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Sound quality improvement for a four-cylinder diesel engine by the block structure optimization

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ABSTRACT

High sound quality and low radiated noise are two dominant demands for the vibro-acoustic performance of internal combustion engines. Such engines with high acoustic quality will greatly improve the acoustic environment both inside and outside of the passenger compartment of an automobile. In this paper, this performance of the block of a four-cylinder diesel engine was simulated and bench-tested. Then the vibro-acoustic problems were diagnosed and optimized. The finite element analysis method was adopted to numerically analyze the natural modes of the block. The finite-element model of the block was verified by the experimental modal analysis utilizing the single-input and multiple-output technology. The results indicate that the modal frequency errors from the simulation and experiment are permissible in respect of engineering and the accuracy of the finite-element model highly matching the real one is validated. Then, the flexible multi-body dynamics model of the diesel engine was constructed and excited by the boundary conditions comprised of in-cylinder gas pressures, cylinder liner-piston contact induced lateral forces and valve system motion induced impact forces. The simulated vibration velocity levels from the block surface were obtained under the rated condition (75 kW/3600 rpm) and well verified by the bench test. Boundary element analysis method was employed to acquire the radiated acoustic pressures from the block surface in the frequency range of interest. Optimized schemes are implemented to the block surface in order to reduce the radiated noise and enhance the sound quality of the diesel engine. Finally, the optimal block was cast. And the bench-test results indicate that the sound quality of the new-block engine is substantially improved. The research achievements validate the feasibility and reliability of the optimal design for the block.

1. Introduction

Diesel engines possess outstanding advantages of low fuel consumption, high power performance and low emission [1]. However, the severe radiated noise is a negative factor which prevents them from being applied to passenger vehicles on a large scale.

The noise mentioned above is constituted of the aerodynamic and structural radiated noise. The aerodynamic noise has been well controlled by optimizing intake air cleaners and exhaust mufflers [2,3], and thus, is much lower than the structural radiated noise. Therefore, it is of great necessity to reduce the radiated acoustic powers from the structural surface of a diesel engine.

Improving the stiffness is a critical way to decline the structural radiated noise, which is validated by Hambric [4] who investigated the applicability of various approximation methods to broad-band radiated noise design optimization problems, using a rib-stiffened cylindrical shell as a test case to prove the effectiveness of different methods. Besides, Guo et al. [5] predicted the radiated noise from the oil pan of a diesel engine by coupling methodology of finite element analysis (FEA) and boundary element analysis (BEA), and optimized it using rib stiffeners. However, the optimized oil pan was excited by the same boundary conditions utilized for the original one, which would influence the accuracy of the structural responses after optimization. Yang et al. [6] constructed a flexible multi-body dynamic (FMBD) model of a one-cylinder diesel engine and proposed an improved noise reduction design method for the block, by which the radiated sound power level was declined. Whereas, the sound quality optimization for the engine was not taken into consideration, which might lead to a dilemma that little improvement for the acoustic feelings of consumers was achieved though the sound power was decreased.

Sound quality evaluation, closely combined with subjective feelings, has emerged as a very active research area. So far, the sound quality of internal combustion engines (ICEs) has been mainly investigated as follows:

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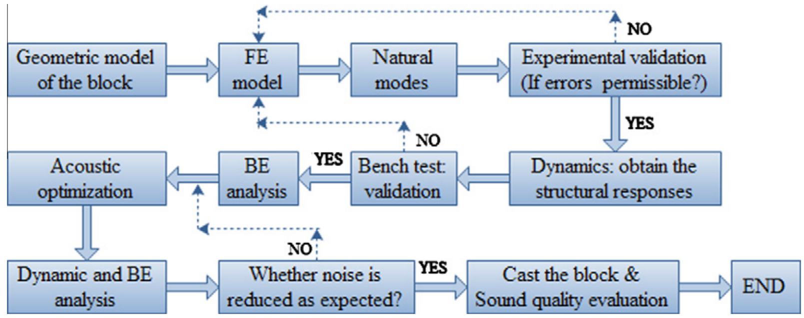

Fig. 1. Flow chart of the sound quality improvement design for a diesel engine by the block optimization.

(a) First, active noise control systems are employed to achieve a more pleasant sound by using digital signal processors and loudspeakers worked as noise source strength spectra receiver and secondary sources, respectively [7,8].
(b) Second, advanced techniques for noise reduction and sound quality analysis (such as valve train system optimization) are employed in ICEs [9].

