Dynamic-characteristic analysis and improvement of 125 motorcycle body structure

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Abstract. In order to improve the vibration of a 125 Motorcycle, the structural dynamic characteristics of its body were analyzed. The results showed that the first six order natural frequencies were relatively low and large deformation exists on the rear. In combination with the analysis results, the influence of road irregularity and engine excitation on the vibration of the 125 motorcycle body was discussed. It was found that the first order reciprocating inertial force excitation of the engine goes in the same direction and has frequency coupling with the first order vertical bending, which was likely to cause the resonance of the car body. Based on the vibration pattern analysis of the car body, the improvement scheme of increasing the wall thickness of the supporting pipe as well as thickening the rear reinforcement pipe was put forward. The structural dynamic characteristics of the modified body were analyzed using analytical methods. The result demonstrated that the vertical bending frequency greatly increased, keeping away from the excitation frequency of the first order reciprocating inertial force of the engine, on the other hand, the vibration mode of the rear part was also improved. The effectiveness of the improvement plan was also validated by prototype test drive.

Keywords: Motorcycle, vibration, dynamic characteristics, simulation analysis, improvement.

1. Preface
The structural dynamic characteristics of motorcycle frame have a significant impact on its vibration [1-3]. Motorcycle frame is mainly welded steel pipe. The engine, usually connected with the motorcycle frame through bolts, is much heavier than the frame.

After installation of the engine, the dynamic characteristics of the frame will change greatly [4-5]. Therefore, the structural dynamic characteristics of the car body are of more reference significance to the analysis of motorcycle vibration.

To explore the possibilities for solutions to the over-vibration phenomena appearing in the 125 motorcycle, analytical and experimental methods were adopted to analyze the structural dynamic characteristics of its body. In combination with the analysis results, the influence of road irregularity and engine excitation on the vibration of the 125 motorcycle body was discussed. It was found that the first order reciprocating inertial force excitation of the engine may cause the resonance of the car body. Based on the vibration pattern analysis of the car body, the improvement scheme of increasing the wall
thickness of the supporting pipe as well as thickening the rear reinforcement pipe was put forward. The structural dynamic characteristics of the modified body were analyzed using analytical methods. The result demonstrates that the first six order natural frequency generally increased with improved vibration mode. The effectiveness of the improvement plan was also validated by prototype test drive. The test drive of the modified prototype also proves that the improved scheme is feasible and easy to implement.

2. Dynamic characteristic analysis of car body
The dynamic characteristic analysis of car body is actually the process of solving modal parameters, which could be achieved through analytical and experimental methods.

By determining the geometric shape, boundary conditions and material properties of the structure, the analytical method can present the mass distribution, stiffness distribution and damping distribution of the structure by means of mass matrix, stiffness matrix and damping matrix respectively, so as to obtain the structural dynamic characteristic parameters of the system.

The experimental method is to calculate the frequency response matrix by measuring the dynamic input force and output response of several points and then the modal parameters could be further estimated according to the frequency response function.

The analytical method can be carried out early in the design stage, while the accuracy and reliability need to be verified by experimental method. At the same time, the analytical method can provide guidance and help for the experimental method, mutually complementing and reinforcing each other.

2.1. Analytical method
Finite element method is indispensable during the analysis of dynamic characteristics when adopting the analytical method. At present, the finite element displacement method, which takes the node displacement as the basic unknown quantity, is most widely used. Starting with the structure discretization as well as the analysis on the unit, then find out the stress, strain and displacement of nodes and the relationship between the unit force and node displacement to establish stiffness matrix of each unit for overall analysis of the structure, which is namely the total stiffness equation [6]. The required information can be obtained by solving the total stiffness equation with a computer.

According to the two-dimensional design drawings provided by the manufacturer, the geometric model of the frame was established with UG4.0. The finite element model of the frame is supposed to not only reflect the mechanical characteristics of the actual structure of the frame, but also reduce the number of elements as much as possible. With considerations as follows, the finite element model of the frame is established:

1. Simplification of geometric model: there are many accessories on the frame that have little impact on the dynamic characteristics of the structure, making mesh and solving complicate and even affecting the meshing quality of the model. Therefore, the model is reasonably simplified.

2. The main structure of the frame is steel plate and circular pipe, whose thickness and length is very small compared with the section size. Therefore, shell elements are used to discretize the frame structure. The middle surface of each part is extracted and then sewed and repaired in the HYPERMESH.

3. To ensure the accuracy and reliability of the model as well as the computational efficiency, quad4 units are adopted. In modeling, the parts of the frame are directly connected together using shell units, ignoring the impact of welding.

4. To ensure the accuracy of the model, the mesh units should meet certain calculation requirements, such as slope, warping degree, side-length ratio, Jacobi, etc.

The three-dimensional geometric model of the frame was imported into the HYPERMESH and pre-processed, establishing the finite element model of the frame. The finite element model contains 34011 nodes and 30,911 units, among which the tria3 unit, namely the triangular row unit, accounts for 4.3%. Frame material is high quality carbon steel with elastic modulus 2.06E11 N/m², material density 7850 Kg/m³ and Poisson ratio 0.3.

