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Dynamic Study of Bicycle Frame Structure

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Abstract. Bicycle frames have to bear variety of loads and it is needed to ensure the frame can withstand dynamic loads to move. This paper focusing on dynamic study for bicycle frame structure with a purpose to avoid the problem regarding loads on the structure and to ensure the structure is safe when multiple loads are applied on it. The main objectives of dynamic study are to find the modal properties using two method; finite element analysis (FEA) and experimental modal analysis (EMA). The correlation between two studies will be obtained using percentage error. Firstly, 3D model of mountain bike frame structure has been draw using computer-aided design (CAD) software and normal mode analysis using MSC Nastran Patran was executed for numerical method meanwhile modal testing using impact hammer was performed for experimental counterpart. From the correlation result, it show that percentage error between FEA and EMA were below 10% due to noise, imperfect experiment setup during perform EMA and imperfect modeling of mountain bike frame structure in CAD software. Small percentage error differences makes both of the method can be applied to obtain the dynamic characteristic of structure. It is essential to determine whether the structure is safe or not. In conclusion, model updating method is required to reduce more percentage error between two results.

1.0 Introduction

A bicycle is a light structure that has to support a much heavier weight which is the cyclist [1]. There are few consideration need to be taken in the process of making bicycle frame which are support loads of cyclist, surrounding wind and friction. A major concern in analysing practical mechanical structures is to reliably identify their dynamic characteristics, i.e., their natural frequencies and vibration mode shapes. These vibration characteristics are needed in order to achieve effective design and control of the vibrations of structural components [2]. While designing any mechanical system or structure, it is important to do structural design and analysis, since it can predict the mode shapes and the natural frequencies to the expected excitation. It is necessary to know the natural frequency of the structure to model the construction that will not be excited between these frequencies band, if the structure is excited at one of this frequencies, the resonance will occur [3]. Looking into technical view, the weight, stiffness and comfort of a bike are three crucial criteria that still drive most new developments.

Steel, titanium and aluminium are materials that commonly used in the industry but carbon fibre turned to be the most popular material chosen for frames and for almost all bike components [1]. Dynamic study seems necessary to ensure the ability of bicycle frame to endure multiple loads. The components and the frame are subjected to time-varying force excitations dictated by the cyclist and by the road. Frame of bicycle is the substantial component of any type of bicycle, to which the saddle, handlebar and wheels are all attached together. Over the course of improvement of the bicycle, frame has been widely invented with various designs and made from miscellaneous types of materials. Good construction of geometric design result in a durable frame while deducting the cost of materials required, lessened the weight and deducted the usage of material [4]. The light weight of bicycle frame will contribute in minimizing the energy consumption up hills or during acceleration. There are three measurements for bicycle frame geometry, which is head tube angle, fork trail and fork rake which become as the backbone and involved in order to assure the strength of the dynamic structure of bicycle frame.

For this paper, theoretical approach applied the method of Finite Element Analysis (FEA) by acquiring data of natural frequencies and mode shape with a purpose to rectify the dynamic structure of bicycle. FEA involved the usage of CAD Simulation to draw the frame following mountain bike measurement with aluminium material as shown in Figure 1. It is software that enables the adoption of finite element analysis FEA besides authorize user to analyse the structural properties like stress, displacement, and natural frequency [5]. In this paper, modal properties are identified using both methods which are finite element analysis (FEA) and experimental modal analysis (EMA). FE model will undergo normal mode analysis in order to choose the most reliable model. From the result obtained, model updating will be carried out to improve correlation between experiment and numerical counterparts.

Figure 1. CAD of bicycle frame

2.0 Finite Element Analysis (FEA)

FEA is one of the numerical solutions and significant in introductory treatments. In case of structural failure like a wrinkling, FEA may be used to help fix the design modifications to meet the new condition and optimize the parameters [6]. In MSC Patran was used to design finite element model of the structure and MSC Nastran which is post processing solver utilized for vibration analysis. In this project, FEA is study in terms of normal modes analysis for bicycle frame structure, with material properties as tabulated in Table 1 and the result is displayed in Figure 2 below.

