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Modal Simulation and Experimental Analysis of Commercial Vehicle Exhaust Systems

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Abstract: To verify the accuracy of modal simulation analysis for a commercial vehicle exhaust system, a finite element (FE) model of the system was established using FE software. Modal simulation was performed on the FE model to obtain multiple orders of modal frequencies, mode shapes, and other parameters. A real-vehicle modal test was then conducted on the same exhaust system. The test results were compared with the simulation results. The comparison shows that the first-order modal frequency from simulation is 59.586 Hz, which is very close to the experimentally measured value of 58.008 Hz, thereby validating the reliability and accuracy of the simulation method. This provides a basis for shortening the subsequent development cycle and reducing costs.

Keywords: exhaust system; modal simulation; mode experiment; mode shapes

1. Introduction

Commercial vehicles serve as the primary carriers for road transportation. Their exhaust systems are not only core components for emission control but also critical vibration transmission paths connecting the engine to the vehicle body. One end of the exhaust system is rigidly connected to the engine, subjecting it to periodic excitations generated during engine operation, while the other end is connected to the frame or body via suspension hangers, transmitting vibrations to the entire vehicle. In actual operation, if the natural frequencies of the exhaust system coincide with the excitation frequencies at engine idle or common operating speeds, resonance may occur. In mild cases, this deteriorates NVH (noise, vibration, and harshness) performance; in severe cases, it can cause exhaust pipe fractures, bracket cracking, bolt loosening, and other reliability issues.

Modal analysis is a core method for studying structural dynamic characteristics, aiming to determine modal parameters such as natural frequencies, damping ratios, and mode shapes. Through modal simulation of the exhaust system, the constrained modal frequencies and corresponding mode shapes can be obtained, enabling assessment of potential resonance risks and early avoidance of design defects. Currently, both domestic and international scholars have conducted considerable research on exhaust systems. Some researchers have used ANSYS software for modal analysis of exhaust systems while also examining maximum displacement and maximum stress under gravity loads; others have optimized hanger positions using the averaged drive-degree-of-freedom displacement method.

This paper builds a complete FE model based on the actual layout of a commercial vehicle exhaust system. Modal simulation calculations are carried out using Abaqus software, while a real-vehicle modal test is performed using LMS Test.Lab software. The simulation data and test data are compared and analyzed to evaluate the accuracy and reliability of the established simulation approach.

2. Modal Analysis of the Commercial Vehicle Exhaust System

2.1 Model Construction

Modeling was conducted based on the actual exhaust pipeline layout of a certain commercial vehicle model. The free end is defined as the positive X-axis direction, vertical upward as the positive Z-axis direction, and the positive Y-axis direction is determined by the right-hand rule. To improve simulation accuracy, the turbocharger’s turbine housing, center housing, and compressor sections were modeled separately. The resulting FE model of the commercial vehicle exhaust system is shown in Figure 1.

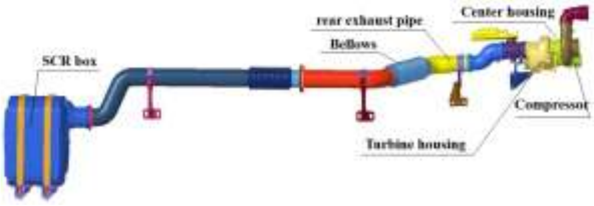

Figure. 1 FE model of the commercial vehicle exhaust system

2.2 Modal Simulation Calculation

HyperMesh software was used for meshing and pre-processing. Solid elements were employed for components such as the exhaust manifold and turbocharger, while shell elements were used for the bellows, rear exhaust pipe, SCR box, etc. The pre-processed model file was imported into Abaqus. In the Property module, material properties and mass attributes were assigned to each component, as listed in Table 1.

Table 1. Material and mass properties of selected components

Component	Material	Young's modulus (MPa)	Poisson's ratio	Assembly mass (kg)
Turbine housing	QT450-18	169000	0.275	8.2
Center housing	HT250	138000	0.156	3.1
Compressor	ZL101A	72400	0.330	2.5
Bellows	Steel_0Cr18Ni9	204000	0.285	2.6
SCR box	Steel_0Cr18Ni9	204000	0.285	140

A linear perturbation – frequency analysis step was used to extract the first six orders of the system's modes. Rigid connections were adopted between components, and boundary conditions were defined at bolt hole locations by constraining all six degrees of freedom. The element types were set to C3D10M for solid elements and STRI65 for shell elements. Finally, the simulation job was submitted for computation.

2.3 Modal Simulation Results and Analysis

The first three modal results of the exhaust system are presented in Table 2. The first-order modal frequency is 59.586 Hz, corresponding to a Z-direction lateral oscillation of the exhaust pipeline, which is identified as the first-order mode of the hot end. The constrained mode shape is shown in Figure 2 (scale indicates displacement in mm).

