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THE STUDY ON IMPACT RESPONSE OF DIESEL ENGINE BASED ON FINITE ELEMENT METHOD

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Key Words: Diesel Engine; Integration; Real-time Simulation; Underwater Explosion.

Abstract. *The diesel engine's ability to function well under impact is directly related to sailing of ship. In previous studies the response of marine equipment under shock has always been studied without considering the interaction between the equipment and hull. This paper investigates the dynamic characteristics of diesel engine and analyzes the dynamic response of the integration model under underwater explosion. The influence of flexibility of hull on dynamic response of diesel engine has been discussed by comparing the results of integration model and non-integration model. A better method of studying the response of marine equipment under shock by underwater explosion has been proposed.*

1 INTRODUCTION

Vessels face more severe operational environment in modern naval battles [1]. The main danger towards vessel when suffer from underwater explosion is the failure of marine equipment. Diesel engine is a necessary component of vessel's power system. Diesel engine has complex structure and its fixed part tends to have large deformation when vessels under shock from non-contact explosion according to scantling explosion test. So the study of response of diesel engine under shock is of great significance. The theory of study the response of equipment under shock has experienced three stages: static equivalent method, DDAM and real-time simulation [2]. These three methods present the characteristics of simple to complex and static to dynamic. In previous studies the stiffness of hull has always been considered as infinite. Therefore, the response of marine equipment under shock has always been studied without considering the interaction between the equipment and hull. This paper first analyzes the characteristics of diesel engine. Second the integration model of diesel engine coupled with hull has been built and then the investigation of dynamic response of diesel engine of integration model under underwater explosion has been conducted. By comparing the results of non-integration model and integration model an appropriate method of studying the response of marine equipment under shock has been proposed.

2 THE DYNAMIC CHARACTERISTICS OF DISEL ENGINE

The structure's dynamic characteristics are the inherent property of structure [3]. Studying the structure's dynamic characteristics can help us to investigate the dynamic response of structure. Modal analysis is the common measure used in engineering to acquire the structure's dynamic characteristics. Modal analysis includes experimental modal method and calculating modal analysis method [4]. As the developing of finite element technology the latter has been widely used in engineering. Therefore, this paper adopts calculating modal analysis method to investigate the dynamic characteristics of diesel engine and its parts.

2.1 Building the finite element model of diesel engine

Finite element model is the mathematical description of the real physical model [5]. The structure of diesel engine is very complex and some of the features are process features which have little influence towards the whole part's structure. Therefore, the small features have been eliminated and the model can be meshed finer. This paper first builds the model of diesel engine's part and then assembles the parts together as shown in Fig.1. The connected relation in diesel engine is mainly bolted connection. Multipoint restriction has been introduced to simulate the bolted connection. By far the finite element model of diesel engine has been built.

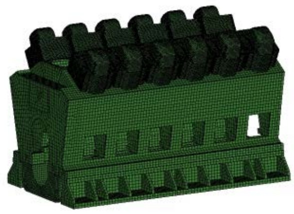


Fig.1 Finite element modal of diesel engine

2.2 The modal analysis of diesel engine

Suppose the diesel engine has been discretized to a N-degree-of-freedom system and its governing equation can be expressed:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=0 \tag{1}$$

$[M]$ is mass matrix, $[C]$ is damping matrix, $[K]$ is stiffness matrix. The material of diesel engine is metal and its damping is very small. Ignoring the damping equation (1) can be written as:

$$[M]\{\ddot{x}\}+[K]\{x\}=0 \tag{2}$$

Take Laplace transform on both sides of equation (2):

$$(s^2[M]+[K])\{X\}=0 \tag{3}$$

Let $s=j\omega$, and substitute it in equation (3):

$$([K]-\omega^2[M])\{X\}=0 \tag{4}$$

Equation (4) has nonzero solution. So we can deduce that:

$$\left|K-\omega^2 M\right|=0 \tag{5}$$

Solve equation (5) and ω can be acquired. Different ω represents different natural frequency. Substitute the ω in equation (4) we can obtain the modal shapes. The lower-order modes are usually being paid attention to. Hence this paper analyzes the first ten order modes of diesel engine and its parts.