When building the finite element model of the car body, considering the complex structure of the engine model and ignoring the dynamic characteristics of the engine itself, the engine has a great impact
on the dynamic characteristics of the frame, especially the moment of inertia, position of the center of mass, mass, etc. Therefore, the engine is simplified as a particle rigidly connected to the frame through RBE2 in NASTRAN to establish the finite element model of the body. Among them, the moment of inertia $I_{XX}$, $I_{YY}$, $I_{ZZ}$ of the engine are calculated by the 3d model provided by the manufacturer. The final finite element model of the 125 motorcycle body is shown in Figure 1.

![Finite element model of car body](image1)

**Figure 1.** Finite element model of car body

The finite element model of the car body was imported into MSC.NASTRAN for calculation, and the first 6 modal frequencies as well as mode information were extracted by Lamczos method [7].

2.2. *Experimental method*

The test system mainly includes force hammer, ICP type acceleration sensor, ICP type force sensor, LMS SCADAS data acquisition, computers and LMS.TESTLAB software.

According to the dynamic characteristic information obtained by analytical method, corresponding measuring points are arranged on the body, as shown in Figure 2.

Based on the excitation signal and response signal measured by the sensor, the frequency response function matrix is estimated according to the Hv method. Within the frequency range of concern, the Polymax identification method is used to identify the system poles according to the steady-state diagram. Then the experimental modal frequency and mode diagram can be obtained. [8-9]

![Map of measuring points](image2)

**Figure 2.** Map of measuring points
2.3. Comparative analysis

The dynamic characteristic analysis results by analytical method and experimental method are shown in Table 1. Obviously, the analysis results are reliable as the frequency difference of each order is small and the vibration mode is consistent.

| Order | Modal frequency and mode | Vibration mode | Difference (Hz) | Relative error |
|-------|--------------------------|----------------|-----------------|----------------|
| 1     | Analytical method (Hz)   | 80.8           | Experimental method (Hz) | 83.3           | First order lateral bending | 2.5 | 3.0% |
| 2     | 111.3                    | 114.6          | First order vertical bending | 3.3            | 2.9% |
| 3     | 148.7                    | 149.5          | Second order lateral bending | 0.8            | 0.5% |
| 4     | 187.4                    | 187.5          | First order integral twisting with large deformation on the tail | 0.1            | 0.1% |
| 5     | 219.8                    | 210.5          | Third order integral bending | -9.3           | -4.4% |
| 6     | 305.0                    | 280.4          | Second order lateral twisting | -24.6          | -8.8% |

There are two main reasons for the error: one reason is that some simplified processing is carried out in the analytical method; the other reason is that there are errors during data collection, processing and experimental consistency in experimental method.

Apparently, the processing method of the finite element model is correct, and the analysis results from analytical method can reflect the dynamic characteristics of the car body, which can be used for the subsequent improvement.

3. Analysis of excitation

Motorcycle is mainly excited by the road irregularity and engine during the driving process, both of which are transmitted to the human body through the motorcycle body. Therefore the dynamic characteristics of the motorcycle body must meet certain mechanical properties.

3.1. Influence of road excitation

Motorcycle will be excited by road irregularities during the driving process. If the excitation frequency of road irregularities is coupled with the natural frequency of the car body, resonance of the car body may be caused, thus making the whole motorcycle vibrate intensely, reducing the ride comfort and even causing certain damage. Therefore, the dynamic characteristics of motorcycle body should satisfy the following conditions:

(1) The natural frequency of the car body should be kept away from the natural frequency of the suspension system.

(2) The natural frequency of the car body is supposed to lie outside the frequency range of road excitation.

For motorcycle suspension system, the general offset frequency of sprung mass is about 1.5-2.5Hz, while the offset frequency of unsprung mass (wheel) is lower than 20Hz. The 125 motorcycle adopts a single cylinder four-stroke engine with the car body first-order natural frequency of above 80Hz, which is far higher than the natural frequency of the sprung mass and unsprung mass. Therefore, the car body will not resonate with the suspension system.

The wavelength of road roughness under various road surfaces is between 0.32 and 6.3[10]. When the motorcycle travels on the road surface at a certain velocity $v$ (km/h), the higher the velocity is, the higher the time frequency can be generated. If the frequency of the road excitation is close to the modal frequency of the motorcycle body, resonance may be produced.

The maximum speed of this 125 motorcycle is 80km/h, and the road roughness is calculated with the minimum wavelength of 0.32, then the maximum excitation frequency generated by the road surface is calculated by the formula (1),

$$f = \frac{1}{2} \cdot \frac{v}{\lambda}$$
\[ f = v / (3.6 \times \lambda) = 80 / (3.6 \times 0.32) \text{Hz} = 69.4 \text{Hz} \tag{1} \]

The lowest natural frequency of the 125 motorcycle body is above 80Hz, higher than the highest excitation frequency of the road surface, which is 69.4Hz. Furthermore, it is not common for motorcycles to travel at top speed on bad roads. From the above, the road roughness excitation is not likely to cause resonance of the car body.

