J. Marine. Sci. Appl. (2009) 8: 316-322
DOI: 10.1007/s11804-009-8081-5

Use of a submodel method to check the bolt strength of marine equipment

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Abstract: A submodel method was proposed that works from computational models of marine gear cases to verify that the proposed bolts will give it sufficient structural integrity. Calculations for marine equipment using this system accorded well with conventional results. As an example, an anti-shock computation was processed for a gear case, and the submodel was then employed to check the strength of individual components. The results showed that the gear case connecting structure can satisfy relative anti-shock requirements, and the dynamic response characteristics seen in the bolt structures had a close relationship with the method used for attaching the bolt. This provides a new means for checking the strength of connecting structures on large-scale equipment and thus has significant reference value.

Keywords: submodel method; gear case; connection component; shock-resistance
CLC number: U664.1 **Document code:** A **Article ID:** 1671-9433(2009)01-0316-07

1 Introduction

The shock resistance ability of ship equipment is one of the most important parts of ship vitality, while there are many examples of connection structures breaking by shock load directly[1]. However, the considering of connection components while researching on the shock resistance ability of ship equipment will be of significance to improving ship vitality roundly.

The connection components are mainly composed of bolts and flanges. Currently, there are two methods for calculating the strength and rigidity of bolts. One is to calculate the stress of bolts by empirical equations, but this method can not reflect the stress distribution of bolts; the other is to calculate and analyze the stress distribution of bolts by finite element method. At present, most of the simulations of loading on bolts by finite element method employ the method of simplifying bolts model, which means using beam element to simulate the actual bolts, and representing the connection of bolts by coupling freedom of motion, and this could save the computer resources greatly, but the result of distribution of stress and strain near the coupling of freedom of motion would not be very accurate. Another method is to establish the bolt model by its actual size, and mesh it with consecutive medium elements. This could get the precise finite element model and stress or strain, but the dealing method of normal grids model will bring too many freedoms of motion and be a large waste of computer resources [2-3].

To most ship equipment, there are too many factors to check when doing emulating calculation of shock resistance ability. Due to its small geometric size, modeling the bolts factually will lead to a large scale of calculation, even too large to calculate. But employing the simplified method above can not get the distribution of stress and the strength of bolts. To solve the above illogicality, the glancing bolts model is used in global model to mainly check the shock resistance ability of the whole model, then the result of the whole model is used as boundary conditions to remesh the bolts, and submodel method is used to calculate the shock resistance ability of bolts directly.

2 Submodel method

The cases below often happen in the finite element analysis, that is, the mesh is fine enough to the global structure, while to some important parts, it is still not enough to get more accurate results. There are two methods to get accurate results of the local region. One is to remesh the whole model with smaller element size. To complex structure, it will make the number of elements and nodes in the finite element model increase rapidly, make the number of freedom of motion very large, cost a lot of computing time, and even can not finish the calculation due to the large scale model which exceeds the computer capability. Another one is to analyse the global model firstly to get the whole displacement distribution, then establish the local remeshing model, compute the stress of the local structure's finite element model with the input load of

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Received date: 2008-11-19
Foundation item: Supported by the Shipbuilding Industry of National Defense Science and Technology Research Projects in Advance (07J1.5.3)
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global displacement, which is called submodel method. Submodel method is a finite element technique to increase the solution precision of local region in large complex structure. It can save a lot of computing time while getting accurate results of some important parts. Early in the development of finite element method, submodel method was a powerful tool to solve practical engineering problems under the computer hardware condition at that time. In recent years, although the computer hardware has been developed quickly, the calculation increased on a large scale and the cost in calculation reduced greatly, submodel method is now still employed in solving complex nonlinear problems in hydraulic engineering, aviation and mechanical fields. Submodel method is still called cutting boundary displacement method or specific boundary method. It is based on the theory of Saint-Venant Principle, that is, after the equivalent load instead of the actual load, the stress and strain change a lot only near the load region, while change little away from the load region. Submodel method is based on the analysis results of global model. Cut the global model to get the local model, remesh the local region with subtle grids to establish the submodel, and define the load and boundary conditions of the local region, while load the displacement of the cutting boundary got in the global model on the submodel, then recalculate it to get more accurate results in local region [4].

