Minimizing Dynamic Loading Resonance of Battery Pack Subjected to Road Profile Loads

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Abstract. One of the main problems in designing battery packing for electric vehicles is the appearance of deformation in the components due to vibration generated by road profile. The vibration brings the most significant effect on the battery packing due to low frequency and high amplitude. Resonance occurs at low frequency since most of the E-trike components have a low natural frequency. This should be avoided to increase the reliability of the battery pack due to mechanical loadings. Modal analysis, Quarter Car Model (QCM), and optimization were conducted in this work. Modal analysis is used to find the natural frequencies of the battery pack on several modes of vibrations. Simulink of the Quarter Car Model (QCM) produces the load from the road profiles based on ISO 8608. The load from the road profiles is used as the input in the Ansys 16.0 Harmonic Analysis. The output is the deformation frequency response for the bottom side case of the battery pack. To reduce the outcome of resonance, a damping mechanism is selected to reduce maximum amplitude from road profile at a resonance frequency. The simulation results show that the damping mechanism is the suitable technology to decrease the major amplitude of the deformations from road profile with reduction up to 54% lower than the previous model. The lower deformations of the battery pack component reduce the battery pack’s possible accident due to vibration.

Keywords: Quarter car model, Battery packing, road profile loads

1. Introduction
The most challenging aspect of the battery pack design is to generate calculations around a new battery solution. There are a few simple calculations that can be made as a principal concept. Another thing is the design for the reliability and service of the battery pack. The safety and security of the battery pack should be the main concern from the design process. The design for reliability is a series of processes of failure mode effects (FMEA), test to failure (TTF), and accelerated life testing [1]. Correspondingly, quality and reliability are the clarification points to judge the battery pack's reliability level. For that reason, the engineers need to develop and design the battery pack that is influenced by the material, dimension, and function.

Some units can be viewed for the battery pack's reliability, which is related significantly to vibration, temperature, and pressure [2]. Vibration of the battery pack must be circumvented from the natural frequency of vehicle suspension system and sprung mass from 0 to 7 Hz, vehicle powertrain, the driveline, and the gearbox, from 7 to 20 Hz, and the vehicle chassis system from 20 to 40 Hz [3-4]. Lithium-ion batteries have to be utilized in safe and reliable operating conditions limited by temperature and voltage windows [3,5]. Battery temperature must be lower than 50°C [3]. Effective control and
management of a battery management system maintain restriction conditions [3]. Marginal deviations such as exothermic reactions in producing toxic and flammable gas that can lead to the explosion can be triggered by the excessive heat build-up and physical damage of the battery packs [2].

The industry pushes battery pack technology to enhance more modern features such as high energy density. The lithium-ion battery pack's advantage, such as high energy density, generates challenges that must be faced. The battery pack tends to be sensitive to extreme conditions such as high temperature, overcharge, and short-circuit. The battery pack's standard components are combustible, e.g., plastic packing, separator, and electrolyte [6-7]. The abusive conditions destroy the battery pack's stabilization, which triggers chain reactions inside the battery and leads to thermal runaway. Besides the danger of abusive conditions, limited research has been investigated toward the battery pack's safety, mainly focusing on the fire-retardant battery pack components [8].

When the battery pack is damaged in the accident, there is a potential of the battery thermal runaway, fire, and explosion [9-11]. The conditions and prevention of the thermal overheating and electrical overcharging of the batteries are explained in the literature [12-13]. The literature review is mostly the innovation of rigid objects placed into the battery cells, modules, and packs. US Patent 7614469 also provides hollow structural members for battery packing that absorbs undesirable vibrations. Battery pack's structure through positioning elevation to avoid battery pack damage by a rear impact is discussed in US Patent 7070015. About 288 Li-ion pouch cells of Chevrolet Volt battery pack for 70% of the battery mass and around 55% of the pack volume are in the T-shaped steel vertical tray [3]. The battery pack is stranded over the chassis center under the passenger seats.

However, correspondingly, very little research discusses the relations of road profiles loads with velocity. Moreover, narrow findings have been covered about dynamic loadings of road profiles in correlation with battery pack resonance. This paper is aimed to investigate the optimization of the battery pack to reduce the resonance load from road profiles within different velocities. Road profiles are generated from ISO 8608 standard for different road roughness. A simple dynamic system, the quarter car model, is used to describe the loads from road profiles. The natural frequency of the battery pack is examined by simplifying geometry and utilizing finite element analysis. The road profile loads show maximum amplitude at the natural frequency of the battery pack. To minimize this load, the paper illustrates an optimization by using a rubber bolt as a damping mechanism for the battery pack.

