A New Method to Identify the Diesel Engine Modal Parameters based on Self-Excitation

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Abstract. At present, the methods to study the dynamic characteristics of diesel engine structure include finite element analysis method and experimental analysis method. Among them, 60% of the structural stiffness and 90% of the damping ratio of the whole diesel engine come from the joint part, and the dynamic characteristics of the joint part of the diesel engine are very complex, so it is difficult to establish an accurate finite element model, and the results of finite element analysis methods are often not accurate. For the experimental analysis method, it is mainly divided into the traditional Experimental Modal Analysis method (EMA) and the Operational Modal Analysis (OMA). The EMA always needs to measure the excitation force of the diesel engine and the vibration response of the structure, simultaneously. And the influence of motion factors on the structure dynamics cannot be considered. The structure is excited by the working environment, and only analyzes the modal parameters of the structure with the vibration response. Few scholars analyze the OMA for diesel engines. This paper proposes a new method to identify the modal parameters of diesel engine based on dry run. In this paper, the design and research of the motion law of the air-running self-excitation is carried out, and the validity of the method is verified.

1. Introduction
Diesel engines are developing towards the direction of high power, lightweight, reducing fuel consumption and emission, etc., but the vibration and noise problems are increasingly prominent\([1, 2]\). It mainly show in the components wear increasingly, reduce the service life, higher noise, and deterioration of working conditions. Under the periodic change of dynamic loading, the main parts of the diesel engine can cause a strong resonance, and the dynamic stress and dynamic displacement will be several times or even dozens of times as much as static load, and it seriously affected the reliability of the diesel engine. Since it is great significance to study the diesel engine dynamics between the external exciting force and the structure itself inherent characteristics\([3]\). And it plays a very important role, to improve the performance of diesel engine.

In 1982, walterOtt et al. established a finite element model of a four-cylinder in-line engine, respectively established four models for different elements, and conducted free mode analysis. Through modal test comparison, it was concluded that the model of combining plate between the shell elements and solid elements was reasonable. Anderton, D.Ghazy et al. studied the dynamic response of heavy machine with finite element software. J.p.randeis conducted finite element analysis on the diesel
engine body through finite element method, predicted the vibration of the diesel engine, and pointed out that the weak links of the engine body existed in the skirt and oil sump [4]. D. anderton and H. priede studied the noise radiation control of the diesel engine [5]. Lalor N and Birth M analyzed the finite element dynamic characteristics of the diesel engine body, calculated the natural frequency and modal shape, analyzed and summarized each mode, and had a relatively directional understanding of the vibration mode [6] [7]. In addition, many diesel engine manufacturers in the world, such as MTU, TOYOTA and MSSSAN, have also carried out extensive finite element analysis on many parts of diesel engine (body, cylinder head, bearing, connecting rod, sealing ring, etc.). In 1990, Shung. H Sung et al. used the finite element analysis software Nastran to study the vibration and noise of a diesel engine body [8]. The ISVR laser room has developed a laser velocimeter that can be used to monitor the running state and performance of an engine, as well as whether the engine can reduce noise. Through its strong experimental capability, LMS can better determine the incentive force of the body, so that the study of dynamic characteristics can be closer to the actual situation. Austria AVL consider the internal combustion engine has a good NVH (noise, vibration, ride comfort) performance as the main standard of a product can occupy a place in the market. A.F.Seybert, D.A.Hamilton used finite element software to conduct finite element sonic-solid coupling analysis on many parts of diesel engine [8].

In 1997, Shung.H.sung, Donald.J.Nefske et al. carried out finite element analysis of vibration and noise prediction to the diesel engines [9]. The university of Kentucky A.F.Seyber did a lot of finite element analysis to the various parts of the engine and completed the acoustic vibration coupling analysis [10]. In 1997, Robert Sou Thai J et al. developed Perkins V6HSDI (High Speed Direct Injection) diesel engine that met European standards by using finite element analysis technology [11]. AVL (Austria) and LMS (Belgium) have made great achievements in determining the excitation force of cylinder block by virtue of their excellent experimental capabilities. Finite element analysis technology has been applied in practical engineering design, which makes the dynamic response results obtained by computer simulation closer to the actual situation [12]. In 2002, Baverstock L studied the structural performance of diesel engine body by means of experiment, and pointed out that the maximum stress appeared on the joint surface of main bearing cover [13].

