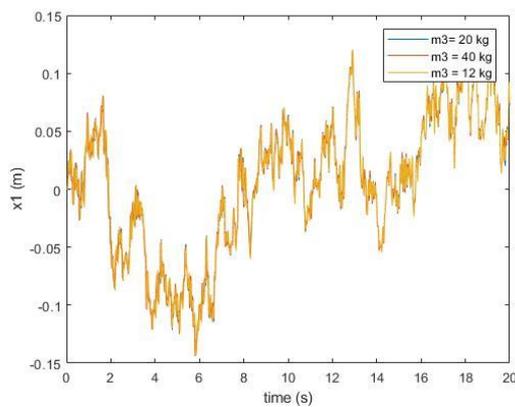


Figure 25. x_1 - mass variation

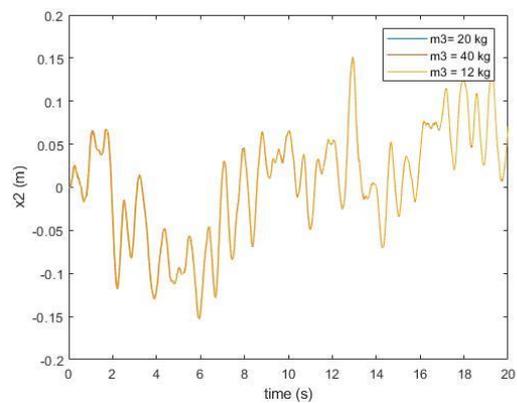


Figure 26. x_2 - mass variation

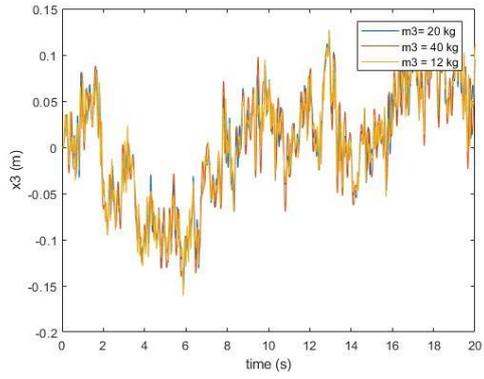


Figure 27. x_3 - mass variation

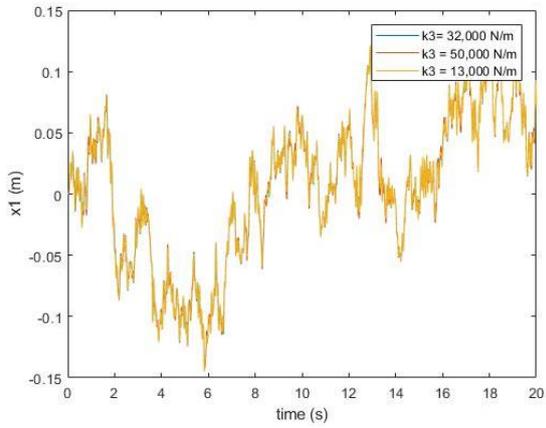


Figure 28. x_1 - k variation

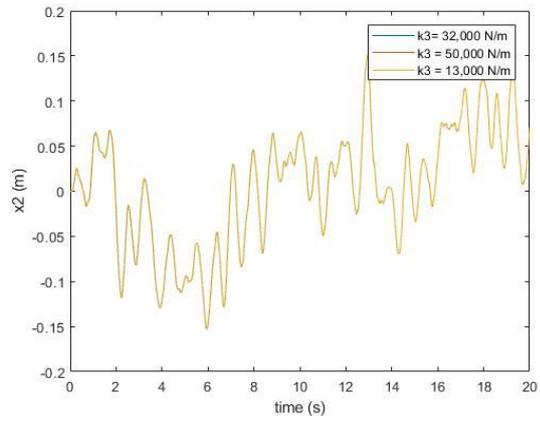


Figure 29. x_2 - k variation

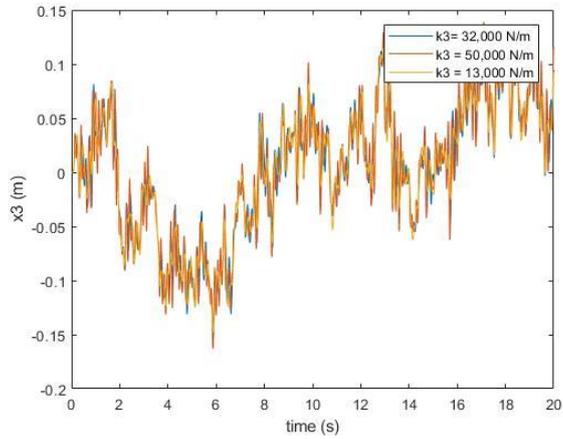


Figure 30. x_3 - k variation

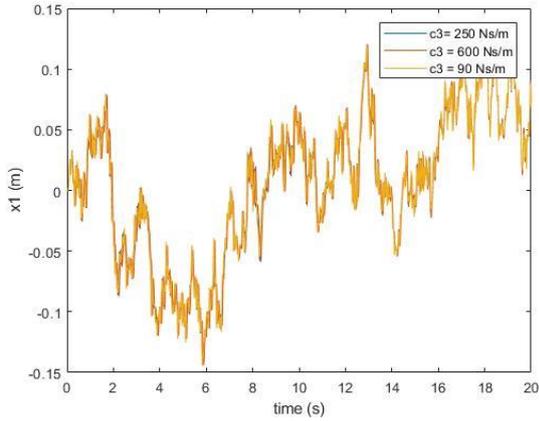


Figure 31. x_1 - c variation

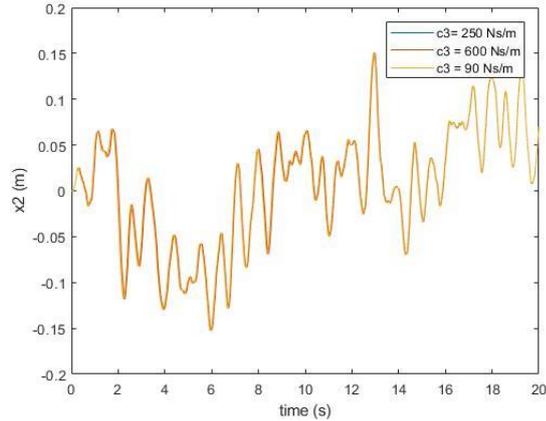


Figure 32- x_2 - c variation

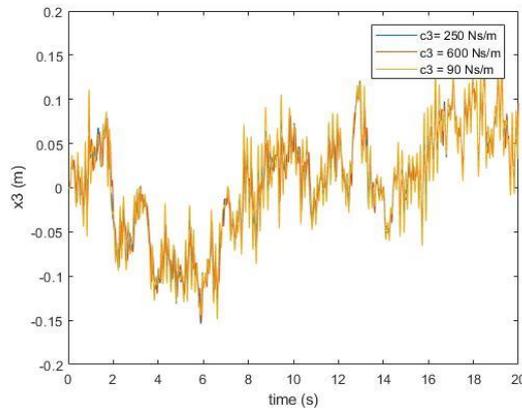


Figure 33. x_3 - c variation

4.4. **Conclusions of first analysis**

The results obtained after the first analysis indicate that the performance of the three models does not present a qualitative differentiation. Even with the parameters variation, the displacements obtained result quite similar and do not suggest any straight conclusion.

Comparing these results with the outcomes of the previously considered literature review papers, where the performance results are clearly altered by the parameters, it is determined that the dynamic operation of the models is not being analysed within the appropriate range of frequencies to show a functional result.

In order to verify this assumption, the road excitement expression will be evaluated using a frequency spectrum, it will be transformed using the Fourier scheme and then plotted so as to determine the magnitude distribution of the excitation frequencies.

The resulting figure, showed below, indicates that the excitation frequency distribution is mainly situated around 0.5 Hz, since the peak value is located around that frequency. Therefore, the study frequency range becomes reduced, as it demonstrates that the systems working with this excitation are functioning range shaped by this range.

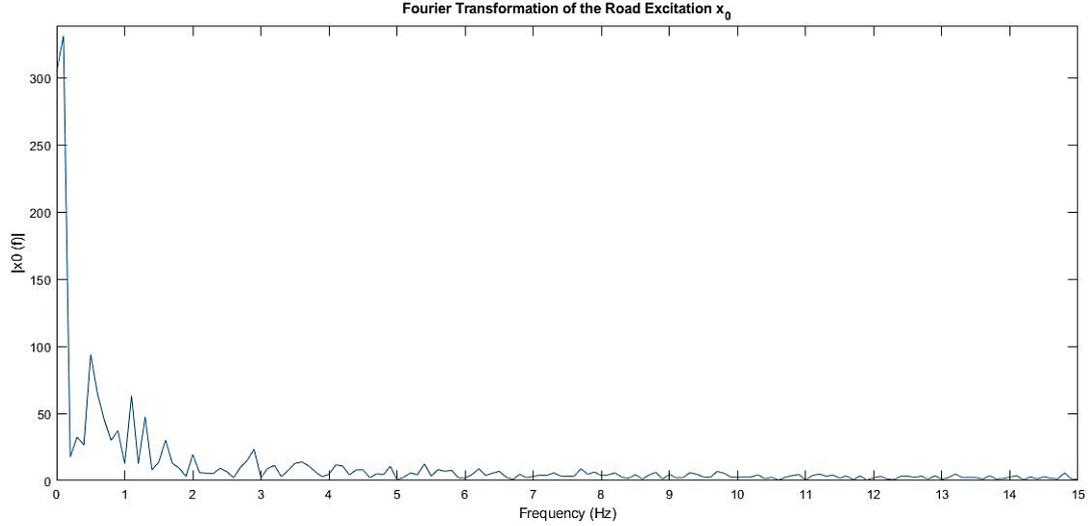


Figure 34. Road Excitation Frequency Spectrum

4.5. Bode Analysis