Table 1. Properties material of Aluminium

DATA	VALUE
Material	Aluminium
Density	2700 kg/m^3
Poisson's ratio	0.34
Modulus Elasticity	68.3 GPa

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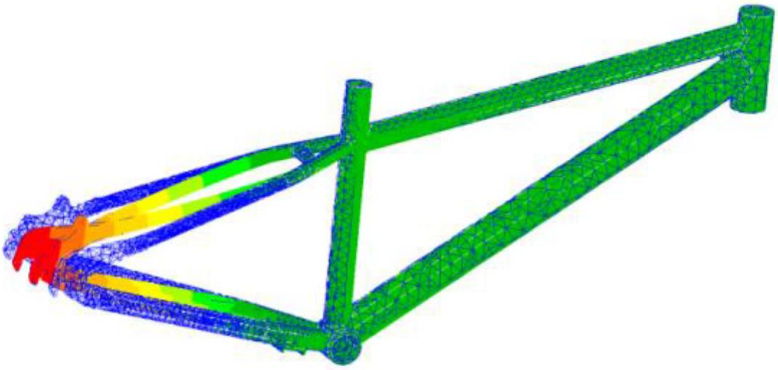


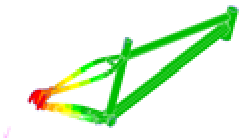
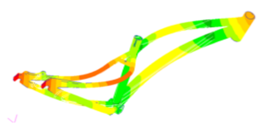
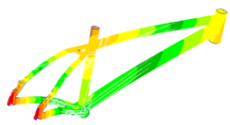
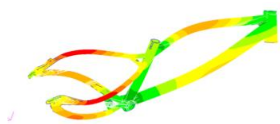
Figure 2. Modeling of structure in FEA

Two modal properties are obtained which are natural frequency and mode shape. The normal mode analysis module allows computing normal modes of an input atomic or EM structure as well as an interactive visualization of the computed modes by animating displacement of the structure along the modes. Besides, the evaluation of the natural frequencies and the corresponding mode shapes plays a crucial role in vibration analysis since it provides a great deal of information concerning the dynamic characteristics of a system. Natural frequency results that have been gain from the FEA that has been run using MSC Nastran/Patran as is displayed in Table 2 below. Meanwhile Table 3 presents the result for mode shape in which mode 1 and 2 experienced bending, mode 3 faced torsional 1, mode 4 undergone torsional 2 and for mode 5, the condition is torsional and bending.

Table 2. Result of natural frequency for FEA

MODE	NATURAL FREQUENCY (Hz)
1	82.71
2	106.2
3	258.46
4	291.01
5	312.48

Table 3. Result of mode shape for FEA

MODE	MODE SHAPE	MODE	MODE SHAPE
1		4	
2		5	
3			

3.0 Experimental Modal Analysis (EMA)

Modal testing is carried on in order to do vibration testing regarding natural frequency, mode shape and damping ratio which can be described as EMA. This testing consists of two phases which is experimental and numerical with purpose to complete the modal analysis process [7]. Impact hammer testing is applied as the system was provided with energy, parameters were evaluated by fitting the curve in the transfer function and there is multiple ways to predict the modal parameter indeed. This test has a function to covert time history signals collected from impact hammer and accelerometers sensor into frequency spectra the Fourier transformation was used. The ration of Fourier transformed output and input signals were obtained using Frequency Response Functions (FRF) [8]. Figure 3 below shows the example of impact hammer test for EMA.

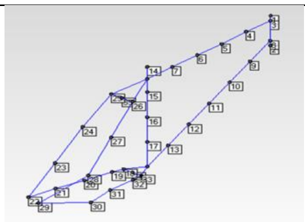
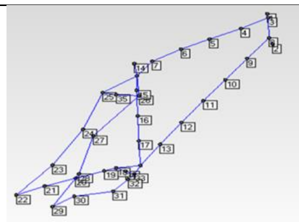
Figure 3. Impact test for EMA

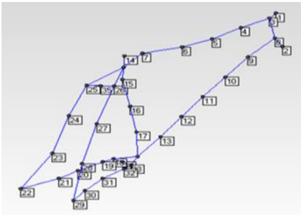
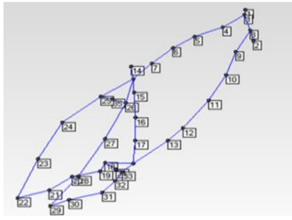
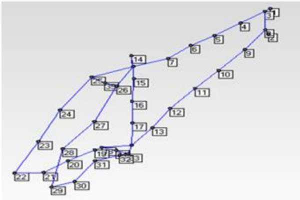
ME'scopeVES software is needed for modal testing in which this software can be utilized to examine and figure out noise & vibration complications in machinery and structures using either experimental or analytical data. The values for natural frequency and mode shape were obtained as shown in Table 4 and Table 5 respectively using curve fitting method where the values were taken based on the nearest value to the FEA obtained previously. Result acquired from EMA was performed using roving accelerometer method whereas the accelerometer will change according to the node point that has been set on frame structure.