Besides getting the local accurate results, submodel method has other advantages as below:

1) Reduce and even annihilate the complex transfer region which is needed by finite element solid model.
2) Analyze different designs (for example, different radius of corner) of the part that users are interested to realize.
3) Help users certify if the mesh is fine enough.

3 Validity check of submodel method

3.1 Calculation model

The gear case is used as calculation model to check the dynamic response under shock load, in order to proof the validity of submodel method. Mesh the model with larger element size firstly, and then remesh the model with smaller element size. Load on the global models with two element sizes above respectively, and then recalculate the bolts in the finer remeshing model by submodel method, with the results of rough meshing model as boundary condition. As the structures of gear case and its bolts are simple, the calculation quantity and calculation time are acceptable. So the global results of finer meshing model and the results of submodel method can be compared to certify the validity of submodel method. Fig.1 and Fig.2 are the glancing model and refining model of gear case respectively.

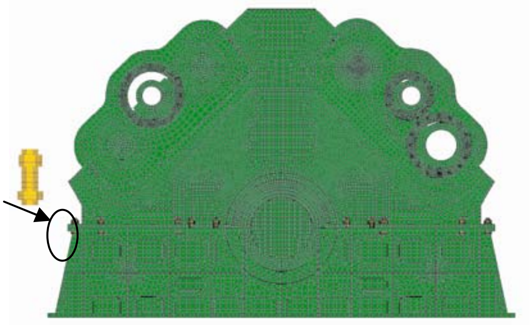


Fig.1 Glancing model of the gear case

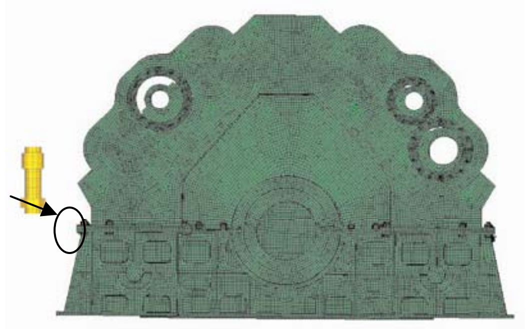


Fig.2 Refining model of the gear case

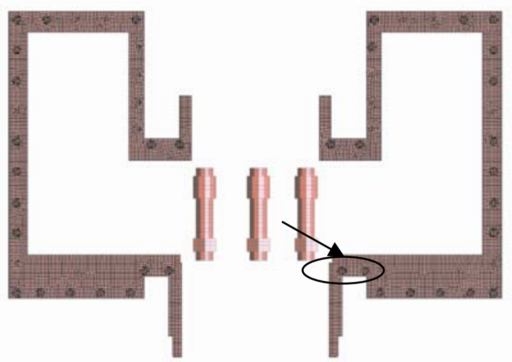


Fig.3 Submodel of bolt and its joint construction

3.2 Material mode

Table1 shows the material characteristics of gear case and bolts.

Table 1 Material parameter

Component	ρ / kg·m^{-3}	E / GPa	μ
Gear case body	7650	201	0.3
Bolts	7800	200	0.3

3.3 Load boundary conditions

3.3.1 Load condition in pretightening

There are two steps in loading on the bolts in this research. Firstly, simulate the pretightening condition of bolts, load the tension stress of 280 MPa on the middle of bolts, and make the calculation time long enough to ensure its balance. Then, load on the position where both sides of cylinder and stayed structure connected. While to the submodel, take the results of the global model on its cutting boundary as load condition.

3.3.2 Shock load

The shock environment refers to the basic input of equipment under the condition of underwater explosion[5]. If represent the shock input signal in frequency-domain, basic displacement motivation is in the main place in low-frequency stage; velocity motivation is in the main place in middle-frequency stage; and acceleration motivation is in the main place in high-frequency stage[6]. So, the triple polygon line spectrum in four-dimensional coordinate shown in Fig.4 is usually used as system shock input spectrum [7]. The shock spectrum is an atlas in which the most severe response of single-degree-of-freedom oscillator with some damp or without damp changed with the free frequency. As the load condition, the shock input spectrum in Fig.4 was changed into the form of pulse and negative triangle waves as shown in Fig.5.