In order to establish a more appropriate model analysis and to determine the actual performance of the systems, the simulations will be performed again in the frequency domain. By transforming the dynamic equations using the Laplace scheme, the operation of the systems could be expressed using a Bode diagram where the amplitude of the displacements will be plotted against the frequencies. That representation will show the response of the systems when they are exposed to the selected road excitation spectrum, by their magnitude within the excitation frequency range, and their general performance with the remaining frequencies.

That way, the earlier stated impression will be verified and the actual operation differences should be exposed.

4.5.1. Initial Models

The transformation to the frequency domain will begin by taking the conventional EV matrix expression

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} c_1 + c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix} \begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} + \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{Bmatrix} k_1 x_0 + c_1 \dot{x}_0 \\ 0 \end{Bmatrix}$$

And renaming as,

$$M = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \quad K = \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \quad C = \begin{bmatrix} c_1 + c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix}$$

$$\ddot{x} = \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix}; \quad \dot{x} = \begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix}; \quad x = \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix}$$

$$\begin{Bmatrix} k_1 x_0 + c_1 \dot{x}_0 \\ 0 \end{Bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} (k_1 x_0 + c_1 \dot{x}_0); \quad L = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

Obtaining the following simplified expression

$$M\ddot{x} + C\dot{x} + Kx = L(k_1x_0 + c_1\dot{x}_0)$$

If we now apply the Laplace transformation of the expression, explained in chapter 3,

$$Ms^2\ddot{x}(s) + Cs\dot{x}(s) + Kx(s) = L(k_1 + c_1s)x_0(s)$$

$$[Ms^2 + Cs + K]x(s) = L(k_1 + c_1s)x_0(s)$$

And finally obtain the transfer function of the system (output/input)

$$\frac{x(s)}{x_0(s)} = [Ms^2 + Cs + k]^{-1} \times L \times (k_1 + c_1s)$$

The process will be the same for the Fixed and Suspended IWM, just adjusting M, C and K and considering L as $\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$ for the Suspended IWM.

Utilizing MATLAB techniques, the Bode Plot of the three models will be as showed in the following figures.