Table 2. Modal simulation results of the exhaust system

Mode order	Frequency (Hz)	Mode shape description
1	59.586	Z-direction lateral swing of pipe
2	89.325	Y-direction vertical swing of pipe
3	99.652	XY-plane swing of pipe

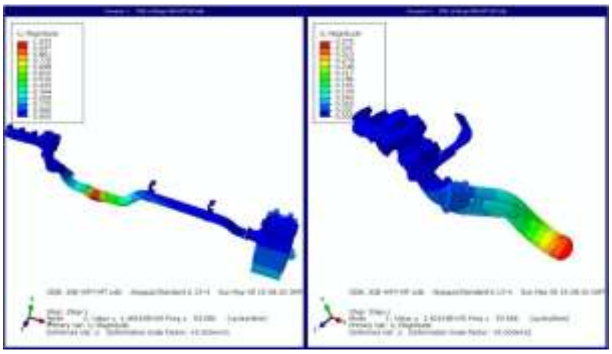

Figure. 2 First-order constrained mode shape of the hot end

3. Modal Test Validation of the Commercial Vehicle Exhaust System

3.1 Exhaust System Modal Test

The test was conducted using LMS Test.Lab equipment, including a noise and vibration analyzer, tri-axial accelerometers, and an impact hammer. The multiple-input multiple-output (MIMO) method was employed. To align with the simulation, the frequency range for the free-modal test was also set to 0–200 Hz. Key parameters including modal frequencies, mode shapes, and modal damping ratios were obtained. The measurement point locations on the tested system are shown in Figure 3.

Figure. 3 Measurement point locations on the tested system

3.2 Modal Test Results

Mode shapes describe the spatial deformation pattern of the system at a given frequency. Like natural frequencies, mode shapes reflect the inherent dynamic characteristics of the exhaust system. Each natural frequency corresponds to a unique mode shape. Comparing simulated and experimental mode shapes mutually validates the effectiveness of the modeling and testing approaches.

According to the modal test results, the first-order constrained modal frequency of the system is 58.008 Hz, with a modal damping ratio of 1.90% and a Z-direction swing mode shape, which is consistent with the simulation result. The experimentally obtained constrained mode shapes are shown in Figure 4.

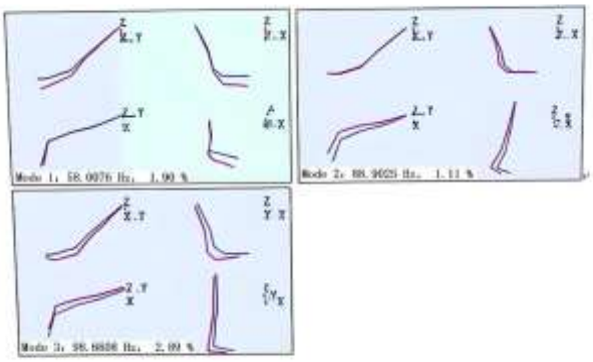

Figure. 4 First three mode shapes obtained from the test

In the Colormap plot, bright vertical regions of finite width along the frequency axis indicate resonance bands. The Colormap plot for the measurement point located before the bellows under the stationary run-up condition is shown in Figure 5.

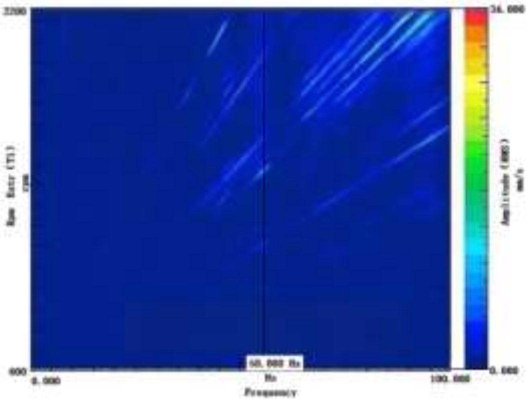

Figure. 5 Colormap plot at the pre-bellows measurement point

3.3 Comparison and Analysis of Simulation and Test Results

The first-order constrained modal frequency measured in the test is 58.008 Hz, which is close to the simulated first-order hot-end modal frequency of 59.586 Hz. The deviation is only 1.5 Hz, and the error between the test and simulation data falls within the acceptable range for engineering applications. Moreover, the mode shapes are consistent. These results confirm that the established modal simulation method for the commercial vehicle exhaust system is accurate and reliable.

4. Conclusions

(1) In modal simulation analysis, the accuracy of the 3D model, material properties, constraints, boundary conditions, and other inputs significantly affects the precision of the simulation results.

(2) Based on the established FE model, modal simulation of the commercial vehicle exhaust system yielded a first-order modal frequency of 59.586 Hz, which agrees well with the experimentally obtained value of 58.008 Hz, with a relative deviation of 2.5%. This validates the reliability and accuracy of the proposed modal simulation method.

(3) The established modal simulation method enables accurate acquisition of system modes and mode shapes, identification of potential resonance points, and subsequent design improvements. It reduces the number of physical vehicle pipeline modal tests, shortens the design cycle, and offers significant practical engineering value.

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