Diesel engine has the lowest frequencies while head has the highest frequencies. The modal shape of diesel engine has been shown in Fig.2. The modal shapes of diesel engine and its parts present the characteristics of torsion and bend and they are continuous. This shows that the finite element modal is suitable for analyzing the dynamic response. The modal shapes also include localized modes. The distribution of frequencies of lower-order modal of diesel engine and its parts has been shown in Fig.3. The natural frequencies of head and head cover are above that of diesel engine while cylinder, pedestal and the oil pan have some common ranges with diesel engine in natural frequencies. This illustrates that cylinder and pedestal and the oil pan tend to resonance when diesel engine under shock.

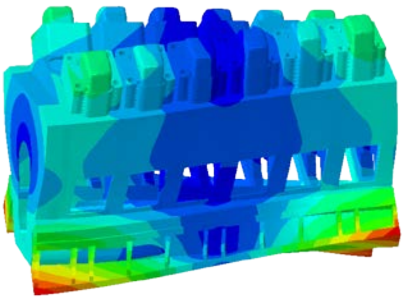


Fig.2 Modal Shape of Diesel Engine

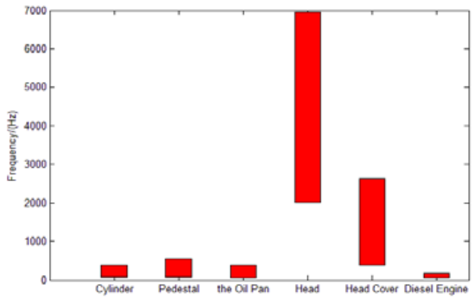


Fig.3 Frequency Distribution of Diesel Engine and its Parts

3 THE RESPONSE OF INTEGRATION MODEL UNDER UNDERWATER EXPLOSION

Non-integration model has always been used when analyzing the response of marine equipment under shock by DDAM method or real-time simulation method [6]. In non-integration model the stiffness of hull is assumed to be infinite and the interaction between diesel engine and hull is ignored. In modern vessels equipment is usually installed on shock absorber [7]. Therefore the interaction between equipment and hull need to be considered.

3.1 The coupled system of diesel engine and hull

Diesel engine and hull are flexible systems [8]. Suppose diesel engine is system A and hull is system B in the coupled system as shown in Fig.4. There are many shock absorbers connecting diesel engine and hull.

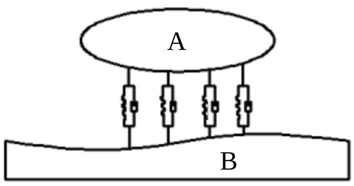


Fig.4 the Coupled system of diesel engine and hull

The kinetic equation of the coupled system can be written:

$$[M_A]\{\ddot{q}_A\}+[C_A]\{\dot{q}_A\}+[K_A]\{q_A\}=\{F_A\} \tag{6}$$

$$[M_B]\{\ddot{q}_B\}+[C_B]\{\dot{q}_B\}+[K_B]\{q_B\}=\{F_B\}$$

$[M_A]$ and $[M_B]$ are mass matrices, $[C_A]$ and $[C_B]$ are damping matrices, $[K_A]$ and $[K_B]$ are stiffness matrices, $\{q_A\}$ and $\{q_B\}$ are generalized coordinates. $\{F_A\}$ and $\{F_B\}$ are forces which provided by shock absorbers. The forces provided by the i-th shock absorber can be expressed:

$$\{F_{Ai}\}=[R_i][C_i][R_i]^T(\{\dot{X}_{Bi}\}-\{\dot{X}_{Ai}\})+[R_i][K_i][R_i]^T(\{X_{Bi}\}-\{X_{Ai}\}) \tag{7}$$

$$\{F_{Bi}\}=[R_i][C_i][R_i]^T(\{\dot{X}_{Ai}\}-\{\dot{X}_{Bi}\})+[R_i][K_i][R_i]^T(\{X_{Ai}\}-\{X_{Bi}\})$$

