DESIGN METHOD OF AN ANTI-SHOCK ELASTIC FLOOR FOR ATTENUATING THE SHOCK RESPONSE OF SEAFARERS

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Under certain conditions of navigation, the strong shock wave from underwater suffering by surface ship, would cause the hull to produce violent shock movement, and effect the ability to work, even endangering the health and life of seafarers, if no protective measures are taken. In order to attenuate the shock response of seafarers, the shock environments of surface ship caused by underwater blast was refined introduced firstly, which referred to the shock wave characters, injury symptoms, safety limits and protection measures. Then, an anti-shock elastic floor was brought forward to protect the above seafarers, especially, the design method of the anti-shock floor was described emphatically, which including the input conditions, performance requirments, scheme framework and main components, and so on. Finally, the performance of anti-shock elastic floor was verified via static and impact tests, which has a good agreement with the design requirments, as well as, could protect the seafarers from the ship shock injury efficaciously.

Keywords: underwater shock environments, protection measures, anti-shock elastic floor, design method

1. Introduction

The ship may be suffered non-contact underwater explosion in specific navigation environment, and the hull will produce violent shock movement, especially the vertical impact is more vigorous[1]. If no effective shock protection measures were taken, ship's shock load will cause moderate damage to the seafarers in the bottom cabins, which will lose normal work ability for a certain period of time, or even threaten the safety of life, and seriously affect the combat effectiveness of the seafarers. For a long time, researchers at home and abroad have established a relatively complete technical system for shock loading, shock damage, shock design and assessment test method for ship structures and equipments, however the research on human impact protection started late. R.M.Mahone[2]、P.R.Payne[3] study on biomechanics response of ship underwater
shock response in the sitting crew of different locations, and the danger of injury was evaluated. Zhang Wei\textsuperscript{4}, Liu Xin-xiang\textsuperscript{5} and Huang Jian-song\textsuperscript{6-8} established the lumped parameter model of human body, and studied the response of human body to underwater explosion under sitting posture, standing and walking state, and carried out shock injury assessment for human. In terms of human shock protection, Wu Jing-bo\textsuperscript{9}, Zhang Lei\textsuperscript{10}, Zhao Yong-jie\textsuperscript{11}, studied on the protection efficiency of anti-shock ground tiles on rubber and metal foam materials based on the response model of human-floor shock, and produced types of human impact protection fittings, such as anti-shock clothing\textsuperscript{12}, shoes\textsuperscript{13}, seat\textsuperscript{14}, helmet, vest etc.

The research on the shock response of human provided an analytical method for the assessment of human shock protection, but there is still no widely accepted standard of evaluation. At the same time, measures been taken have played a shock protective role for the seafarers, for example, anti-shock ground tiles can provide anti-shock environment for important position, but impact on cabin space, equipment layout and personnel walking feeling. In order to provide better anti-shock environment for seafarers, and more stable walking feeling for staffs, this thesis sums up the anti-shock criterion and safety limits based on the analysis of the underwater shock wave and body injury characteristics, then a more effective anti-shock elastic floor is designed, at last its good shock protection effect is verified by impact test.

2. Underwater shock environments

2.1 Characteristics of underwater shock

The shock movement of ship is caused by the shock wave generated by underwater explosion, so the factors such as medium, quantity, location and condition of underwater blast have a direct effect on the magnitude, duration, and destructive power of shock wave. The physical characteristics of a ship shock wave show that the action time is very short (several to dozens of ms), and the shock acceleration is very high (up to 1000G). For surface ships, the vertical shock response is mainly due to the attenuation of the water surface. The damage degree of the underwater explosion to the ship and its hull structure is usually described by the parameter of the keel shock factor (KSF)\textsuperscript{15}, as shown in Figure 1 and Equation\textsuperscript{(1)}.

\[
KSF = \frac{\sqrt{W}}{R} \times \frac{1 + \sin(\theta)}{2}
\]

where \(W\) is the explosive equivalent (unit kg), and \(R\) represents the distance from the explosion point to the keel(unit m), \(\theta\) represents the angle from the line between the blasting core to the keel and the horizontal plane(unit \(^\circ\)).