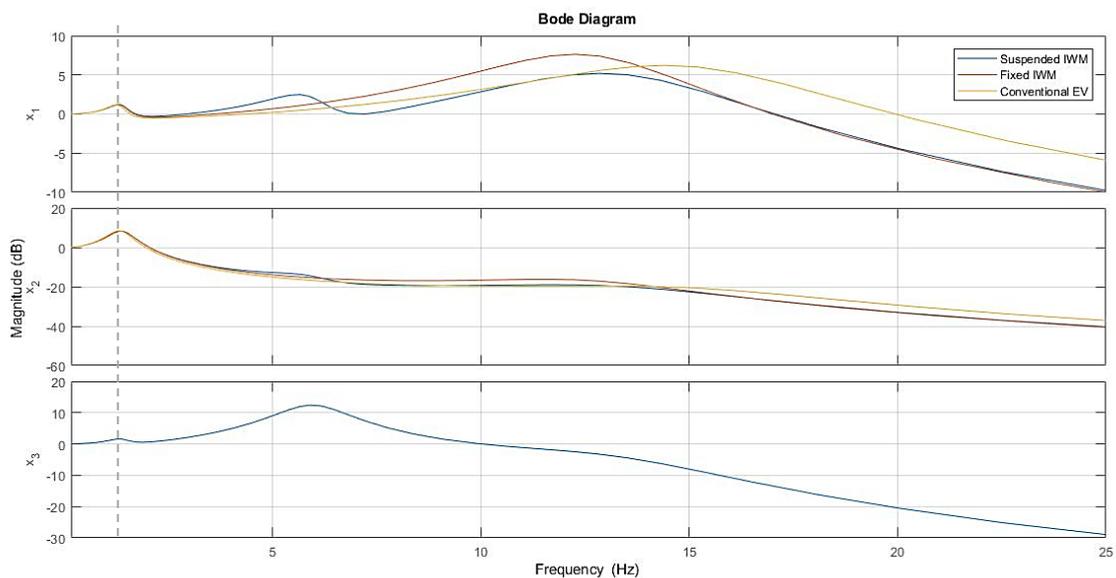


Figure 34. Initial Models Bode Diagram

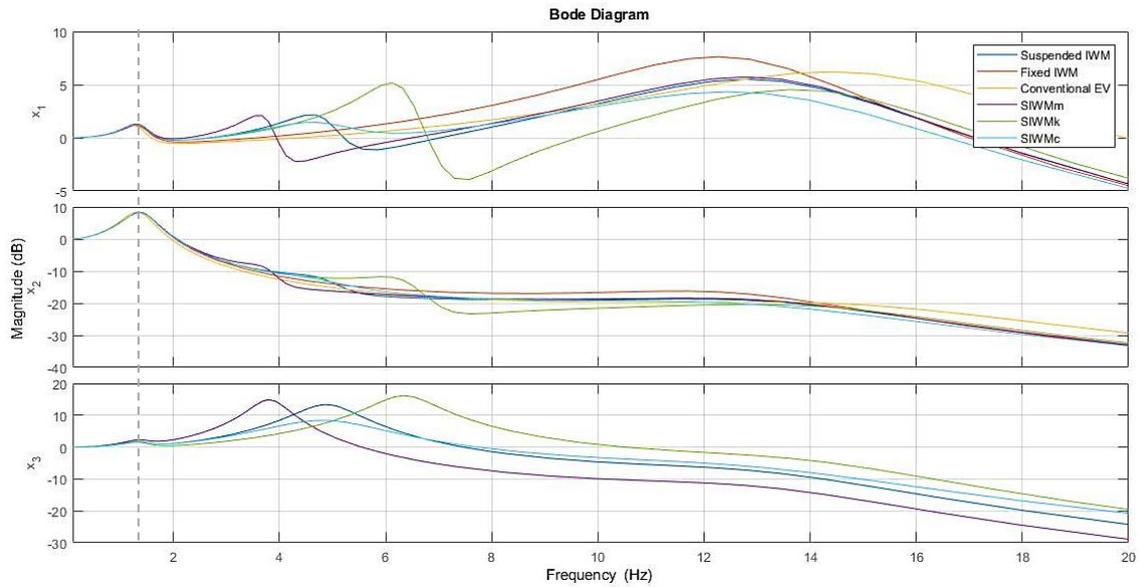


Figure 35. Initial Models Variation Bode Diagram

The first figure shows the Bode plot of the three initial systems with their original parameters, while the second one includes an increasing variation of the SIWM parameters, which purpose is to show their influence in the system operation. A discontinuous line is included in both figures to indicate the frequency range in which the excitation is mainly operating.

The results obtained prove that the three models have a moderately similar magnitude performance in the frequency range limited by the road excitation but show an alike performance within the other frequency values, proving the assumption stated and corroborating the literature review conclusions. Given another excitation, with an alternative frequency distribution, the disparity between the systems will be proved more apparent.

As the three systems describe a positive magnitude peak in the performance frequencies, the aim of the project will be to diminish the peak by introducing several altered models that will have a divergent operation.

4.5.2. New Models

Examining all the achieved results and conclusions, 5 new models are introduced and the analysis process is repeated with all of them in order to compare their performance with the initial systems and to establish if any of them improves the general operation of In-Wheel Motor vehicles.

The following figures illustrate some drafts of each system physical representation and their corresponding block diagram.