$\{X_{Ai}\}$ and $\{X_{Bi}\}$ are displacements at the mounting point and they can be expressed by deformation matrix:

$$\{X_{Ai}\}=[W_{Ai}]\{q_A\} \tag{8}$$

$$\{X_{Bi}\}=[W_{Bi}]\{q_B\}$$

Substitute equation (7) ~ (8) into (6) and write in matrix form we can get:

$$[M_{AB}]\{\ddot{X}_{AB}\}+[C_{AB}]\{\dot{X}_{AB}\}+[K_{AB}]\{X_{AB}\}=0 \tag{9}$$

$[M_{AB}]$ is mass matrix of the coupled system, $[C_{AB}]$ is damping matrix, $[K_{AB}]$ is stiffness matrix, $\{X_{AB}\}$ is generalized coordinates matrix. Their expressions are in equation (10) ~ (13).

$$[M_{AB}]=\begin{pmatrix}[M_A] & \\ & [M_B]\end{pmatrix} \tag{10}$$

$$[C_{AB}]=\begin{pmatrix}[C_A]+\sum_{i=1}^{N}[W_{Ai}]^T[R_i][C_i][R_i]^T[W_{Ai}] & -\sum_{i=1}^{N}[W_{Ai}]^T[R_i][C_i][R_i]^T[W_{Bi}] \\ -\sum_{i=1}^{N}[W_{Bi}]^T[R_i][C_i][R_i]^T[W_{Ai}] & c_{22}=[C_B]+\sum_{i=1}^{N}[W_{Bi}]^T[R_i][C_i][R_i]^T[W_{Bi}]\end{pmatrix} \tag{11}$$

$$[K_{AB}] = \begin{pmatrix} [K_A] + \sum_{i=1}^{N} [W_{Ai}]^T [R_i][K_i][R_i]^T [W_{Ai}] & -\sum_{i=1}^{N} [W_{Ai}]^T [R_i][K_i][R_i]^T [W_{Bi}] \\ -\sum_{i=1}^{N} [W_{Bi}]^T [R_i][K_i][R_i]^T [W_{Ai}] & [K_B] + \sum_{i=1}^{N} [W_{Bi}]^T [R_i][K_i][R_i]^T [W_{Bi}] \end{pmatrix} \quad (12)$$

$$\{X_{AB}\} = \{\{q_A\}^T, \{q_B\}^T\}^T \quad (13)$$

Diesel engine and hull has been coupled to an integration model through equation (9). Combining finite element method the response of diesel engine coupled with hull will be investigated based on real-time simulation method. Diesel engine assembled on hull has been shown in Fig. 5.

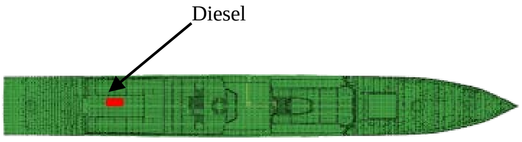


Fig.5 the Assembly of Diesel Engine in Hull

The fluid field surrounded by hull will be modeled by sound elements. The inner fluid field will be meshed finer to catch the hull's response in low and medium frequency and the outer fluid field will be meshed coarsely to increase the computing efficiency. The degree of freedom of sound elements and the degree of freedom of solid elements will be coupled by principle of conservation of linear momentum at their interface.

3.2 Design of load based on underwater explosion

Vessels face attacks from different direction and distance of underwater ordnance. This paper adopts the working condition of shock based on the impact factor of 0.32 according to the Standard. The shock wave of underwater explosion will be described by spherical wave. According to literature the pressure of shock wave can be expressed:

$$p = p_0 e^{-\frac{t}{\theta}} \quad (14)$$

p_0 is the peak of pressure and θ is time constant. They can be defined:

$$p_0 = K_1 \left(\frac{\sqrt[3]{W}}{R}\right)^{A_1}, t < \theta \quad (15)$$

$$\theta = K_2 \sqrt[3]{W} (\frac{\sqrt[3]{W}}{R})^{A_2} \tag{16}$$

W is the mass of explosive, A_1, A_2, K_1 and K_2 are coefficients which depend on the type of explosive. This paper adopts TNT as explosive and the load computed by equation (14) ~ (16) has been shown in Fig. 6. The pressure will be used to as the boundary condition of the integration model.