In Fig.4, horizontal ordinate represents frequency *f*, vertical ordinate represents the velocity of spectrum *V*, the included angle of spectrum displacement *D* with horizontal axis is 45degree, and the included angle of spectrum acceleration *A* with horizontal axis is -45degree. And the relationships of the four variables above can be established as below:

$$V = \omega D \tag{1}$$

$$a = \omega V = \omega^2 D \tag{2}$$

$$A = \frac{a}{g} = \frac{V\omega}{g} = \frac{\omega^2 D}{g} \tag{3}$$

where, the unit of *a* is m/s^2, the unit of *A* is *g*.

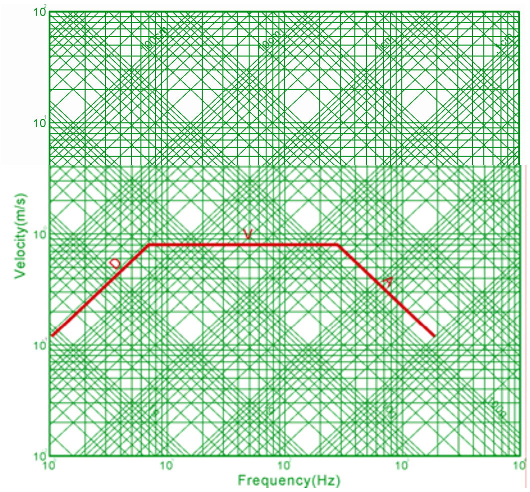


Fig.4 Typical triple-fold line shock input spectrum

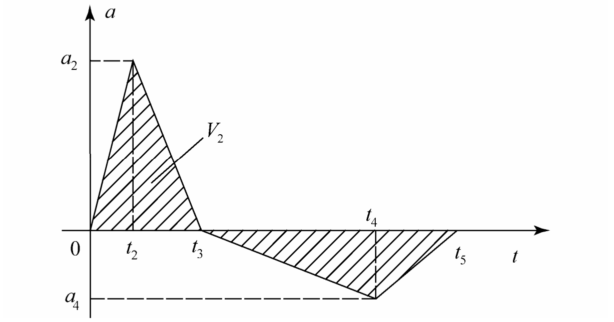


Fig.5 Triangle wave

The triangle transform course in Fig.5 consists of a positive triangle and a negative one whose areas are the same. According to SAS (shock response spectrum), the acceleration peak value of the first triangle is about 0.6 times of the biggest acceleration of a_0. The area of the first triangle is about $3/4$ of the biggest velocity V_0. The area of the second negative triangle is the same as the first one, so the basic final velocity is zero. The secondary integral of the acceleration is displacement, and it will be a little bigger than the biggest displacement of SAS (1.05times). It is appropriate to make $t_2 = 0.4t_3$ and $t_4 - t_3 = 0.6(t_5 - t_3)$, so we can get the relationships as below:

$$a_2 = 0.6 \times a_0 \tag{4}$$

$$V_2 = \frac{3}{4} \times V_0 \tag{5}$$

$$t_3 = 2 \times \frac{V_2}{a_2} \tag{6}$$

$$(t_5 - t_3) = \frac{6 \times d_0 \times 1.05 - 1.6 \times a_2 \times t_3^2}{1.6 \times a_2 \times t_3} \tag{7}$$

$$a_4 = -\frac{a_2 \times t_3}{t_5 - t_3} \tag{8}$$

$$t_4 = t_3 + 0.6(t_5 - t_3) \tag{9}$$

To the ship equipment whose mass is larger than 5 tons, the initial shock acceleration and velocity should be reduced, the reduction formula is as follows:

$$\frac{a}{a_0} = \left(\frac{m}{m_0}\right)^{-0.537} \tag{10}$$

$$\frac{V}{V_0} = \left(\frac{m}{m_0}\right)^{-0.4} \tag{11}$$

This research loads acceleration as in the triangle transform course above on the cylinder, the load peak value a_2 is 15g, pulse width t_3 is 5ms, and the total load time is 50ms.