2. Methodology

2.1. Road Profiles

It is possible to construct an artificial road profile using an equation and assuming a random phase angle $\varphi$ with probabilistic distribution within the 0 until $2\pi$ range. The artificial profile $h(x)$ can be described as Equation (1):

$$h(x) = \sum_{i=0}^{N} \sqrt{2. \Delta n. Gd (i. \Delta n)} \cos(2\pi. i. \Delta n. x + \varphi).$$  \hspace{1cm} (1)

The Matlab program is developed to give the output of the chart by Equation (1). The equation has the variable of $L$, $N$, and $k$ that respectively are the length of the road simulation, the number of data points, and the value for ISO road classifications [14]. Equation (1) has the Fourier series function, and then the programs try to loop the function to store the data in variable $h(x)$ that is the road function over the length of the road. The spatial frequency in the range between $1/L$ and $N/L$ $m^{-1}$. Consequently, Equation (1) is programmed through Matlab R2018b of generating road profiles by assuming $L$ is 2,500 m, and the number of the data points is 50,000. The constant ISO classes $k$ of road profiles are determined to show roughness levels of road profiles. For each value of $k$, ranging from 3 to 9, road profiles are generated to see the different road roughness levels. This value represents the level of road surfaces causing high input force for different E-trike velocities, respectively, 40 km/h, 30 km/h, 20 km/h, and 10 km/h. Also, a graph of road displacements over time is made simultaneously in Simulink.
Matlab R2018b for different road classes and time-variable that depends directly on the E-trike velocities.

2.2. Loads from road profiles
The road profile generates the E-trike oscillation, which depends on the road surface's displacement level. This randomness of road profile is described from Matlab R2018b program with representing equation that describes the roughness of road profiles. The dynamic vibrational load is not constant in time, but it depends on several factors such as vehicle mass, speed, and road surface randomness. For analytical purposes, Quarter Car Model (QCM) is generated to study E-trike's dynamic response [15]. Correspondingly, Figure 1 shows the QCM Model of a vehicle with a base movement of the road profiles of \( h \) with \( k \) is the equivalent stiffness of the E-trike, \( m \) denotes the mass of the battery pack, and \( c \) is the equivalent damping coefficient of the E-trike. The assumptions regarding the body of the E-trike is rigid and does not have relative displacement with the road surfaces. The assumption that the variable \( z \) is more than \( h \) is used in the equation of motion, which is shown by the following equation:

\[
m \ddot{z} + c (\dot{z} - \dot{h}) + k (z - h) = 0
\]  

(2)

![Figure 1. Quarter car model of the battery pack](image)

2.3 E-trike
E-trike is a three-wheel vehicle to transport goods for medium ranges. The vehicle is suitable in Indonesia's traffic road since it has high mobility than the car and the truck. It is an electric vehicle that uses the electric motor as the driver. A battery pack is used to store the electrical power source. It consists of a connector, bracket, rubber, bolt, cell board, isolator, electric module, and 240 battery cells of Lithium Nickel Manganese Cobalt Oxide (NMC) battery (see Figure 2(a)). It is fixed by the bolt which is attached to the chassis. Battery Pack is mounted on the E-trike chassis below the driver, as shown in Figure 2(b). Two battery packs are used to drive SRM DC Electric Motor 5 kW and create the E-trike's maximum speed of 40 km/h [16].

![Figure 2. (a) E-trike' battery pack and (b) E-trike structure with the battery pack](image)
2.4 Modal Analysis and Harmonic Analysis of Existing Design

To get vibration response at a different location, harmonic analysis is set in the frequency range of 0 Hz until 100 Hz with the solution intervals of 200 segments. The output is the deformation graph at different locations, which are the bottom side. The vibration response does not work for all sides, but only one side that represents similar geometry. The setting in Ansys 16.0 starts with creating two sides as a fixed point and the other two as force excitations that are the load from road profiles. The reason is the usual possible movement, such as twisting from different existing edges. The force data is generated from Matlab R2018b Simulink, and the input of force in Ansys 16.0 is in the frequency domain. The harmonic analysis is specified into different E-trike velocities. It is possible to get the natural frequencies value from the graphs from the deformation frequency responses.

2.5 Optimization

The main issue in this paper is the resonance occurrences on the battery pack. The vibration load is produced by road profile displacements that excite force on the battery pack. The simplification of the battery pack is an important process for the analysis, and then the battery pack only remains the steel cases. The deformations of the battery pack cases may enhance the short circuit of the batteries due to the dynamic loadings from road profiles. To minimize the resonance damage, rubber bolts are simulated on the two small plates which is used to connect battery pack with the E-trike chassis in Figure 2(b). The small plates are located on the bottom side of the battery pack casing in Figure 2(a), where the load from road profiles occurs. The rubber bolt is meant to reduce the major amplitude of the deformation frequency responses from the load of road profiles.