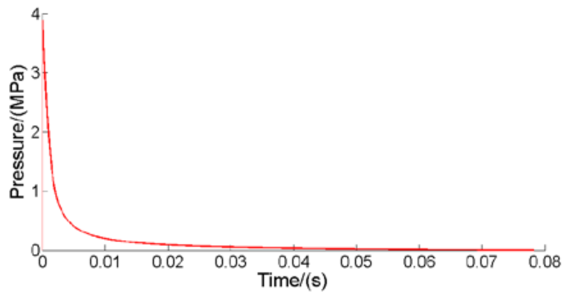


Fig.6 Pressure Curve of Underwater Explosion

3.3 The response of diesel engine coupled with hull under shock

The mises stress nephogram of diesel engine has been shown in Fig. 7. Stress mainly distributes in pedestal, cylinder and the oil pan. The stress of the oil pan is larger than other part. The stress of head and head cover is small compared with pedestal, cylinder and the oil pan.

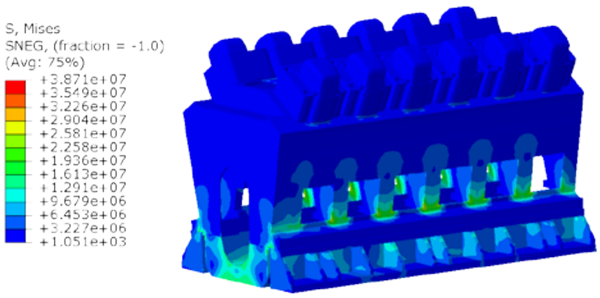


Fig.7 The Mises Stress Nephogram of Diesel Engine

The stress distribution of diesel engine is similar to non-integration model. But the stress is smaller than non-integration model. This illustrates that hull and shock absorber buffer the shock and the non-integration model is conservative. Some elements have been selected to record the stress in order to compare the results between different methods. These elements have been distributed uniformly on diesel engine. The stress distribution in non-integration model and integration model has been shown in Fig.8 and Fig.9.

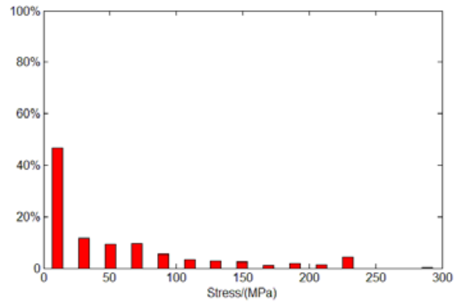


Fig.8 Stress Distribution in Non-Integration Model

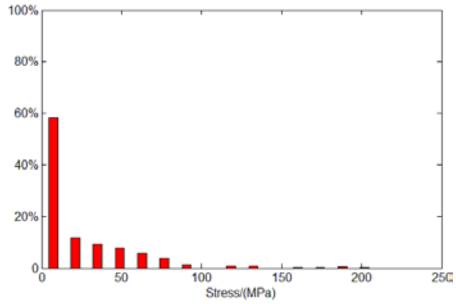
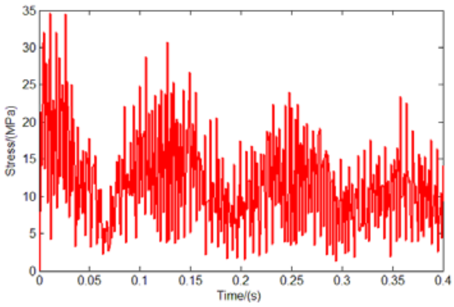
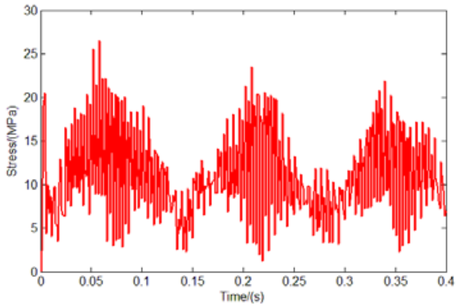