3.4 Analysis of calculation results

Fig.6 and Fig.7 are the stress nephograms (the above is the enlarged view of bolts) of gear case got by submodel method and normal method with refining model respectively. It can be seen that, the response regularity of bolts with the two methods are basically the same, the middle of the bolt receives larger stress and extends gradually to the roots of nuts.

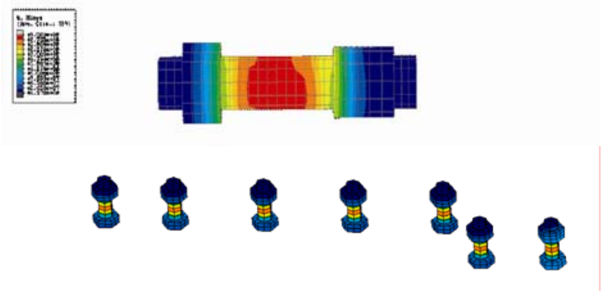


Fig.6 Stress nephogram of the bolt in submodel

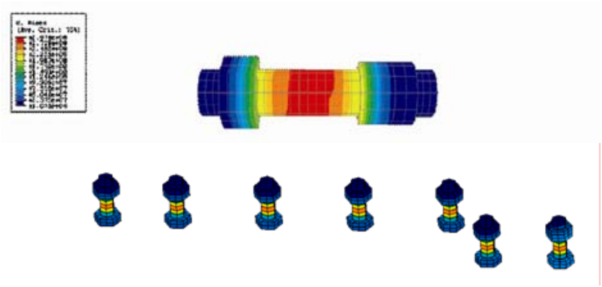


Fig.7 Stress nephogram of the bolt in refining model

It can be seen directly form the two pictures above that the responses regularity of bolts are basically the same for the two methods. Fig.8 shows the comparison of bolts acceleration time history curves between submodel method (red curve) and normal method with refining model (green curve). We can see that the acceleration response regularity of bolts is basically the same by the two methods, and also the same in the magnitude of acceleration response.

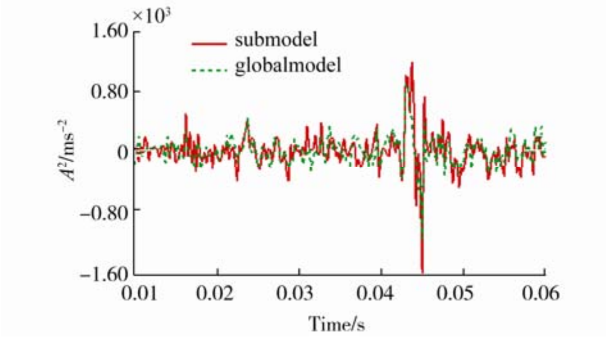


Fig.8 Acceleration curves along with time by two methods

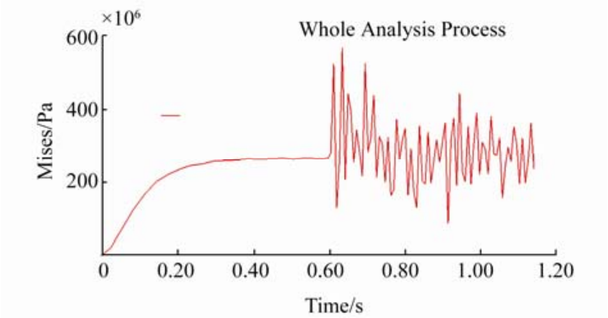


Fig.9 Acceleration curves along with time of the bolt in the whole loading process

Submodel method can be used to simulate the balance process of bolts and the shock load process. Fig.9 shows the Mises time history curve of some bolt in the whole loading process. It shows in the picture that, in the first half of the curve, there are pretightening load on the bolt and balance on it gradually. In the last half of the curve, the results of glancing model are used as the boundary condition of the bolt. As the effect of the dynamic shock load, the bolt Mises shows the characteristics of high-frequency concussion.

