Dynamics investigation on motorcycle chassis based on Finite Element (FE) modelling and updating

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Abstract. Motorcycles built from multiple materials such as steel and aluminium that formed a welded of beams to construct the chassis. The frame is designed by combining the part-by-part saddle, handlebar and wheel that are attached together. In this study, the identification of structural dynamics study for motorcycle chassis was conducted to identify modal properties such as natural frequencies and mode shapes. This could be achieved by using two different analysis approaches; Finite Element Analysis (FEA) and Experimental Modal Analysis (EMA). For FEA analysis, 3D modeling of the chassis frame is needed and modelled using CAD software. Normal mode analysis was run on modelled structure to determine modal properties after meshing type and properties of materials declared. Impact hammer testing using roving accelerometer method was conducted for EMA study and comparison of modal properties with FEA is carried out. Discrepancies that appeared after correlation among two approaches attempted to be reduced by performing model updating procedure and it was successfully reduced the average percentage of error to be less than 10%. The results show that the model updating was an effective technique for improving the discrepancy that may exist due to modelling issue and material properties prediction in FEA. This study clearly shows that model updating technique is an effective way of reducing the discrepancies between EMA and FEA.

1. Introduction

Transportation is one of the most important things for human kind. For thousands of years ago, animals such as horse, camel, and others have been used as the transportation for war, trade, cultural development and sport. Throughout the time, this field has gone through a lot of improvement for the design; comfort ability, the structure and the capability for human satisfaction based on their need and safety as well as reduce the environmental pollution. Without transportation, the knowledge would not spread all over the world, technologies would never be able to develop, people do not have enough supply for goods and resources, and the economy would never be developed to the current state. The dynamics of the single-track vehicles is affected by the stiffness of the structural element, because the influences on the stability of this type of vehicle that is weaving and wobbles. There are no specific methods of measuring the critical stiffness of the chassis, front fork or the swing arm. There would be a different for the
stiffness characteristics measured in static and dynamic condition and the construction of the chassis frame is highly related to high rigidity and accessibility for loading and unloading of an engine. The higher rigidity of the frame can be achieved when it is made from steel pipes compared to steel plates. Motorcycle chassis frame has a similarity in function with human skeleton. The chassis hold together the different parts rigidly. That is the most basic function. A motorcycle with a well-designed frame can make the rider more enthusiasm during the ride. The motorcycle would feel more stable, effortless, and confident riding around corners, in straight line and during braking. The approved modelling techniques or guidelines principle have to be followed for designing chassis for the minimum vibration and have it within control [14]. Since the chassis frame acts as a backbone for a vehicle, a characteristic of a potent rigidity is a must in order to withstand stress in case of crash and absorb vibration. The vibration occurred due to the dynamic excitation which may cause when the dynamic forces induced by the power unit, transmission, the condition of the terrain and many more. If there is any excitation frequencies concurred with the natural frequencies of the chassis, it can lead to the resonance phenomenon [12]. It would be a disaster for a chassis frame which experience the resonance phenomenon. The chassis would undergo unfortunately large oscillation which may cause an excessive deflection and failure. Besides, the effects from the vibration could increase the stress concentration, fatigue of the structure, loosening of the mechanical joints and create some noise and vehicle discomfort. So, due the awareness of the severity of those accident that might be happened, the structure dynamics of the motorcycle chassis frame would be identify through two different methods; FEA and EMA. From both methods, the natural frequency and mode shape of the chassis frame would be identified. Then, all the data can be take into optimization during constructing others part or satisfy the surrounding condition on which the final product would be used [8].