Fig.9 Stress Distribution in Integration Model

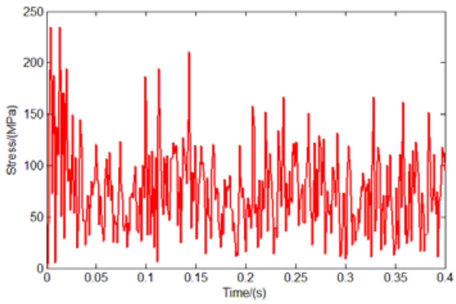
Stress distributions in both models are similar. Stress in integration model is smaller than non-integration model. The proportion of lower stress in integration model is larger than non-integration model. In non-integration model the proportion of elements with stress larger than 200MPa is 8% while the proportion of elements with stress larger than 200MPa is only 0.1%. This illustrates that the non-integration model is a conservative method. The same of the two models is that elements with stress larger than 200MPa belong to the oil pan. In the view of stress response in time domain the two models have presented different characteristics. The stress curves of diesel engine's part in non-integration model and integration model have been shown in Fig. 10 and Fig. 11.



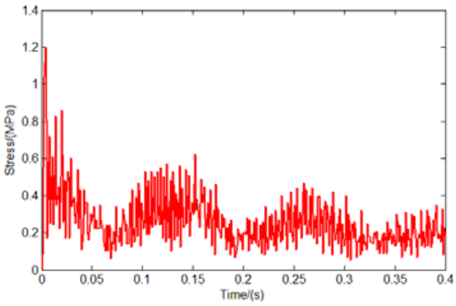
(a) Stress Curve of Pedestal



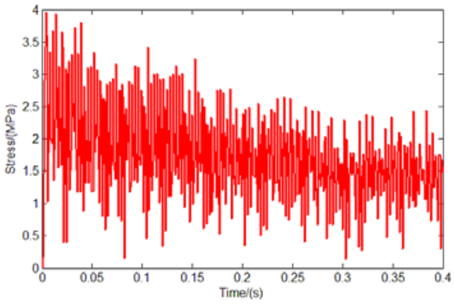
(b) Stress Curve of Cylinder



(c) Stress Curve of the Oil Pan

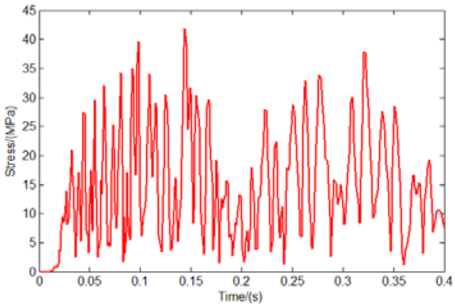


(d) Stress Curve of Head

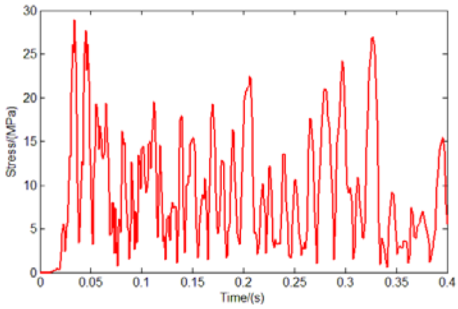


(e) Stress Curve of Head Cover

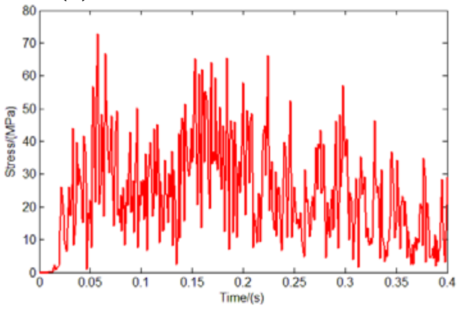
Fig.10 Stress Curves of Diesel Engine's Part in Non-Integration Model Under Shock In Vertical Direction