3. Results and Discussion

3.1 Results of Modal Analysis

Modal analysis results are natural frequency values on several modes depending on the settings that the user picks. There are four boundary conditions as fixed support at the four small plates. The shape of first mode vibration can occur since the motion of the battery is mostly in the gravity directions; thus, the top side has the greatest deformations. The maximum deformation on mode vibration 1 is 20 mm from Figure 3(a) to the inside of the battery pack on the top side. The rear side's deformations maximum value is 9 mm, which also exceeds allowable deformations of the battery pack. The least value of the deformations is 1 mm, which should be the maximum number. This error in real applications can damage the batteries. Figure 3(b) shows the deformation of mode vibrations 2 with the maximum values of 21 mm. The battery pack on the rear side only accepts maximum deformation of 1 mm on normal conditions based on the spacing between the cage and the batteries. Figure 3(c) shows the deformation caused by mode vibration 3, in which the direction is to the inside of the battery pack. Nevertheless, the simulations still can be used as information of deformation directions and natural frequency values for different modes [4].
Figure 3. Several modes for different element sizes: (a) first mode; (b) second mode; (c) third mode

3.2 Road Profiles Graphs
Figure 4(a) shows road displacement from Matlab R2018b, which results from the ISO 8608 equation for 40 km/h. Also, Figure 4(b) illustrates road profiles for 30 km/h, and Figure 4(c) demonstrates road displacement for 20 km/h. Additionally, road displacement for the lowest velocity of 10 km/h is shown in Figure 4(d). The road class from the legend indicates lower limit from two consecutive road class. Equation (1) is used to generate road profiles over 2500 m length road over different velocities; 40 km/h, 30 km/h, 20 km/h, and 10 km/h [17]. The displacements are in meters for the four graphs below. Road class A-B has the least road displacements over time, meaning that it is the best quality road to give the E-trike the least force. Otherwise, road class G-H is the worst quality road since it has the displacements of 4 meters. Road profiles A-B has the averaged \( h = \pm 5 \) mm, which is the best quality road condition. Road class B-C displacements are in the average of \( h = \pm 10 \) mm. Also, road class C-D has the average value of \( h = \pm 15 \) mm, and road class D-E has averaged road displacements of \( h = \pm 300 \) mm. The results agree with other research in [14]. Road Class F-G and G-H have the worst road class conditions. Figure 4(a) shows road class G-H of 4 meters displacement at about 20 seconds. This road class is usually located in rural areas. From the four graphs, it can be concluded that E-trike may only be used in city areas that have a road roughness of not less than 15 mm. Therefore, road class A-B, road class B-C, and road class C-D are the only road classes generated further in the harmonic analysis.

Figure 4. Road profiles (m) versus time (s) for: (a) 40 km/h, (b) 30 km/h, (c) 20 km/h, and (d) 10 km/h.
3.3 Force versus frequency graphs

The force versus time data from Simulink Matlab R2018b is used as the input for the Fast Fourier Transform (FFT) process. The signal filter that is used in the process is the Yulewalk with the matrix \( M = \begin{bmatrix} 1 & 1 & 0 & 0 \end{bmatrix} \) and \( F = \begin{bmatrix} 0 & 0.2 & 0.2 & 1 \end{bmatrix} \) for the 8th order. The frequency range is picked 0 Hz until 100 Hz since the maximum amplitude occurs below 100 Hz. The sampling frequency is 1000 Hz because the sampling frequency needs to be twice or larger than the maximum frequency in the analysis. The signal from Simulink Matlab R2018b is transferred to the low-pass filter before it is used as the input in the FFT. Figure 5 is the result of the force versus frequency data for different velocities.

Load by road profiles in 40 km/h shows that the maximum amplitude is 383,000 N² at the 15.32 Hz and 43.84 Hz frequencies. This indicates possible resonance at these frequencies. The force amplitude is decreasing highly at 32.72 Hz, and 62.81 Hz. Other velocities, however, show the maximum amplitude at these frequency ranges. Road displacements of the highest velocity have the least time spacing due to the highest velocity. This might alter the amplitude in Figure 5, which is larger than the maximum amplitude from the force on lower velocities.