To compare the results of submodel method and normal method with refining model, define four check points on the bolts, check the maximum value of Mises, as shown in Table 2.

Table 2 Max Mises stress of these two methods

Compute methods	Check point A	Check point B	Check point C	Check point D
Normal method	459	483	465	492
Submodel method	475	504	486	512
Relative error	3.49%	4.35%	4.52%	4.07%

It can be seen from the table that, the results by submodel method and normal method with refining model are almost the same, and the error is less than 5%, so the bolts' strength in shock load can be solved by submodel method accurately. While refining the submodel structure by submodel method can not only reduce the model scale, shorten the compute time greatly, but also get more accurate results.

4 Calculation example

The validity of submodel method is certified by calculation of bolts in gear case, while to large complex ship equipment, if we mesh the whole model too fine, it will cost too much calculation time to compute. So, submodel method can be employed to recalculate with refining parts which are concerned. The global model can be used to get the dynamic response to shock load of the main parts, while submodel can be used to get the shock resistance performance of such local structures as bolts. Take the navy gear case as an example, the shock resistance ability is checked by submodel method.

4.1 Finite element model of gear case

The gear case model is established with hexahedron grids, glancing mesh is used in bolts and flanges, and the shock resistance isolation equipment is simulated with three-dimensional spring damping units. Then employ the calculation results of glancing model to remesh the bolts and connecting structures, and check the strength of bolts by submodel method. Fig.10 shows the whole finite element model of gear case (bolts are highlighted). Fig.11 shows the bolts model.

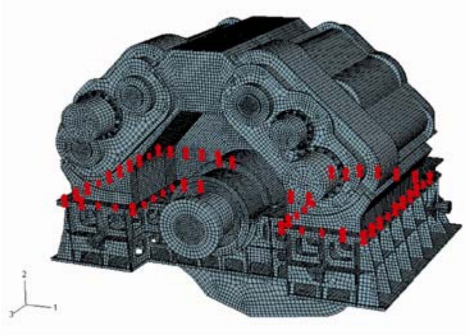


Fig.10 Finite element model of gear case

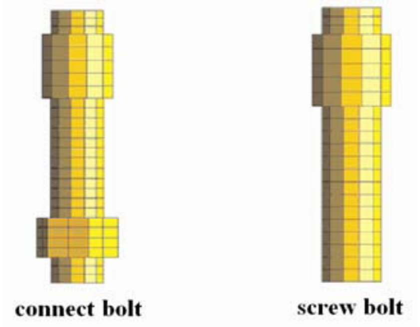


Fig.11 Finite element model of the bolt

4.2 Material pattern

The gear case consists of many components, and different components have different material parameters. The specific parameters are shown in Table 3.

Table 3 Material parameter

Component	P / kg·m^{-3}	E / Pa	μ	σ_s / Pa
Case	7.65×10^3	2.01×10^{11}	0.3	235×10^6
Rotor	7.85×10^3	2.11×10^{11}	0.3	700×10^6
Baffle	7.91×10^3	2.02×10^{11}	0.3	265×10^6
Bolts	7.80×10^3	2.00×10^{11}	0.3	750×10^6

4.3 Strength criterion

According to relative regulations, the maximum stress of connecting bolts of ship equipment under shock load can not be larger than static yield limit[8]. Only when this principle is satisfied can the bolts be safe, that is

$$\sigma < \sigma_s$$

Where σ is the response stress, σ_s is the static yield limit of material.

4.4 Shock load

According to the method introduced in chapter 3.3, and through the reduction calculation of the mass of gear case, the vertical shock load is as follows:

Peak value: 45g, impulse width: 6ms, shock time: 100ms, the pretightening force of bolts is also 280 MPa , loading on the two sides of bolts.