At present, most domestic and foreign researchers studied the dynamic characteristics of diesel engine are mainly focus on showing the working stability of diesel engine through simulation software, so as to guide the structural optimization of diesel engine. Occasionally, some scholars conduct experiments under the static condition of diesel engine with LMS or other test instruments, so as to input the obtained dynamic parameters into the simulation model or verify simulation results.

Therefore, this paper proposes a new method to identify the diesel engine modal parameters based on its self-excitation

2. Design of self-excitation motion law

2.1. The basic principle of self-excitation modal analysis method

The method of self-excitation analysis for diesel engine is mainly used the exciting force which generated by the deflagration of the combustion chamber against the engine body, and then used the vibration response of the structure to identify the modal parameters. The schematic diagram of the self-excitation modal analysis method as the figure 1. shown. Under the action of the excitation force, the structure of the diesel engine will produce the corresponding vibration response. Finally, the vibration response signal is analyzed by the response-based modal analysis algorithm, and the modal parameters of the diesel engine can be identified with the vibration response signal of the structure.
Figure 1. The schematic diagram of self-excitation modal analysis method

Airflow generated at the moment of deflagration combustion chamber (Turbulent) incentives the cylinder head, piston, cylinder liner, and then passed on to the diesel engine structure. The structure of the diesel engine can produce vibration response under the action of the exciting force. At the moment, the piston confined to a relatively small range, the small changes of piston connecting rod component will not affect the structural dynamic characteristic dynamic behavior of diesel engine. At the same time, the crankshaft movement caused by the centrifugal force and coriolis acceleration can be ignored. Therefore, the structure of the diesel engine can be considered as linear time-invariant under this condition. Under the assumption of viscous damping, the dynamic Eq. of the diesel engine structure can be expressed as:

$$ M\ddot{X} + C\dot{X} + KX = F $$  \hspace{1cm} (1)

Where $M$, $C$ and $K$ are the discrete physical mass, damping and stiffness matrices of the whole engine structure, $X$ is the vibration displacement vector of the diesel engine structure, and $F$ is the excitation force of the diesel engine structure generated by deflagration. The left side always represents the dynamic characteristics of the diesel engine structure, and the right side represents the inertial force generated by the self-excitation movement. If the inertial force can be measured, the Fourier transform of formula (1.1) can be obtained as follows:

According to the modal theory, the frequency response function matrix of diesel engine structure can be further expressed by the modal parameter model:

$$ H(\omega) = \sum_{r=1}^{N} Q_r \Psi_r \Psi_r^T \frac{1}{j\omega - \lambda_r} $$  \hspace{1cm} (2)

Where $\Psi_r$ is the $r$-order mode mode vector of diesel engine structure, the real part of $\lambda_r$ is the $r$-order mode damping ratio of diesel engine, and the imaginary part is the natural frequency of the $r$-order mode of diesel engine. The Eq. (1.4) indicates that if the frequency-response function matrix of the diesel engine structure can be measured, the modal parameters of the diesel engine can be obtained through the corresponding experimental modal analysis algorithm. However, due to the complexity of the system composed of piston connecting rod, crankshaft, bearing, cylinder body and cylinder head, etc., the inertial excitation force acting on the structure of diesel engine is difficult to be measured, so the frequency response function of the structure of diesel engine under the self-excitation of empty operation cannot be obtained.

2.2. Self-excitation motion characteristics analysis of diesel engine in dry run

(1) Free response signal extraction

When the excitation force meets the assumption of "white noise", the NEXT can extract the free response from the vibration response signal that can reflect the dynamic characteristics of the structure.
The figure 2 is a schematic diagram of the self-excitation motion law of the diesel engine in dry run. The figure (a) is the diagram of self-excitation: when the diesel engine in dry run, the structural change of the combustion chamber is limited to a small area during the moment of compression combustion, since the influence of the change of self-excitation movement position on the structure can be ignored in a small area. Figure (b) shows the one turbulence generated by deflagration during combustor combustion and the random pulse excitation striking the diesel engine.