![Figure 5. Force versus frequency for different velocities](image)

3.4 Result of harmonic analysis

The frequency response graphs are used to find the resonance frequency of the battery pack under road profiles load. The reason is to choose optimized solutions regarding the value of natural frequency. The location of the peak amplitudes of deformation frequency response on every velocity in Figure 6(a) is at 10 Hz. The low-speed frequency response has the least value of maximum deformation within the range of 0 Hz until 100 Hz. Correspondingly, the deformation frequency response produces notable results of deformation under 20 Hz. By means that the frequency range of the battery pack under road profile loads only alters the natural frequency on the range of 0 Hz until 20 Hz. To validate the result, another harmonic analysis is generated to the normal stress frequency response of the bottom plate in Figure 6(b). The resonance frequency shows the same value of 10 Hz, meaning that 10 Hz is the valid natural frequency of the battery pack. The electric vehicle battery's natural frequency in urban driving response is at about 5 Hz [18]. The natural frequency of the dynamic load from road surfaces is about 10 Hz [18]. The natural frequency at all deformation frequency responses is at about 10 Hz, and the natural frequency value agrees with the results from previous research. However, the value of the maximum deformation is not rational, but it still gives a significant result of resonance frequency from the frequency response graphs.
3.5 Optimization by rubber bolts

The natural frequency results from modal analysis do not represent exact values. The different locations of boundary conditions alter the natural frequencies of the battery pack. These frequency locations can give excessive dynamic force to the battery pack due to the resonance phenomena. The E-trike motor driver is the SRM DC 5 kW motor, which has low maintenance costs [16]. The revolution speed of the motor shows the maximum values of 10,000 rpm. The motor is simulated between 2,000 rpm and 10,000 rpm, and the median value for 85% efficiency is about 2500 rpm. From this result, the critical frequencies from the motor speed are at 32.27 Hz, 41.67 Hz, and 166.67 Hz. By these values, the actions to minimize damage from the road profile loadings can be interpreted in two ways: shifting the natural frequencies higher than the motor’s critical frequencies and minimizing the peak amplitude from the resonance phenomena.

Since the natural frequency is at 10 Hz, it is chosen to minimize the peak amplitude by using a rubber bolt. The rubber bolt is mounted on the battery pack to see the difference result of peak amplitude. The bottom side becomes the reference side to the analysis because it has similar shapes with the opposite side. The deformation direction of the bottom plate is on the z-axis that is parallel to the displacement of the road profiles. The harmonic analysis is used with the road profile loads by 10 km/h velocity. The reason is the data for four speeds represent similar graphs, and only one of the data should be analyzed as a source to show the optimized design result, which is 10 km/h. The optimized design by mounting rubber bolts, which the vibration characteristics are found in [19], on the connecting plates reduces the maximum amplitude of road profiles load. The damping coefficient of soft, medium, and hard rubber are respectively 103 Ns/m, 125 Ns/m, and 150 Ns/m [19]. The battery pack is simulated with The critical frequencies of the harmonic analysis without the damping mechanism are at 10 Hz. Figure 7 is the deformation frequency response for the soft, medium, and hard rubber damping mechanisms for 10 km/h. The natural frequency after mounting the rubber bolt is still at about 10 Hz. The maximum amplitude on the bottom side with soft rubber fastenings is reduced to 26.975 mm, which is 8% lower than the undamped battery pack. The natural frequency from medium rubber fastenings is at about 10 Hz. The peak amplitude on the bottom side is reduced to 19.47 mm, which is about 33% lower than the previous results. Similarly, the natural frequency from hard rubber is at about 10 Hz. The peak amplitude on the bottom side is reduced to 16.414 mm, which is about 45% lower than the previous results. It is proved that rubber acts to reduce the peak amplitude; following that, the hard rubber is the perfect type for reducing considerable maximum amplitude.

![Figure 6](image-url)
Figure 7. Rubber bolts assembling on the small plates of the battery pack for 10 km/h.

4. Conclusion
Road profiles are generated from the Equation (1) into road displacements to show the level of roughness for different class roads. Because E-trike is only used on the city roads, road class A-B, road class B-C, and road class C-D are used in the analysis. The results show that the displacement of the road profiles generates deformations to the battery pack as harmonic loadings from the QCM to show the loads from road profiles. Moreover, it is found that the E-trike accepts more load for greater velocities, and the frequency for each amplitude is also greater than fewer velocities. The harmonic analysis is generated to exhibit the resonance frequency from the battery pack that is given the road profiles in terms of twisting movement. The result shows that the original battery pack model shows the resonance frequency at 10 Hz. The maximum amplitude of deformation increases correspondingly with the expanding velocities. To minimize the resonance occurrence, the battery pack’s proposed design consists of rubber fastenings attached to the bolt. The major amplitude of loads is decreased due to the vibration isolations. Rubber only acts as vibration isolation, which absorbs energy from road profile loads by internal frictions. The remaining energy is still transferred to the battery pack, which creates 55% of the original model's deformations. The simulation result is based on general calculations from the QCM model to harmonic analysis in FEM. Several assumptions are made to simplify the research. An experimental study should be examined further to get the accurate results of using rubber bolts to minimize resonance occurrences.

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