4.5 Analysis of calculation results

Vertical shock is the most basic shock environment of ship equipment, and it is the most normal shock form too[9]. Therefore, Fig.12 shows the whole stress nephogram of gear case under vertical shock, Fig.13 shows the stress nephogram of two kinds of bolts by submodel method.

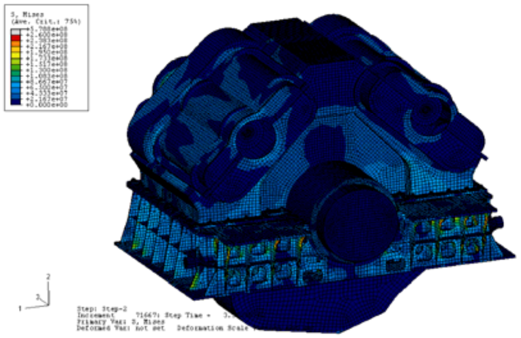


Fig.12 Stress nephogram of gear case

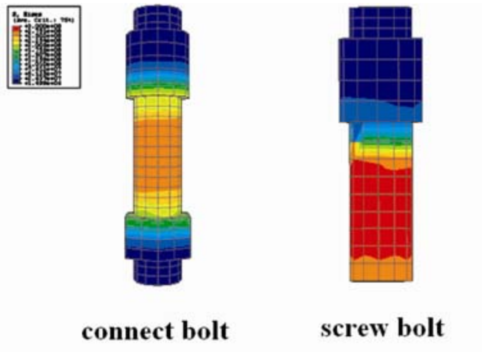


Fig.13 Stress nephogram of bolt by submodel method

It can be seen from Fig.12 that the integral response of gear case is severe, the stress near bolts of gear case and the connection structure such as flange is higher than other parts, and it is reduced so that the transmission of force between components is supported by bolts[10]. Therefore, the stress on both kinds of bolts in Fig.15 is high, and the stress on highlighted bolt is higher than the connection bolt, because the highlighted bolt would also suffer some shearing stress. Fig.14 and Fig.15 show the acceleration curves along with time of connection bolt and tightening bolt respectively.

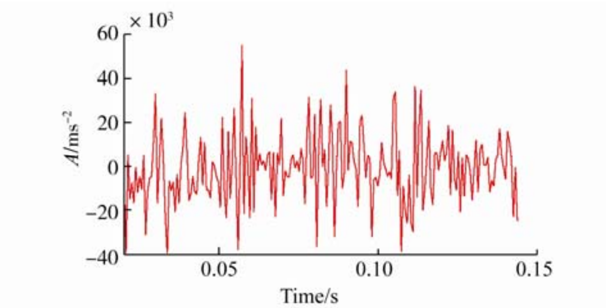


Fig.14 Acceleration curves along with time of connection bolt

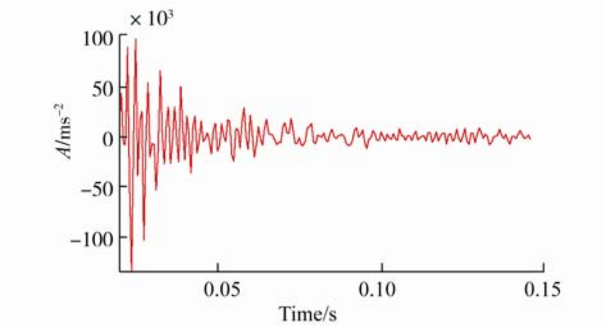


Fig.15 Acceleration curves along with time of tightening bolt

It can be seen from Fig.14 and Fig.15 that the acceleration response of the highlighted bolt is obviously higher than connection bolt, and the acceleration response characteristics of the two kinds of bolts are distinctly different, that reduced to the connection mode of each kind of bolt. To check the strength of bolts, select some check points in each kind of bolts, and the check results of Mises stress are shown in Table 4.

Table 4 Mises stress of bolt

Type	Connect bolt				Screw bolt			
Check point	1	2	3	4	5	6	7	8
Mises stress /MPa	458	462	445	451	512	520	518	524

It also can be seen from Table 4, the stress response on highlighted bolt is obviously higher than the connection bolt, and it proves the conclusion above. While both of the values of Mises stress are not beyond the static yield limit, so it can be said that the bolts' strength of gear case is satisfied with the requirements.