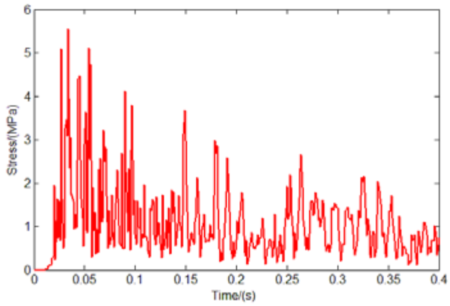
(a) Stress Curve of Pedestal



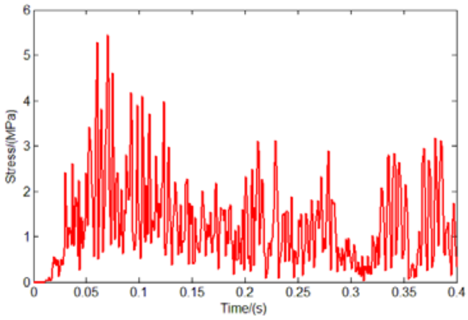
(b) Stress Curve of Cylinder



(c) Stress Curve of the Oil Pan



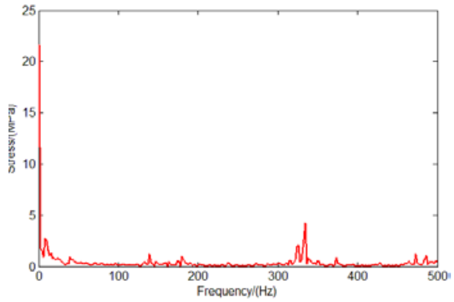
(d) Stress Curve of Head



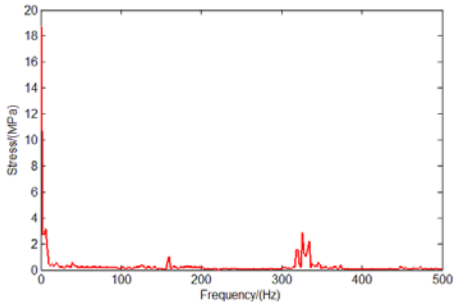
(e) Stress Curve of Head Cover

Fig.11 Stress Curves of Diesel Engine's Part in Integration Model

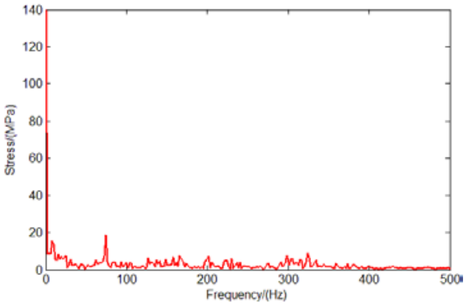
These curves present the similar characteristics of attenuation vibration. The period of stress in non-integration model is shorter than that in integration model. The waveform of stress in non-integration model is more obvious than that in integration model. Take spectral analysis of these curves of both models. The spectrum analysis diagrams have been shown in Fig.12 and Fig.13.



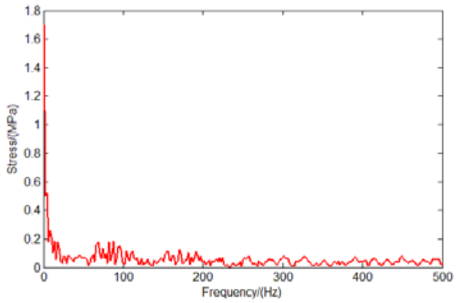
(a) Spectrum Analysis Diagram of Pedestal



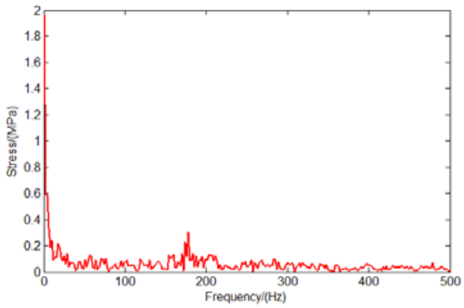
(b) Spectrum Analysis Diagram of Cylinder