Figure 1: Shock wave of underwater explosion to surface ship

The shock environment is the basic input for the design and assessment of underwater shock resistance for equipment and human. The shock environment is usually described by shock response spectrum (referred to as shock spectrum). In document\textsuperscript{16-17}, a more detailed method for calculating
the shock spectrum is given. In order to understand the physical meaning of the shock spectrum, the shock spectrum is described by mathematical formula. Assume that the shock of the equipment or human on different parts of the ship is expressed by the acceleration curve $z(\tau)$ on time domain, the shock spectrum is calculated by Equation (2-4).

\[
\text{Spectral velocity: } V = \left[ \int_0^\tau z(\tau) \sin \omega(t - \tau) d\tau \right]_{\text{max}} \tag{2}
\]

\[
\text{Spectral displacement: } D = V_0 / \omega \tag{3}
\]

\[
\text{Spectral acceleration: } A = \omega V_0 \tag{4}
\]

where $\omega$ is circular frequency, $\tau$ is the time variable of shock, $t$ is the duration time of shock. The spectral velocity $V$ represents the static initial velocity of a single degree of freedom system at $t<0$, spectral displacement $D$ is the maximum relative motion between the base loading mass $m$ and the base, spectral acceleration $A$ is considered to be the maximum effective acceleration of the mass $m$ to obtain $D$. The translation from shock response of acceleration on time domain to the shock spectrum is shown in Figure 2.

![Figure 2: Translation from shock response acceleration to shock response spectrum](image)

In the actual calculation and test, the input value of human shock environment is the parameters in time domain, which is translated from the spectrum parameters (maximum spectrum displacement, maximum spectrum velocity, maximum spectrum acceleration) on each position to double sinusoidal wave form.

The response process of non-contact explosion suffering by ship has two distinct stages: the first stage is the response movement with short duration and high acceleration caused by shock wave, the second stage is the pulsating pressure of the negative pressure bubble formed by the explosion, which is mainly vertical shock. In the process of transmission, the energy is constantly consumed, and the shock response from the bottom deck to the upper deck, until the superstructure gradually weakened. According to the simulated values of ship shock environment in 1000kgTNT equivalent explosion\(^{[18]}\), the shock environment of the lower deck is harsher, and the staff is more concentrated, the spectrum velocity in shock spectrum is about 3.3~4.2m/s, the spectrum displacement is about 3.8~8.6cm, the spectral acceleration is about 110~170G.

### 2.2 Injury mechanism of shock wave to human

Injury mechanism is a description of the mechanical factors that cause human anatomy and function damage, that is, how to damage human tissues or organs during shock process. The body injury caused by underwater explosion is mainly due to the shock acceleration. In the shock stage with positive acceleration, the deck suddenly has an upward shock acceleration motion, and the staffs on deck are overweight due to the downward inertia force, which makes the human body in compression state. If the compression stress of the weight-bearing bone is more than the compressive strength of the bone, it would cause the damage of crew.
It is generally believed that the shock acceleration (action time less than 1 s) mainly causes pain, transient loss of consciousness and various mechanical injuries, such as tissue and organ deformation, tear and destruction, and so on, even death in serious case. The tolerance limit of shock acceleration on human body is not only related to 3 parameters of acceleration peak value, duration and overload rate, but also related to acceleration direction, location, personnel position and restraint condition. The injury to the standing staffs mainly occurred in the lower extremities and foot calcaneus, especially the comminuted fracture of the calcaneus, and the lumbar contusion occur in the sitting staff. The foot joints, lower limbs, lumbar joints, muscles and soft tissues of the human body are excellent impedance elements to absorb shock energy. The shock is instantaneous, so the impact from the lower portion of the body transferred to the upper limbs, chest and abdomen, head and neck have been greatly attenuated, the protection keynote should be the load of the weight-bearing limbs, lower limbs and heels for standing staff, hip and lumbar spine for sitting staff. The research shows that the shock tolerance of sitting body is greater than that of standing. Therefore, the shock tolerance value of standing body is usually taken as the safety limit of ship shock environment on human body.

Secondary injury is usually occur in the shock process, when the critical value of the shock velocity or acceleration exceeds the body kickoff velocity or acceleration, the staff would fly off deck due to inertia. For standing staff, the critical value of the kickoff velocity and acceleration\(^3\)\(^{[18]}\) can be obtained with Equation (5-6).

\[
V_{fm} \geq \frac{\pi^2 - \omega^2 t_0^2}{\sqrt{2\pi \omega^2 t_0^2} \cdot \sqrt{1 + \cos \omega t_0}} g
\]  
\[
a_{fm} = \frac{\pi V_{fm}}{t_0} \cdot \cos \frac{\pi T}{t_0}
\]

where \(V_{fm}\) is the critical kickoff velocity, \(a_{fm}\) is the critical kickoff acceleration, \(\omega\) is the natural vibration frequency of human body, \(T\) is the natural vibration period of human body (about 100ms), \(t_0\) is duration time of shock process.