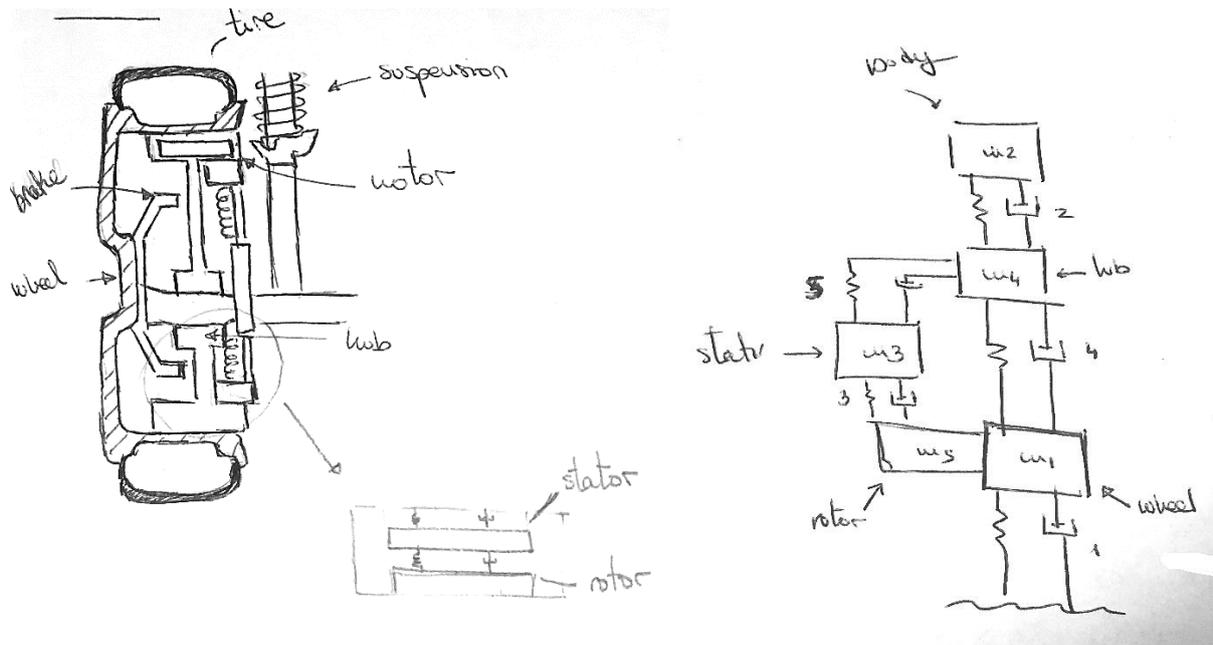


Figure 36. New Design 2 Physical and Block representation

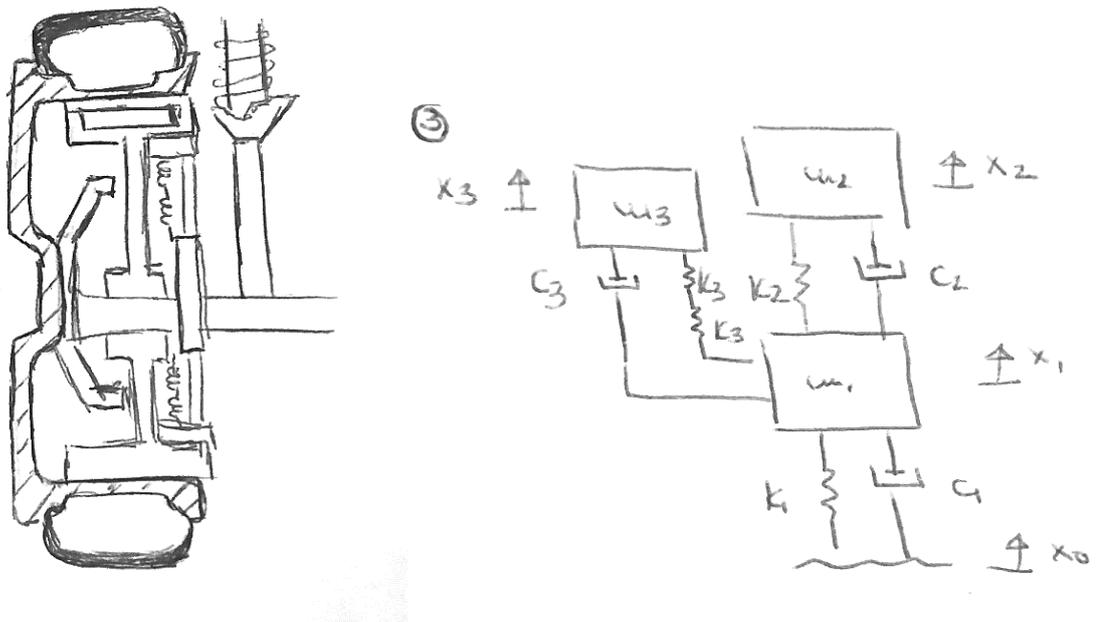


Figure 37. New Design 3 Physical and Block representation

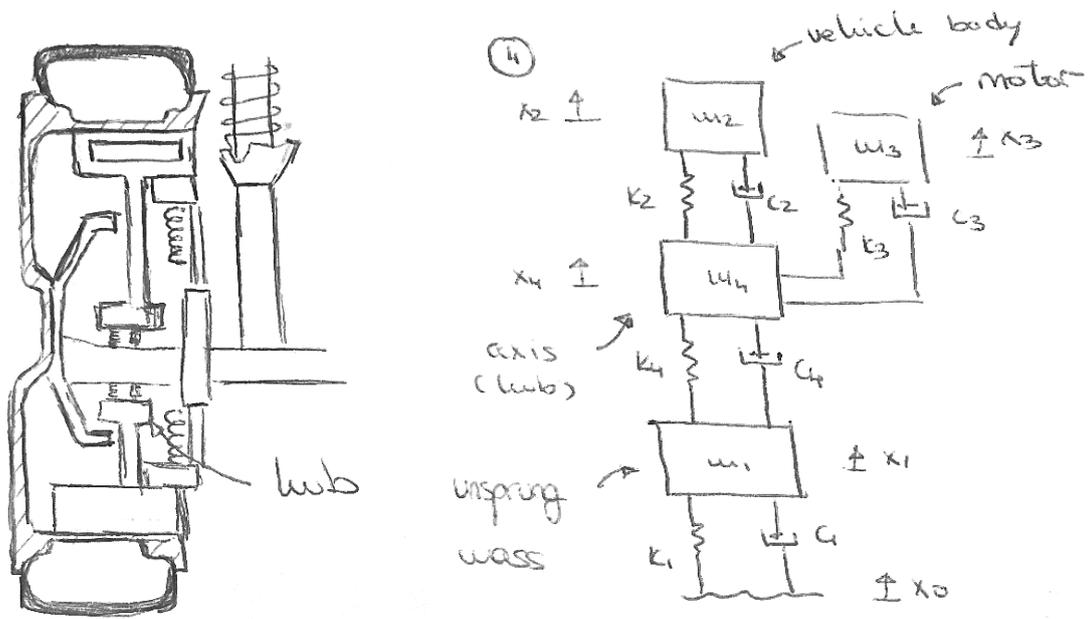


Figure 38. New Design 4 Physical and Block representation

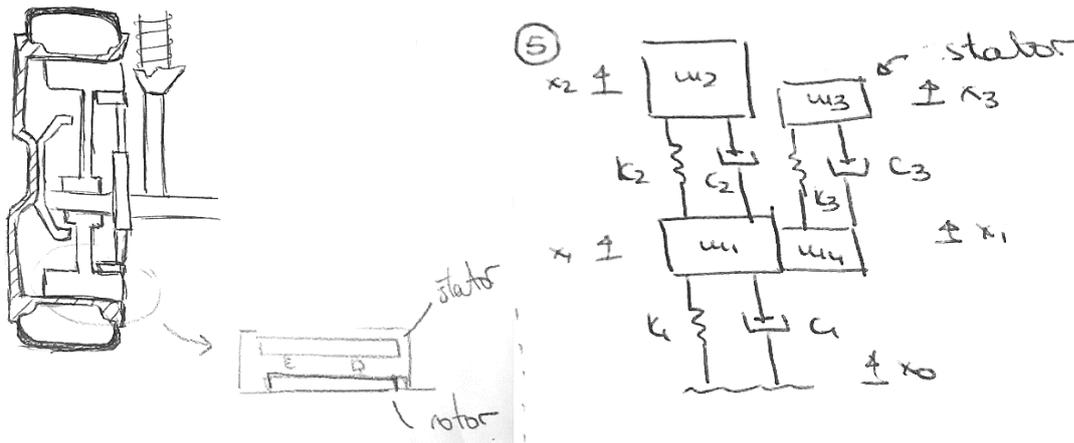


Figure 39. New Design 5 Physical and Block representation

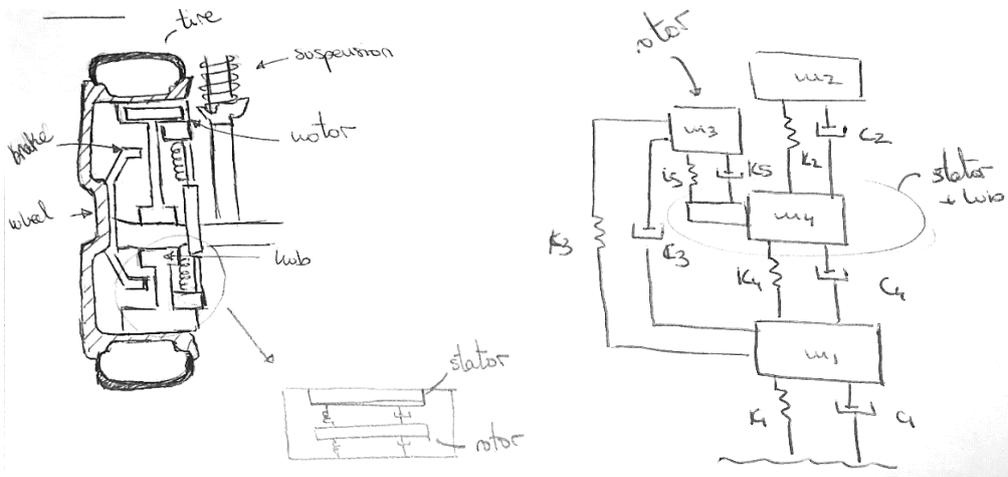


Figure 40. New Design 6 Physical and Block representation

The selected values for the physical parameters of each New Design (ND) are expressed in the table below. They all have been picked considering the analysed papers and with the objective of resembling the models to actual vehicles in a proper manner.

Table 4. New Models parameters

	m_1 (Kg)	m_2 (Kg)	m_3 (Kg)	m_4 (Kg)	k_1 (kN/m)	k_2 (kN/m)	k_3 (kN/m)	k_4 (kN/m)	k_5 (kN/m)	c_1 (Ns/m)	c_2 (Ns/m)	c_3 (Ns/m)	c_4 (Ns/m)	c_5 (Ns/m)