(c) Spectrum Analysis Diagram of the Oil Pan

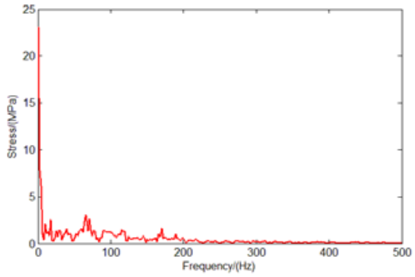


(d) Spectrum Analysis Diagram of Head

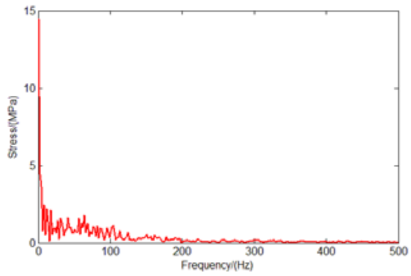


(e) Spectrum Analysis Diagram of Head Cover

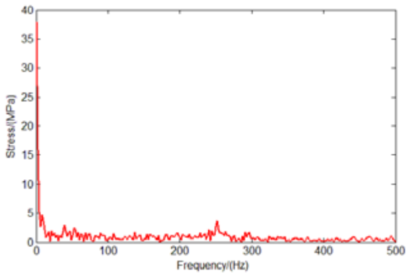
Fig.12 Spectrum Analysis Diagrams of Stress Curves in Non-Integration Model



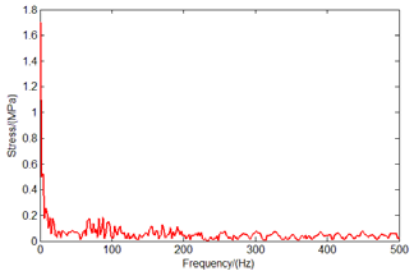
(f) Spectrum Analysis Diagram of Pedestal



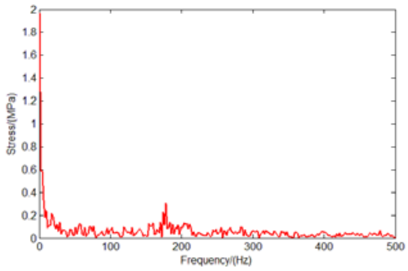
(g) Spectrum Analysis Diagram of Cylinder



(h) Spectrum Analysis Diagram of the Oil Pan



(i) Spectrum Analysis Diagram of Head



(j) Spectrum Analysis Diagram of Head Cover

Fig.13 Spectrum Analysis Diagrams of Stress Curves in Integration Model

The spectrum analysis diagrams of two models present different characteristics. Diesel engine's parts have the same frequency ranges in which the stress has mainly distributed in non-integration model while diesel engine's parts have different frequency ranges in integration model. To be specific, the main frequency ranges of stress in spectral analysis is 300~400Hz in non-integration model. However, in integration model this is not the case. The stress of cylinder and pedestal mainly distributes in 0~100Hz. The stress of head and head cover mainly distributes in 0~200Hz and the stress of the oil pan mainly distributes in 200~300Hz. The stress mainly distributes in low and medium frequency when diesel engine under shock. But the frequency ranges in which the stress distributes is lower in integration model. The stress of diesel engine's part distributes in different frequency ranges is in consequence of the load. The load in integration model is coupled with three directions instead of one direction. Hence, the response is also coupled with characteristics of vibration in different directions. This is better illustrated by comparing the spectrum analysis diagrams in both models. In conclusion, it is necessary to consider the flexibility of hull and it is a more appropriate method to study the response of marine equipment under shock from underwater explosion in integration model.

4 CONCLUSION

This paper builds the finite element model of diesel engine and adopts the calculating modal analysis method to acquire the characteristics of diesel engine and its parts. The frequency of diesel engine is lower than its parts. Pedestal, cylinder and the oil pan tend to resonate with diesel engine. Then the integration model of diesel engine coupled with hull has been built based on the theory of elastic coupling system. The fluid field surrounded with hull has been modeled by sound elements. By comparing the results of integration model and non-integration model the stress distribution is similar in both models, but the stress in non-integration model is smaller. The spectrum analysis diagrams of stress curves in integration models shows that the shock and response of diesel engine are coupled with three directions which is different from non-integration model. The flexibility of hull buffer the shock and it is necessary to analyze the response of marine equipment in integration model.

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