For determining the dynamic properties of the chassis frame, EMA is one of the techniques suggested and well known as a classic approach [18]. In this study, impact hammer testing is selected for EMA study. The dynamic response is determined and analysed using post processing software and the accelerometer is needed to read the excitation from input source; impact hammer. EMA is considered as extremely important in verification of analytical models, identification of vibration and structural modification and sensitivity analysis. Presently, the involvement of EMA can be grouped in four categories; forced normal mode excitation method, frequency response function method, damped complex exponential function method, and mathematical input-output model methods [15]-[16]. In some software such as ME’ scope, the computed FRF can be extracted using a special process called curve-fitting method. From this method, a set of modal parameters, which are the natural frequencies, damping and residues, for each of the defined point can be obtained [1]. In other research, curve-fitting process seems to be as a process of matching the mathematical expression to the set of empirical data points. It happened when the squared error between the analytical function and the measured data is being minimized.

FEA is one of the techniques that has been developed for numerical modelling. Problem in structural design, construction, maintenance of mechanical systems and civil engineering structures are not a new issue in modelling the structure to conduct FEA [9] [11] [14]. FEA is also known because of the effectiveness and the easiness since it can be implemented by only using single computer [18]. The determination of natural frequency is the essential properties that are very helpful to avoid resonance on a structure [4]. Modelling the structure is very important step for FEA. However, to modelling an exact structure is quite impossible to achieve due to the inability to model the structure perfectly including the joining, irregular shapes and angle parts. Most of the commercial finite elements solvers have elemental coordinate systems used in defining the material orientations. The application of local element coordinate is so effective but it slightly difficult to define material orientation when comes to 3D meshes because it requires very accurate control of meshing procedure [18]. Even FEA method is being considered to be reliable tools in engineering design and product development [3]. EMA method is still be needed in order to determine the reliability of the gathered data because of the accuracy due to complex and large structure is still inaccurate [1].
Model updating used for correcting finite element input parameters by improving the material input properties such as Young Modulus, density and Poisson ratio to be closer to the real structure tested by EMA [2]. This is one of the reasons why the model updating is considered as an important process in reducing the existed discrepancies [13]. The difference in the results among the FEA and EMA can be happened due to the inappropriate selection of element material and geometrical properties. Thus, because of those error, they can affect the dynamic properties of the 3D modelled structure and bring discrepancies to actual model [3]. In this process, the finite element model would be adjusted through the alteration of dynamics response data from the test structure and updating the structure of the finite element in order to assume more accurate structure of dynamics [15] [3]. Before model updating process can be done, a sensitivity analysis is needed in order to ensure the sensitiveness of parameters which give significant effects on modal parameters when it experienced changes. The parameters that have the huge difference with the actual value would be optimize. The evidence from this study testifies that model updating technique would help to establish a greater degree of accuracy on this matter. If the investigation is to be moved forward, more information on model updating technique and parameterization should be a better understanding needs to be developed. For further study, it is very recommended to include the welded joint in modelling the structure. Then, during the process of model updating, the joint element and the joint properties can be included as the updating parameters. As result, the updated FEA can be more accurate and reliable.

2. Finite Element Analysis (FEA)
Numerical prediction is becoming method that is more popular currently in structural analysis and well known as finite element analysis (FEA) that using computational iteration to analyse the model structure numerically to find out modal properties.

2.1 Preliminary FE modeling
The FE model of motorcycles structure is imported to MSC Nastran/Patran with geometry input. The constructed finite element model a viewed in graphic interface of MSC Nastran/Patran. The FE structure is meshed using shell element as portrayed in Figure 1 and consists of 43636 numbers of elements with 85481 numbers of nodes. The completed FE model is declared with respective material type and input properties as summarized in Table 1.

| Table 1. Material properties of stainless steel (SUB304). |
|-----------------|-----------|
| Parameter       | Value     |
| Young Modulus (E) | 200 GPa   |
| Poisson’s Ratio (ν) | 0.29      |
| Density (ρ)    | 7900 kg/m³ |
| Thickness (t)  | 0.002     |