Fast-burning stage in the process of diesel engine combustion time, the highest pressure appear. The growth rate of average pressure $\frac{\Delta p}{\Delta \psi}$ is great, but unfavorable exceed 0.4 MPA / °CA. Therefore, when the gas hits the combustion chamber as shown in Figure b., the inertial impact sequence shown in Figure c. will be generated. Under the inertial impact sequence, the structure will produce corresponding vibration response. According to the RDT, the displacement response of structural vibration of diesel engine can be expressed as:

$$x(t) = x(0)D(t) + \dot{x}(0)v(t) + \int_{t_0}^{t} h(t-\tau)f(\tau)d\tau$$

Where $x(0)$ is the initial displacement of the vibration response, and $\dot{x}(0)$ is the initial velocity of the vibration response; $D(t)$ is the free displacement response of the structure only under the initial conditions $x(0)=1$, $x(0)=0$. $v(t)$ is the free response of the structure only under the initial conditions $x(0)=0$, $x(0)=1$. $h(t)$ is the unit impulse response function of the structure; The first two parts are deterministic and the second part is determined by the random inertial excitation sequence.

when the diesel engine is driven by dry run, the gas impact diesel engine should be as dense as possible in unit time, so as to obtain a higher capability level. The shorter the duration of gas impact sequence, the larger the energy spectrum bandwidth.

Therefore, when the research object is certain, it is necessary to improve the speed of the diesel engine as much as possible. However, if the speed is set too high, it may cause some damage to the diesel engine. Therefore, the principle of selecting the speed of the diesel engine that it is possible to select the speed under normal operation.

3. The validity of experimentally verified

In this paper, the self-excitation modal analysis experiment and the traditional percussion modal experiment are carried out. For the validity of the self-excitation modal analysis method is studied, and the experimental object of diesel engine is TBD234V12.


3.1 Self-excited experimental platform
Diesel engine TBD234V12 is the experimental object of self-excited mode verification. The front end of the vibration signal acquisition of the self-excited mode experiment is dynamic acquisition equipment of Belgium LMS company. The vibration signal is measured by the 356A16 ICP three-phase acceleration sensor produced by PCB company.

3.2 Self-excitation experiment scheme
In order to fully study the whole mode of diesel engine, 66 measuring points were selected. Figure 3 shows the measuring point layout model of the self-excitation mode experiment. Each node of the grid in the model represents the position of the sensor installed.

As shown in the figure 3(b), 8 measuring points are evenly arranged on the cylinder head, 28 measuring points are evenly arranged on the cylinder body, 14 measuring points are symmetrically arranged on the oil sump, and 16 measuring points are symmetrically arranged on the bracket. As the theory described in section 2 and the structural properties of TBD234V12, the engine speed is set to 1500r/min with no load. The sampling frequency set 1024Hz, and the sampling time set 3 minutes. As a comparison, the traditional experimental modal analysis (EMA) method is used to analyze the modal parameters of the diesel engine structure, and the knocking excitation is applied at the input end of the diesel engine. The location of the sensors in the knocking experiment is the same as the self-excited mode experiment.

![Figure 3. Schematic diagram of self-excitation modal analysis experiment](image)

3.3 Validity verification of identification modal parameters
Table 1 is the result of EMA and self-excitation experiment.

|     | modal #1 | modal #2 | modal #3 | modal #4 | modal #5 | modal #6 |
|-----|----------|----------|----------|----------|----------|----------|
| EMA | Natural Frequency | 26.727Hz | 35.352Hz | 55.476Hz | 94.516Hz | 120.085Hz | 135.681Hz |
|     | Damping ratio | 3.25 % | 1.53 % | 1.17 % | 3.89 % | 1.62 % | 1.57 % |
| OMA | Natural Frequency | 24.507Hz | 54.524Hz | 147.260Hz |
|     | Damping ratio | 4.20 % | 1.51 % | 1.95 % |

As the Table 1 shown, it can be seen that the natural frequency identified by the self-excitation modal analysis method is slightly less than that calculated by the EMA method. This is mainly due to the knocking process of diesel engine is in a state of rest. At work, the crankshaft of diesel engine piston component has been at the state of motion, the results of identification has a certain influence.
And the incentive to identify modal parameters less than the result of the EMA experiment, it is mainly because the incentive energy relative to knock experiment, result in some modal parameters are not excited.

4. Conclusions
In this paper, the basic concept of self-excitation modal analysis method for diesel engine is presented. Then the design method of the excitation law and the identification algorithm of the modal parameters are proposed for the modal analysis method of the diesel engine. At last, the modal analysis on TBD234V12 diesel engine, the traditional knocking experimental modal analysis and the self-excitation modal experimental were carried out respectively, and the two results were analyzed and compared. The experimental results show that the self-excited modal analysis method can effectively identify the modal parameters of the diesel engine structure, and the motion state of the diesel engine will affect the modal parameters of the diesel engine structure to some extent.

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