However, few studies have been conducted to improve the sound quality of an ICE by optimizing the structural vibro-acoustic response of the components. In this study, we aim to optimize the vibro-acoustic response from the block surface and improve the sound quality of a four-cylinder diesel engine, which is relatively rare so far.

Coupling methodology of FEA [10], FMBD [11] and BEA [12] is adopted to analyze the natural modes, dynamical responses and radiated noise of the block, respectively, and then to improve the sound quality of the engine by optimizing the block structure in order to reduce the radiated noise as expected. Subsequently, the optimal block needs to be cast and bench-tested in order to verify the effectiveness of the sound quality optimization for the diesel engine. Finally, the sound quality of the engine is evaluated both in objective and subjective ways, and greatly enhanced due to the optimal design of the block. The flow chart of the sound quality improvement design for an ICE by the block optimization is shown in Fig. 1.

2. Background theories

2.1. Basic theory of FMBD

Traditional MBD is mainly utilized to analyze rigid bodies. However, the rigid assumption has great influence on the simulation precision, so the flexible body is introduced in this study.

The flexible-body kinetic equation is established at the generalized coordinate, which can reveal both the rigid displacements and the linear elastic deformations in FMBD, and can be defined as [13]:

$$\left.\begin{aligned} \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\xi}}\right) - \frac{\partial L}{\partial \xi} + \left[\frac{\partial \psi}{\partial \xi}\right]^{\mathrm{T}} \cdot \lambda = F \\ \psi = 0 \end{aligned}\right\} \tag{1}$$

where ξ and $\dot{\xi}$ are the generalized coordinate and its time derivative, respectively; L is the Lagrange equation and its definition is $L = T - V$, where T and V are the structural kinetic energy and the potential energy, respectively; ψ is the constraint equation; λ is the constraint Lagrange multiplier; F is the generalized force caused by external excitations.

The final form of the differential equation based on the Lagrange equation is defined as the following equation:

$$\boldsymbol{M} \cdot \ddot{\xi} + \dot{\boldsymbol{M}} \cdot \dot{\xi} - \frac{1}{2}\left[\frac{\partial \boldsymbol{M}}{\partial \xi} \cdot \dot{\xi}\right]^{\mathrm{T}} \cdot \dot{\xi} + \boldsymbol{K} \cdot \xi + f_g + \boldsymbol{D} \cdot \dot{\xi} + \left[\frac{\partial \psi}{\partial \xi}\right]^{\mathrm{T}} \cdot \lambda = \Delta \tag{2}$$

where Δ is the second-order time derivative of the generalized coordinate; $\boldsymbol{M}$ and $\dot{\boldsymbol{M}}$ are the mass matrix and its time derivative of flexible bodies, respectively; $\boldsymbol{K}$ is the generalized stiffness matrix; f_g is the generalized mass force; $\boldsymbol{D}$ is the damping matrix.

2.2. Introduction of sound quality

Sound quality, comprised of subjective and objective evaluations, was applied in engineering in the late 1980s [14]. The former is based on the experimental psychology, which is not mainly discussed in this study. The latter establishes the relationship between psychological and physical parameters of sounds, with the methods of time–frequency analysis, objective parameter regression analysis and neural network technologies.

Three critical parameters, named loudness [15], sharpness [16] and roughness [17], are selected to evaluate the sound quality of the diesel engine in this paper.

3. Modal analysis of the block

The main parameters of this in-line four-cylinder (L4) diesel engine used in this study are listed in Table 1.

3.1. Prediction of the natural modes of the block

It is necessary to analyze the natural modes because of the close relationship between the radiate noise and the natural frequencies of the block. The finite-element model of the block, as shown in Fig. 2, consists of 160788 four-node tetrahedron elements. The block material is HT 230 with the density, elastic modulus and Poisson's ratio of 7280 kg/m^3, 120,000 MPa and 0.265, respectively.

The first ten natural modal frequencies of the block from the numerical calculation are listed in Table 2.

Modal shapes of the first four modes of the block are shown in Fig. 3. The first mode at 625.7 Hz involves global torsional deformation of the block; the second mode at 954.5 Hz includes bending deformation; the third mode at 1260.3 Hz contains twisting and

Table 1
The main parameters of the diesel engine.

Parameters	Values
Cylinder number	4
Cylinder diameter	93 mm
Idling condition	800 rpm
Rated condition	75 kW/3600 rpm
Maximum torque condition	250 Nm/2000 rpm
Outline dimension	980 × 545 × 571 mm^3