SIWM	50	325	30	-	300	27.5	32	-	-	50	1500	250	-	-
ND2	40	325	20	20	300	27.5	1000	1000	32	50	1500	0	0	50
ND3	50	325	30	-	300	27.5	32	-	-	50	1500	250	-	-
ND4	30	325	30	20	300	27.5	32	500	-	50	1500	250	25	-
ND5	60	325	20	-	300	27.5	300	-	-	50	1500	50	-	-
ND6	30	325	10	40	300	27.5	32	500	500	50	1500	250	25	25

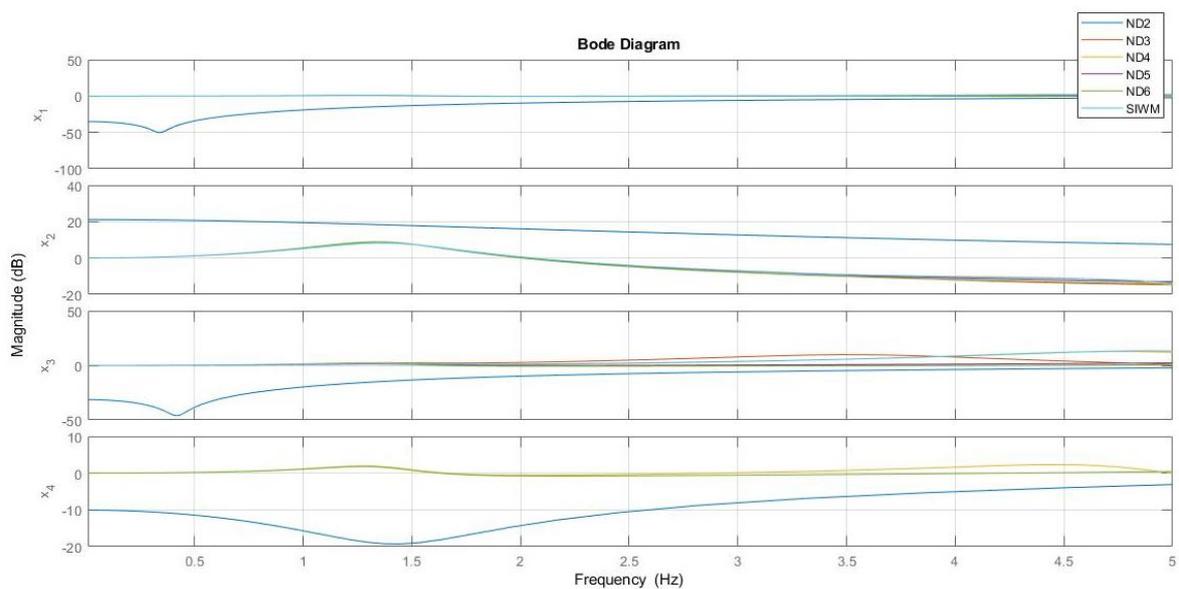


Figure 41. New Models Bode Diagram

As shown in the figure above, the New Design 2 demonstrates a clearly apparent amplitude reduction in the displacements of wheel, motor and axis. This suggests that this model could be of use in the project aims of vibration condition improvement. To deepen into more detailed results, the simulations will be repeated with this model but varying some of its parameters, with the intention to optimise them and specify the best operational setup.