Table 4. Result of natural frequency from EMA

MODE	NATURAL FREQUENCY (Hz)
1	76.4
2	107
3	287
4	300
5	323

Table 5. Result of mode shape from EMA

MODE	MODE SHAPE	MODE	MODE SHAPE
1		4	

2		5	
3			

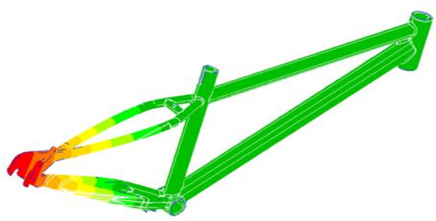
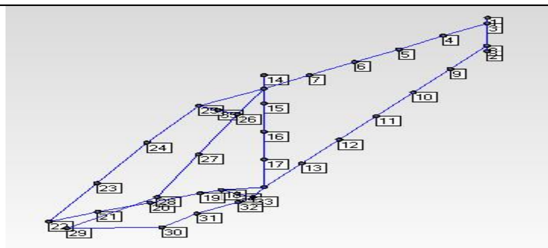
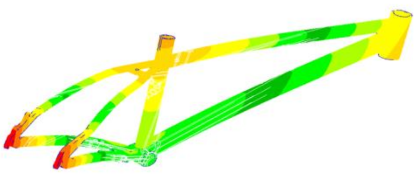
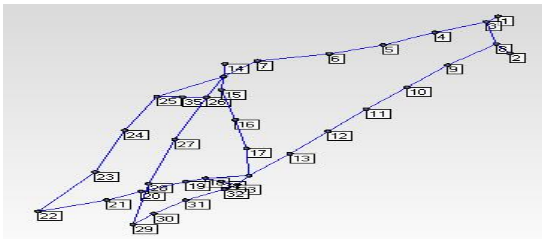
4.0 Comparison between FEA and EMA

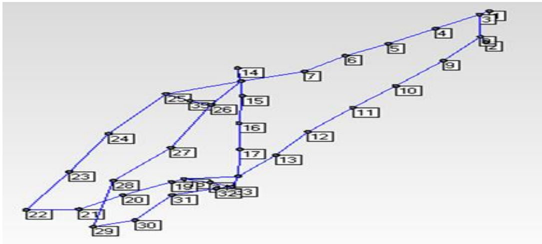
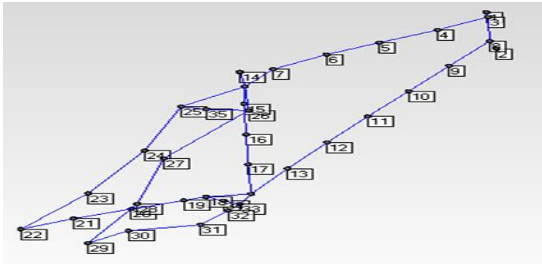
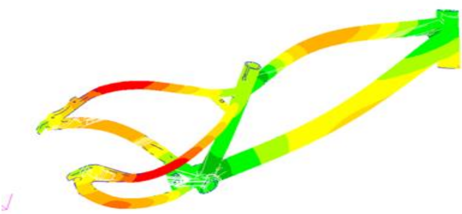
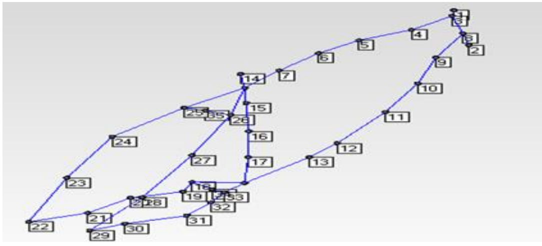
As both method undergone different methods for obtaining result, there were errors existed. The result of percentage error displayed for all 5 modes between FEA and EMA was tabulated in the Table 6 and comparison of mode shape for both analysis is displayed in Table 7 below.

Table 6. Percentage errors of natural frequencies between EMA and FEA for each mode

MODE	NATURAL FREQUENCY (Hz)		ERROR (%)
	EMA	FEA	
1	76.4	82.71	8.26
2	107	106.2	0.75
3	287	258.46	9.94
4	300	291.01	3.00
5	323	312.48	3.26

Table 7. Comparison of Mode Shapes between FEA and EMA

MODE	MODE SHAPES	
	FEA	EMA
1		
2		

3		
4		
5		

Correlation is a process to evaluate how close the FE model resembles the reality or in other words, how good the FE model agrees with the experimental model [9, 10]. It is a good agreement when the discrepancies is small [11]. From this experiment, percentage of error showing a good result between EMA and FEA as the error in this experiment is below than 10%, and the discrepancies is small due to few factors such as noise, imperfect experiment setup during perform EMA and imperfect modelling of mountain bike frame structure in CAD software. Noise due to knocking process during EMA is possible to delay until the structure is fully stop and no more vibration left before proceed to the next knocking process since small vibration on the frame structure is invisible. This also took longer time to complete the process of knocking in order to finish all the 33 node points on the mountain bike frame structure. Hence, the number of node point should be increase in order to get more accurate mode shapes. However, for better correlation between these two analysis, modal updating is needed to take in action.