Figure 1. Meshing structure in FEA.
2.2 **Execution of FEA**

Normal mode analysis is carried out using MSC. Nastran to determine the dynamic behavior of tested structure. The analysis simulate free-free boundary condition with no load or translational and rotational boundary conditions applied to any nodes on the structure [8]. Modal properties obtained from the FEA have been tabulated in Table 2 for natural frequencies and mode shapes for each mode of interests.

| Mode | Natural Frequency (Hz) | Mode Shape |
|------|------------------------|------------|
| 1    | 241.15                 | ![Mode Shape 1](image1.png) |
| 2    | 264.76                 | ![Mode Shape 2](image2.png) |
| 3    | 380.40                 | ![Mode Shape 3](image3.png) |
| 4    | 397.66                 | ![Mode Shape 4](image4.png) |
| 5    | 517.43                 | ![Mode Shape 5](image5.png) |
3. Experimental Modal Analysis (EMA)

Experimental Modal Analysis (EMA) or modal testing explains the details of method use on this paper to investigate the dynamic properties of the motorcycle chassis structure. EMA is an approach to find the modal parameter of specified structure either through impact hammer testing, shaker testing or operational modal analysis. In this study, focus is given to impact hammer test which claimed to be simpler and easier. Before conducting the impact hammer testing, a wireframe model of motorcycle chassis structure was created by using post-processing software. The model consists of lines and points which virtually represent the geometric shape of the motorcycle chassis structure as depicted Figure 2. In order to perform the impact hammer test, the structure of motorcycle chassis structure is hanged from a test rig by using elastic rope in order to put the structure under free-free boundary condition as demonstrated in Figure 3. The measurements were made using modal analysis software and several other equipment such as PCB 086D20 impact hammer with medium soft tip attached, 4-channel NI DAQ device, and a tri-axial PCB accelerometer as depicted in Figure 4. Roving accelerometer method was adopted for the testing procedure, where one excitation point and 31 measurement points was assigned on the motorcycle chassis structure. Roving accelerometer test was done by creating initial disturbance on the motorcycle of structure at one fixed position while tri-axial accelerometer was roved straight other measurement points. The vibrational response was measured by using 4-channel NI DAQ device. The modal analysis software analytical data as shown in Figure 5 used to extract the modal properties of the motorcycle of structure from the computed FRFs. Table 3 tabulated the result obtained from EMA for the natural frequency and mode shape.

![Figure 2. Motorcycle chassis structure](image1)

![Figure 3. Hanging motorcycle structure s under free-free boundary conditions.](image2)
Figure 4. Equipment’s for EMA.  
Figure 5. ME’s Scope software for modal testing analysis.

Table 3. Natural frequencies and mode shapes formed by EMA for motorcycle structure.

| Mode | Natural Frequency, Hz | Mode Shape |
|------|------------------------|------------|
| 1    | 246                    | ![Mode 1](image1) |
| 2    | 288                    | ![Mode 2](image2) |
| 3    | 383                    | ![Mode 3](image3) |
| 4    | 390                    | ![Mode 4](image4) |
4. Comparison between FEA and EMA
After done with collecting the results from both, EMA and FEA, the differences would be determined in order to know about the discrepancies among the data obtained from both methods. Table 4 shows the tabulated data for the comparison of natural frequencies results FEA and EMA. The percentage of error has been calculated by using Equation 1.0.

\[
\text{%Error} = \left( \frac{f_{\text{Experimental}} - f_{\text{Theoretical}}}{f_{\text{Theoretical}}} \right) \times 100
\]

Then, the total average error would be calculated in order to proof that does the result of EMA obtained using more accelerometer would be better compared to a single accelerometer.

| Mode | Natural Frequency, Hz | Percentage of Error, % |
|------|------------------------|------------------------|
|      | FEA                    | EMA                    |                        |
| 1    | 241.15                 | 246.00                 | 1.97                   |
| 2    | 364.76                 | 288.00                 | 8.07                   |
| 3    | 380.40                 | 383.00                 | 0.68                   |
| 4    | 397.66                 | 390.00                 | 1.96                   |
| 5    | 517.43                 | 516.00                 | 0.28                   |
|      | Average Percentage of Error | 2.59                  |