5. Presentation of analytical results/descriptions of final constructed product

Once the most well-behaved model has been selected, the analysis will continue focusing on that system.

The simulation will be repeated while changing some of the mechanical parameters as shown in the following table. The difference that this structure presents is that it includes a stiffness and damping

system that facilitates the motor isolation between the tire and the hub. Since the additional isolation technique is the important factor of this novel design, the further research performed by the analysis repetition will study the performance alteration while variation the isolation coefficients k_3 , k_4 , c_3 and c_4 . The taken values for the parameters are expressed in the following table.

Table 5. New Design 2 parameters variation

	k_3 (N/m)	k_4 (N/m)	c_3 (Ns/m)	c_4 (Ns/m)
ND2	10^6	10^6	0	0
ND2 1	$5 \cdot 10^5$	$5 \cdot 10^5$	0	0
ND2 2	10^6	10^6	50	50
ND2 3	10^5	10^5	0	0

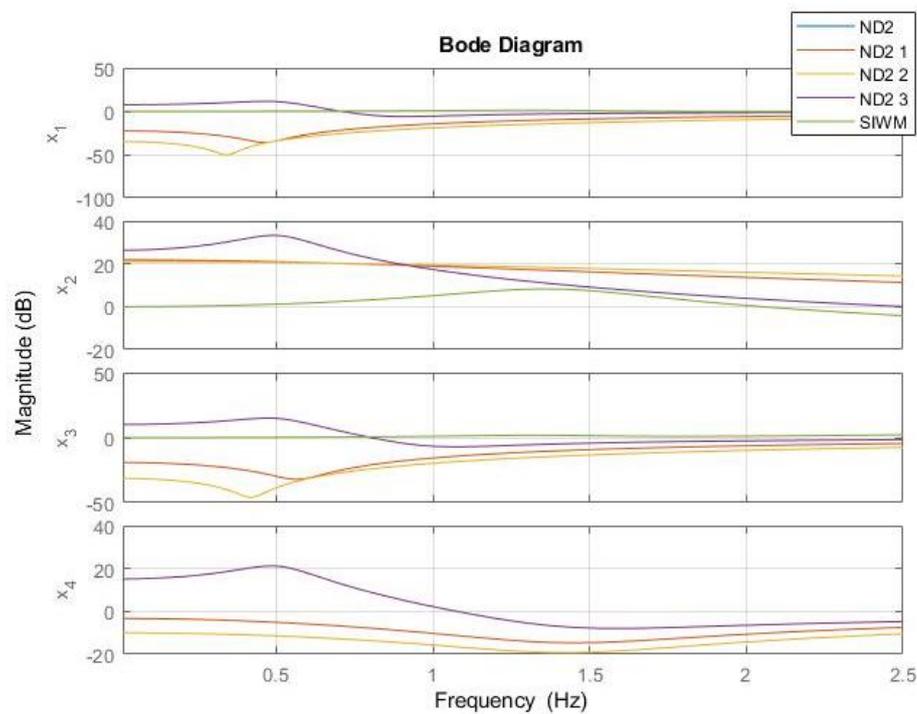


Figure 42. New Design 2 Variation Bode Diagram

From the results, it is established that the damping coefficient variation does not affect the system operation, as the original model and the second variation have superimposed outcomes, and that the higher values of the stiffness coefficients k_3 and k_4 produce a better performance in relation to tire, motor and axis displacements, decreasing their amplitude response, but increases considerably the vehicle body displacement.

In order to reduce this phenomenon, the consideration of a higher stiffness coefficient between the axis and the body, k_2 (suspension), is presented and studied. The new proposed model will work with the following values.

Table 6. Final Design Parameters

	k_3 (N/m)	k_4 (N/m)	c_3 (Ns/m)	c_4 (Ns/m)	k_2 (kN/m)
ND2 4	10^6	10^6	0	0	275

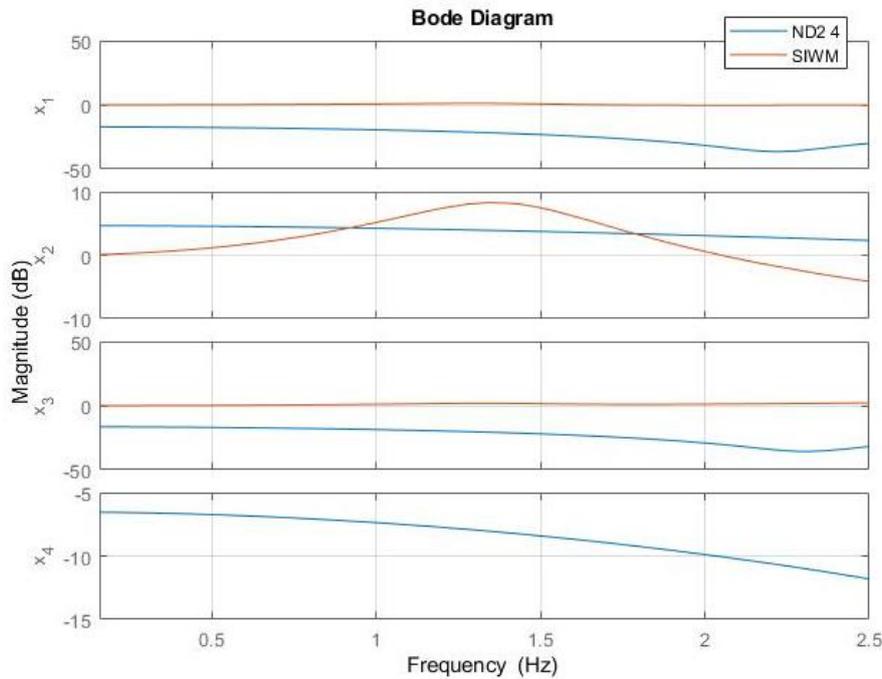


Figure 43. Final Design Bode Diagram

Therefore, this model fits into the project objectives and improves the original SIWM drive vehicle.