3.2. Influence of engine excitation
Bolted to the frame, the engine of the 125 motorcycle is generally excited by the force and torque from the crank linkage mechanism, including reciprocating inertial force, rotary inertia force, air force and overturned couple moment opposite to the crankshaft torque.

Among them, the air force counteracts each other on the engine body, only making the body produce tensile or compressive stress, which isn’t transferred to the frame outside the engine body. On the other hand, the rotary inertia force is balanced by the balance mass block. Therefore, the only forces transferred to the frame are the reciprocating inertial force and the overturned couple moment. [11]

The overturned moment is generated by the gas force and reciprocating inertia force of the engine, which are the main excitations. The fundamental frequency \( f_1 \) of reciprocating inertial force and the fundamental frequency \( f_2 \) of air force satisfy equation (2).

\[ f_1 = n / 60 = 2 f_2 \tag{2} \]

The common working speed of the 125 motorcycle engine is 3000r/min ~ 7500r/min, thus the frequency of the first order reciprocating inertial force excited by the engine is 50Hz ~ 125Hz.

Though the main excitation frequency of the engine covers the first two order modal frequency of the car body, resonance will not appear because the vibration mode corresponding to the first order frequency of the car body is lateral bending, which is inconsistent with the direction of the reciprocating inertial force of the engine.

The vibration mode corresponding to the second order frequency of the car body is vertical bending, which is consistent with the direction of the first order reciprocating inertial force of the engine. Furthermore, the frequency is 111.3Hz, which is within the frequency range of the reciprocating inertial force of the engine. Therefore, when the frequency of the first order reciprocating inertial force of the engine is close to the first order bending frequency of the car body, resonance of the car body may be caused. In order to address this, it is necessary to improve the body structure of the motorcycle.

4. The improvement scheme
The natural frequency of the body has a lot to do with the stiffness of the frame which is influenced by many factors such as the structural form of the frame, the geometric parameters of pipe, the shape of the pipe section and the material.

| Components       | Supporting pipe (mm) Diameter x wall thickness | Rear reinforcement pipe (mm) Diameter x wall thickness |
|------------------|-----------------------------------------------|-----------------------------------------------------|
| The original body| Φ25×2.5                                       | Φ16×2                                               |
| The modified body| Φ25×4.0                                       | Φ20×2                                               |

Considering the factors of easy implementation and low cost in engineering, the modification of the car body is shown in Table 2, and the modified finite element model of the car body is shown in Figure 3.
Analyzed by analytical method, the dynamic characteristics of the modified car body were extracted by the same method and compared with the original car body, as shown in Table 3.

| Order | The original body | The modified body |
|-------|-------------------|-------------------|
|       | Frequency (Hz)    | Vibration mode    | Frequency (Hz) | Vibration mode |
| 1     | 80.8              | First order lateral bending | 98.4          | First order lateral bending |
| 2     | 111.3             | First order vertical bending | 137.7         | Second order lateral bending |
| 3     | 148.7             | Second order lateral bending | 165.4         | First order lateral twisting with small rear deformation |
| 4     | 187.4             | First order lateral twisting with large rear deformation | 217.2         | Third order lateral bending |
| 5     | 219.8             | Third order lateral bending | 258.0         | Second order lateral twisting |
| 6     | 305.0             | Second order lateral twisting | 325.4         |                        |

It can be seen from Table 4 that the vibration modes between the original car body and the modified car body are the same in the first six orders. However, the corresponding modal frequencies are increased, the tail deformation is decreased, and the vibration modes are improved. The main reason is that the overall stiffness of the motorcycle is increased with the thickening of the support pipe, thus improving the natural frequency of the car body. The improvement of the rear reinforcing pipe also addresses the large deformation at the rear of the frame.

In addition, the first order vertical bending frequency of the modified car body is increased from 111.3Hz to 137.7Hz, far higher than the highest frequency of 125Hz excited by the engine's first order reciprocating inertial force. Therefore, the modified car body effectively avoids the excitation frequency of the engine and thus improves the structural dynamic characteristics. The improvement scheme is effective and easy to implement in engineering. The test drive of the prototype also shows that the ride comfort of the 125 motorcycle has been greatly improved.

5. Conclusion

(1) To explore the possibilities for solutions to the over-vibration phenomena appearing in the 125 motorcycle, analytical and experimental methods were adopted to analyze the structural dynamic characteristics of its body. The results showed that the first six order natural frequencies were relatively low and large deformation existed on the rear.

(2) Taking the practical driving situation of the motorcycle into considerations, the influence of road irregularity and engine excitation on the vibration of the 125 motorcycle body was discussed. It was found that the first order reciprocating inertial force excitation of the engine had frequency coupling with the first order vertical bending, which was likely to cause the resonance of the car body.

(3) Based on the dynamic characteristic analysis results of car body and the influence evaluations of engine excitation on the vibration of the car body, the improvement scheme of increasing the wall...
thickness of the supporting pipe as well as thickening the rear reinforcement pipe was put forward. The structural dynamic characteristics of the modified body were further analyzed using analytical methods. The results demonstrated that the dynamic characteristics were significantly improved. And the test drive of the modified prototype also proved that the improved scheme was feasible and easy to implement.

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