5. Model updating
Even though the percentage of error is 10% less, model updating of the FEA results is still being carried out because it could be a big help in during the analysis, either imperfection in experimental setup or modelling the chassis frame. So, in this paper, the FEA natural frequency would updated by referring EMA as a benchmark. However, before proceeding into model updating, a sensitivity analysis should be done first. From this analysis, the most sensitive parameters among Young’s Modulus, $E$, density, $p$ and Poisson Ratio, $\nu$ which mostly would affect the updated FEA could be discoverable. Table 5 depicted 4 mode of interest that has been selected, with three possible parameters. Rule of updating is that to have the number of parameters less than the number of modes to avoid any problem of accuracy during updating.
Table 5. Sensitivity analysis of 3 parameters for 4 modes

| Output Type | Young’s Modulus, E | Density, ρ | Poisson Ratio, ν |
|-------------|--------------------|------------|-----------------|
| NF 1        | 120.97             | -123.41    | -10.88          |
| NF 2        | 132.51             | -135.19    | -3.119          |
| NF 3        | 190.24             | -194.08    | -0.132          |
| NF 4        | 198.95             | -202.97    | -2.341          |

Referring to the previous table, it can be seen that all the three parameters show the significant value which means that they are sensitive for model updating work. Hence, the model is being updated using three parameters; Young’s Modulus, E, density, ρ and Poisson ratio, ν. Result of updating can be seen in Table 6.

Table 6. Updating result for 4 mode shapes using 3 model updating parameters

| Mode | Natural Frequency, Hz | Initial Percentage of Error, % | Updated FEA, Hz | Updated Percentage of Error, % |
|------|-----------------------|--------------------------------|-----------------|--------------------------------|
| 1    | 246.00                | 1.97                           | 244.32          | 0.94                           |
| 2    | 288.00                | 8.07                           | 267.62          | 7.14                           |
| 3    | 383.00                | 0.68                           | 384.22          | 0.32                           |
| 4    | 390.00                | 1.96                           | 401.81          | 2.99                           |

Average Percentage of Error 3.17 2.78

Based on table above, the updating process is conducted by using 4 mode of interest and the error value decreased by 0.39%. The model updating process has been done for several times in between the minimum and maximum boundary limit of updating parameters’ value until the value of natural frequencies converged. After updating is completed, the optimum value of Young’s Modulus, density, and Poisson ratio was tabulated in Table 7.

Table 7. Changes of updating parameters

| Parameter                   | Parameter’s Value | Deviation, % |
|-----------------------------|-------------------|--------------|
| Modulus of Elasticity, E    | 200 GPa           | 1.00         |
| Density, ρ                  | 7900 kg/m³        | 1.00         |
| Poisson Ratio, µ            | 0.29              | 6.90         |

6. Conclusion
This study set out in order to perform modal based on motorcycle chassis to minimize the discrepancies between the EMA and FEA. The findings suggest that optimization of the selected parameter able to revise the modal data of the FE model. Simultaneously, the contrarieties in the experiment data and finite element data are successfully reduced. Results from FEA and EMA were than being compared
and the total percentage of error was being calculated. Then the updating process was performed in order to reduce the error, so the natural frequency of FEA could be improved based on updating. After updating work is conducted, the error value decreased by 0.39%. Three parameters which is confirmed to be sensitive are Young’s Modulus (E), density (ρ), and Poisson’s Ratio (ν). The evidence from this study testifies that model updating technique would help us to establish a greater degree of accuracy on this matter. If the investigation is to be moved forward, more information on model updating technique and parameterization should be a better understanding needs to be developed. For further study, it is very recommended to include the welded joint in modelling the structure. Then, during the process of model updating, the joint element and the joint properties can be included as the updating parameters. As result, the updated FEA can be more accurate and reliable.

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