5.1. Final Design Description

After the progression through all the analysis of the introduced systems and models, the results obtained from the last optimisation show that the second proposed design improves the general performance of the vehicle by adjusting some of its parameters. The setup includes a damping and stiffness system that mainly isolates the stator from the rotor and the hub. To increase the isolation behaviour, the parameters that affect the rigidity between rotor and stator (k_3) and wheel and axis (k_4) have been chosen of great magnitude: 1 MN/m.

As the structure increased the body vehicle movement, the notion of analysing the suspension system (k_2 and c_2) of the vehicle was considered. It was deduced that an increase of the stiffness parameter k_2 enhance the body displacement response while maintaining the previous improvements.

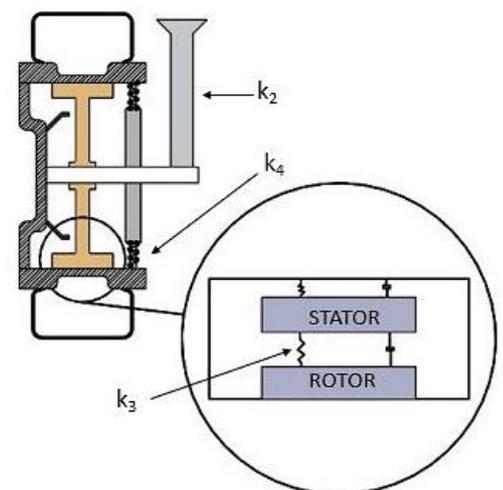


Figure 44. Final Design CAD Sketch

To create a more visual representation of the final design, a Computer Aided Design software (*SolidWorks*) was used for the sketch implementation of the model.

6. Discussion and conclusions

This report has presented the design process of an improved drive structure for the reduction of vibrations in Electric Vehicles with an In-Wheel Motor Drive.

During the course, the different performances of various mechanical systems have been exposed both in time and frequency domain. That double representation was guided during the project by the importance of the excitation frequency spectrum, clearly showing that frequency distribution affects how the systems performance is seen in the time domain representation.

Also, the Bode plot allowed to clearly demonstrate if the new proposed designs had a beneficial or detrimental operation in relation to the original systems. That means, if the displacements exhibit a positive or negative amplitude, in dB, and at what rate they are modified.

Working within the excitation frequency spectrum dominance range, the models were classified by their best operation in that frequency peak, disqualifying those with a worse performance.

During the simulation analysis, the influence of the different mechanical parameters was also examined and it was concluded that in every system only the stiffness coefficient variation presented an evident alteration in the dynamical response. That is the reason why the final analysis was only focused on that parameter optimisation.

After the examination of all the data obtained from the project analysis and tests, the final proposed design achieves the initial project aims and objectives satisfactorily.

It can be concluded that an isolated design can reduce the vibration phenomenon while a road surface excitation is applied to the vehicle.

6.1. Further Research

Although this project has presented a novel In-Wheel Motor drive setup, it would be necessary to work on further research in order to validate the model and obtain experimental outcomes. It would be encouraging to obtain more information from a different working area by physically constructing the final design and reproduce the tests as to attach more data to the final conclusion.

Considering also the physical development of the project, the space optimisation and component cost could be of great interest as supplementary research. This could include the consideration of possible fitting elements that would create the physical structure of the proposed design. In addition, an optimisation of their physical and economic factors (material, form, weight, price, ...) would improve the complete development of the project aim.

7. Project management, consideration of sustainability and health and safety

7.1. *Project Management*

The project followed a building blocks method extended in paragraph 3, including a forward and backward feedback procedure where the initial background were used to develop the proposed designs and to foresee the outcomes, and those obtained results were evaluated and used to rebuild the design plan and final concept. That way, this report is complete and embraces all the steps that made the final design proposition the most optimal one for the project initial requirements.

To provide the project management with a visual representation of the duration times taken for each activity, a Gantt Chart was created. It is divided into 5 main activities that are fulfilled while developing a series of tasks. The duration of each task was overestimated in order to have a timeframe that could assure the project completion on time even if there were unexpected delays. Also, the schedule was readjusted during the course of the year with the aim of regulate the project structure with the course variations and make the schedule more realistic to the circumstances.

The next page shows the Gantt Chart divided by the two main stages: Term 1 (Right) and Term 2 (Left).

Adhering to this, weekly meetings with the supervisor were held in order to maintain a continuous progress and resolve any incoming inconvenient.

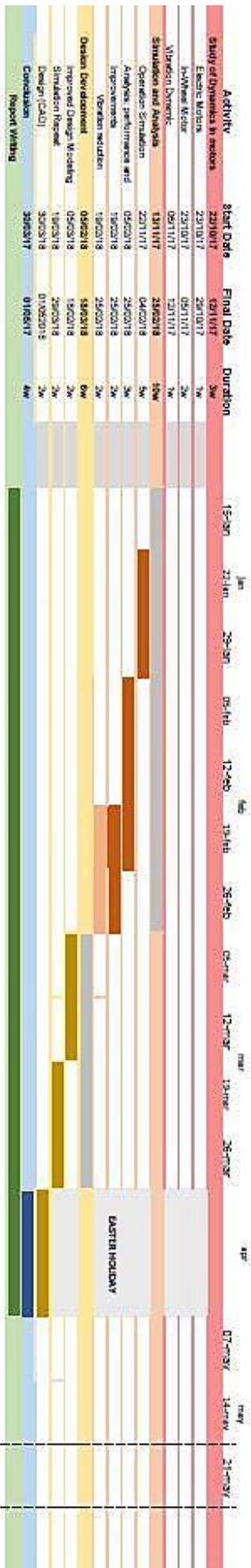
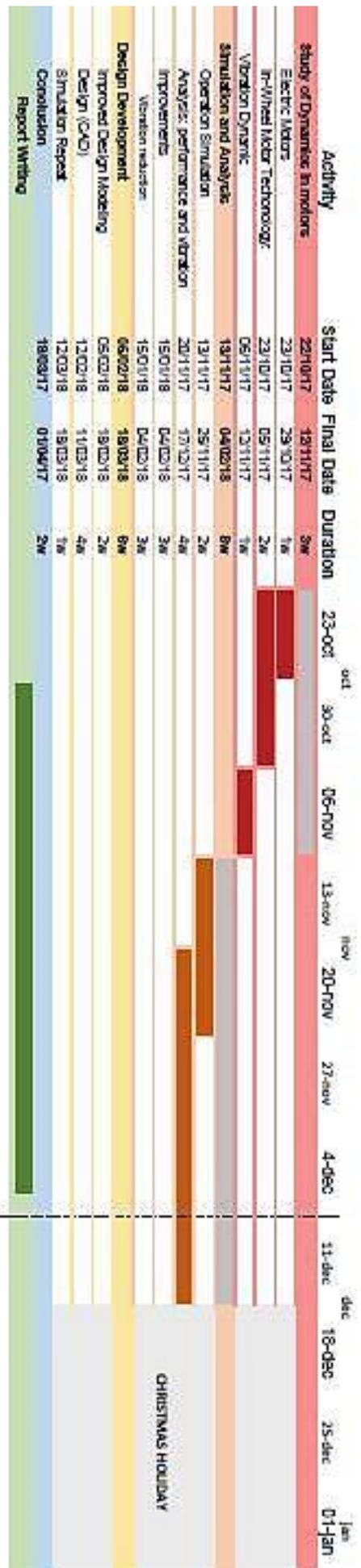
As this project did not require the use of any machinery or equipment, there was no need of foreseeing their utilization and, therefore, their possible booking delays.