Imperfect experiment setup while performing EMA also affected the results of natural frequency and mode shapes. Among the imperfectness is when the accelerometer is not correctly placed on frame, the position of frame mountain bike not stable when hanging and other part of mountain bike that cannot be removed. Besides, it is quite complicated to get an exact modelling of mountain bike frame structure in CAD software due to a little problem while carry on measurement of actual mountain bike frame since unavailability of special tool to do measuring.

5.0 Model Updating

The ambiguity in the results among the Finite Element Analysis (FEA) and the Experimental Modal Analysis (EMA) is due to the expectations made in defining inappropriate element material property and geometrical property [12]. Model updating is focused with the adjustment of finite element models by altering data of dynamic response from test structures and updating a finite element model of a structure so that it can assume more accurate dynamics of a structure [13,14]. The main objective of model updating is to decreases the imprecision in the finite element model and blunders in expected results acquired from inaccurate modelling of the boundary conditions and damping, for example [15]. In model updating, the selection of updating parameter is the most important task. There are two methods of model updating which are direct method and sensitivity method [16]. Model updating will be acted as an optimization method and is being presented using the structural optimization capability [17].

In order to decrease the problems in FEA, model updating is conducted to the data of finite element by applying the first-order optimization method. The optimization algorithm in MSC, NASTRAN (SOL200) is utilized in this study. The main goal function for the prediction error can be formulated as

$$\boldsymbol{g}\ (\boldsymbol{x}) = \sum_{i=1}^{n} \boldsymbol{W}\ \left(\frac{w_i^e}{w_i^a} - \mathbf{1}\right)^{\mathbf{2}} \tag{1}$$

where $\boldsymbol{w_i^e}$ and $\boldsymbol{w_i^a}$ are the experimental and computational natural frequencies respectively, with $\boldsymbol{W}$ as the real positive weighing factor. The prediction of the modal data is bestowed for detraction in the updating operation. The operation prolongs until convergence is achieved, where the contrariness between values of *g(x)* from the following iteration is adequately small [10]. Three crucial parameters are chosen for updating which are Young Modulus (E), Poisson Ratio (ν), and density (ρ). The original value for Young Modulus, Poisson Ratio and density are 68.3 GPa, 0.34 and 2.7 kg/m^3 respectively. For updating, upper and lower bound values for Young Modulus are 64.9 GPa to 71.7 GPa. Otherwise, for Poisson Ratio, the values are 0.306 to 0.374. Meanwhile for density, 2.43 kg/m^3 to 2.97 kg/m^3. Result of model updating can be seen as in Table 8 below.

Table 8: Comparison of natural frequency between initial result and updated result

Mode	EMA Frequency (Hz)	Initial FEA Result		Model updating FE Result	
		Frequency (Hz)	Error (%)	Frequency (Hz)	Error (%)
1	76.4	82.71	8.26	83.85	9,75
2	107	106.20	0.75	107.67	0.63
3	287	258.46	9.94	262.86	8.41
4	300	291.01	3.00	294.99	1.67
5	323	312.48	3.26	316.6	1.98
	Total Error		25.20		22.44

As shown in Table 8 above, it is clear that the initial value of FE result and model updating result for natural frequency show dissimilarities. Percentage of errors shows diminishing result. As the summary, updating result succeed by deducting the value of errors compared to the initial result.

6.0 Conclusion

As the conclusion, problems of every close modes frequently arise in engineering practice due to structure symmetries with little damping and the accurate determination of the modal parameters. It is suggested to make sure removed all the part at bicycle frame using appropriate tool and use a correct tool to measure actual dimension of bicycle frame. This is because; dimension plays an important role to modelling an accurate bicycle frame. The percentage differences between finite element analysis (FEA) and experimental modal analysis (EMA) are below 10%. Natural frequency acquired from

EMA and FEA shows small percentage error differences makes both of the method can be applied to obtain the dynamic characteristic of structure. After updating results, the total errors between FEA and EMA are lessened and objective of model updating is achieved.

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