5 Conclusions

This research employs submodel method to check the bolts' strength of ship equipment, certify the validity of submodel method with cylinder, check the bolts' strength of some ship gear case as an example, and get the conclusions as follows:

4) The gross model of bolts could be used to calculate shock resistance of ship equipment, check the dynamic response of the whole equipment. It can reduce the scale of model, save computation time, while remeshing the bolts by submodel method to get more accurate results.
5) Submodel method could be applied to the concerned part, remesh and recalculate it to solve the strength of bolt connection structures exactly, improve calculation accuracy and cave computation time.
6) Check the connection structure's strength of some ship's gear case by submodel method, the calculation results show that the connection bolts of the gear case are satisfied with shock resistance requirements. The dynamic response of bolts is related to connection modes, the screw bolts suffer some shearing stress, so their dynamic responses are more severe than connection bolts.

References

[1] The sixth mechanical industry department of the ship systems engineering office. Underwater explosion material collection of 028G real boat.[M]. 1982.

[2] GAO Bin, SONG Xiao-wen, LU Bin, HAO Yong-gang. Finite element analysis of engine cylinder thread joint strength[J]. Journal of Engineering Design, 2005，8: (56-60)

[3] XIE Hui-min, MA Yue-feng, HAN Jian-bao. The FEM simulation of workpiece connected by bolts [J]. Machinery Manufacturing Engineer, 2002，(1)：48- 49.

[4] ABAQUS Analysis User's Manual[M].Beijing：Machinery Industry Press, 2006.

[5] LIU Jian-hu. Theory and its applications of ship dynamic responses to non-contact explosions [D]. Wuxi: The Research Center of Warship Technology of China, 2002.

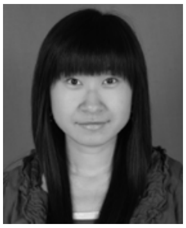
[6] YAO Xiong-liang. Vibration, shock and noise of warship structure[M]. Beijing: China National Defence Press, 2007.

[7] LIANG Cho-Chung, YANG Min-Fang, TAI Yuh-Shioui. Prediction of shock response for a quadrupod-mast using response spectrum analysis method[J]. Ocean Engineering, 2002, 29(8): 887-914.

[8] LIANG Cho-Chung, TAI Yuh-Shiou. Shock responses of a surface ship subjected to noncontact underwater explosions[J].Ocean Engineering, 2006, 33(5-6.): 748-772.

[9] YAO Xiong-liang, CHEN Jian-ping. A study on anti-underwater-explosion performance of ship subjected to gas bubble impulsive pressure [J]. Shipbuilding of China, 2001 (2): 48-55.

[10] HU Yi-gui. The Analysis of shock experimentation on ship equipments [D]. Hrabin: Harbin Engineering University Press, 2002.



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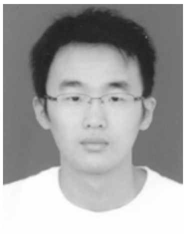

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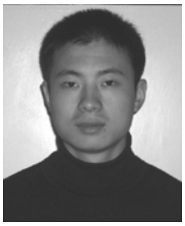

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子模型方法在舰船设备连接结构强度研究中的应用

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摘　要：对子模型方法进行了详细的介绍，并以某舰用齿轮箱为计算模型，验证了冲击载荷下子模型方法计算舰船大型设备中的连接结构强度问题的有效性，其计算结果与常规计算方法的结果十分吻合. 以某舰用齿轮箱为算例进行抗冲击计算，应用子模型方法对该齿轮箱连接构件进行了强度校核. 计算结果表明，该齿轮箱的连接构件可以满足相关抗冲击要求，螺栓结构的动态响应特性与螺栓的连接形式有密切关系. 研究结果对大型舰载设备连接构件的强度校核提供了新思路，具有一定的参考价值.

关键词：子模型方法；齿轮箱；连接构件；抗冲击