7.1. *Health and Safety*

As the completion of this project has only been made through computational analysis, the Health and Safety regulations are limited and do not reference to many areas.

One of the main health considerations is to respect the regulations while working with computers for an extended time [14]. This directive secures the issue risk prevention and has been followed during the working hours with the computer.

Also, considering that the majority of the working stage were completed in my own working location, it was important to assure that the environment was safe and was provided with anything necessary in case of any hazard to occur. Since every building and location has its own health and safety regulations, they all have been acknowledged before the beginning of the project and respected during the complete duration of the development.



In relation to the project accomplishment, the following risk matrix has been created in order to introduce any possible situation that could affect the project development.

RISK	CONSEQUENCE	RISK ASSESMENT	PREVENTIVE ACTIONS
The proposal could not have enough advantages	The project would not be convenient to amend the existing designs	MEDIUM	Concentrate the project objectives in the weaker aspects of the actual design so they can be improved
The scope of the project is poorly defined	The final conclusions could be too general for the purpose of the project	HIGH	Increase the research sources in order to obtain a clear vision of the project
The software used for the first simulations could not be adequate	The project objectives could not be achieved	MEDIUM	It would be necessary to look for another software or to change the project objectives
The project fails to adjust to the project organisation schedule	The project could come unfinished to the deadline	HIGH	Assure that the project plan organization is realistic and being followed

7.2. Sustainability

Although the project does not have any direct sustainability consequences, because there was no prototype manufacturing, the main purpose of the entire presented work has a clearly sustainable perspective.

As it has been exposed through this report, the main purpose of the project was to develop an improved system that could be used for the increasing Electric Vehicles business and production. Looking at the sustainability description through its main factors (environment, economy and society), the importance of the development of Electric Vehicles seems clear. The use of an electric motor instead of a combustion one has proven results of reducing the carbon footprint of vehicle utilisation, being much more environmentally friendly.

In relation to the direct sustainability importance, the reduction of the vibrations in the car supposes money and time savings regarding maintenance and renovation. Besides, since the motor will work in a higher efficiency situation, the energy savings should also be significant.

References

- [1] J.-S. Chen, "Vibration Reduction in electric bus during acceleration and gear shifting," *Advances in Mechanical Engineering*, pp. 1-16, 2015.
- [2] S. Murata, "Innovation by in-wheel-motor drive unit," *International Journal of Vehicle Mechanics and Mobility*, vol. 50, no. 6, pp. 870-830, 2012.
- [3] G. Nagaya, Y. Wakao and A. Abe, "Development of an in-wheel drive with advanced dynamic- damper mechanism," *JSAE Review*, vol. 24, no. 4, pp. 477-481, 2003.
- [4] L. Xiong, Y. Wang, C. Yang and Y. Meng, "Vehicle dynamics control of four in-wheel motor," *International Journal of Vehicle Mechanics and Mobility. Vehicle System Dynamics*, vol. 50, no. 6, pp. 831-846, 2012.
- [5] K. M. Rahman, N. R. Patel and T. G. Ward, "Application of Direct-Drive Wheel Motor for Fuel Cell Electric and Hybrid Electric Vehicle Propulsion System," *IEEE Transactions on Industry Applications*, vol. 42, no. 5, pp. 1185-1192, 2006.
- [6] F. Profumo, M. Madlena and G. Griva, "State Variables Controller Design for Vibrations Suppression in Electric Vehicles," *PESC Record. 27th Annual IEEE Power Electronic Specialist Conference*, vol. 2, pp. 1940-1947, 1996.
- [7] W. Sun, Y. Li, J. Huang and N. Zhang, "Vibration effect and control of In-Wheel Switched Reluctance Motor for electric vehicle," *Journal of Sound and Vibration*, vol. 338, pp. 105-120, 2015.
- [8] S. Yamada, T. Beauduin, H. Fujimoto, T. Kanou and E. Katsuyama, "Model-Based Longitudinal Vibration Suppression Control for Electric Vehicles with Geared In-Wheel Motors," *IEEE International Conference on Advanced Intelligent Mechatronics (AIM)*, 2017.
- [9] W. Tong and Z. Hou, "Vertical Vibration Analysis on Electric Vehicle with Suspended In-wheel Motor Drives," *EVS*, vol. 27, 2013.
- [10] Y. Luo and D. Tan, "Study on the Dynamics of the In-Wheel Motor System," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 8, pp. 3510-3518, 2012.
- [11] K.-J. Tseng and G. Chen, "Computer-aided design and analysis of direct-driven wheel motor drive," *IEEE Transactions on Power Electronics*, vol. 12, no. 3, pp. 517-527, 1997.
- [12] Y. E. Zhao, J. W. Zhang and X. Q. Guan, "Modeling and Simulation of Electronic Differential System for an Electric Vehicle with Two-Motor-Wheel Drive," *Intelligent Vehicles Symposium*, 2009.
- [13] Kirkpatrick, L. and Francis, G. *Physics (ISE)*. 7th ed. Australia: Brooks/Cole, p.42. 2010.
- [14] Health and Safety Executive, "Health and Safety (Display Screen Equipment) Regulations", 1992