Therefore, the shock injury of seafarers caused by underwater explosion can be divided into two types of contact injury and non-contact injury. The damage caused by the collision between the body and other objects is contact damage. The damage caused by the overload of the body limit value of velocity or acceleration is non-contact injury.

### 3. Assessment and limit of human shock protection

The purpose of human shock protection is to take necessary protective measures according to the tolerance limits of body under the shock environment, so as to reduce the probability of human shock injury.

The contact injury is mainly the secondary injury caused by the collision with the deck, bulkhead, or equipment when the crew fly off the deck under the shock inertia. According to Equation (5-6), the shock time is more short, the required shock strength for body flying-off is more powerful. The shock duration time that applying on the deck gradually increases from the lower to the upper, so the probability of kickoff or falling-off is greater for staffs on upper deck. The limit velocity of body kickoff is required less than 3m/s to prevent from collision\(^3\)\(^{[19]}\).

The protection of non-contact impact damage should consider the shock tolerance of the human body. According to the limit given by the anti-shock standard cited in the references, when the shock time of ship is less than 15 ms, the shock injury mainly depends on the shock velocity. The velocity range of mild injury is 2.2 m/s~3.0 m/s, the range of moderate injury is 3.0 m/s~4 m/s, and the scope of severe injury is more than 4 m/s. When the shock time of ship is more than 15 ms, the shock injury mainly depends on the shock acceleration, and the limit range of the safety shock acce-
The shock tolerance in the tibia of the lower limbs was 5400 N and that of calcaneus was 6306 N. Since the shock response of human body is a process of acceleration, velocity and process time, various factors should be taken into consideration when making human protective measures.

4. Anti-shock elastic floor

According to the tolerance limits of seafarers to the ship underwater blast shock and the possible shock injury, a series of individual protective equipment were taken to prevent kickoff or falling-off in contact shock injury, including anti-shock shoes, anti-shock helmet, anti-shock seat, and so on. Non-contact shock protection needs to provide an anti-shock platform in the relatively dense area of staffs, which would make sure that when the shock occurs, the staffs carried on will not cause non-contact injury and keep the operational ability under the shock environment. The existing shock protection device is anti-shock ground tiles.

In order to improve the more effective platform for shock environment, a kind of anti-shock elastic floor is designed. The anti-shock elastic floor is composed of shock damping buffer, floor and mounting frame, as shown in Figure 3. The shock damping buffer mainly includes wire rope elastomer and cylinder dampers. The shock damping buffer has mechanical properties with variable stiffness. Under steady working condition, it has enough load capacity and small deformation to ensure normal working and better walking. When the shock deformation exceeds the loading critical point, the stiffness quickly becomes smaller, while the shock energy from the deck is rapidly isolated or reduced, and the staff on floor is effectively protected.

![Diagram of Anti-shock Elastic Floor]

The mechanical performance curve of variable stiffness in Figure 8 is the design goal of the anti-shock shock elastic floor, which requires that the deformation when bearing the standard body weight of 77kg is less than 2mm, and the critical deformation of stiffness varying is 3mm. The severe shock environment (the maximum acceleration is 82G, the maximum velocity is 4.2m/s, the duration 6s~8s) is used as the assessment shock input.

![Force-strain curve of anti-shock elastic floor]
The anti-shock elastic floor is equivalent to a single degree of freedom shock isolation system. According to the relationship between maximum velocity $V_1$ and maximum buffer deformation, as shown in Equation (7), the maximum shock displacement of the buffer system $\delta_m$ can be obtained. According to the capacity, stiffness varying and deformation of the buffer device, the structure parameters of wire rope elastomer are determined, and the damping coefficient and compression stroke rate of cylinder damper is regulated, in order to buffer the shock time prolonged, and meet the design requirements of the shock response output.

$$\frac{V_1^2}{(2\pi f_0)^2d^2} = \ln(\cosh^2(\frac{\delta_m}{d}))$$

(7)

where $\delta_m$ is the maximum displacement response of the buffer device, $V_1$ is the maximum velocity of the system output, $f_0$ is the shock excitation frequency, and $d$ is the critical deformation of stiffness varying of the buffer device.

The anti-shock elastic floor is designed via parameters optimization, and three groups of samples are tested on the pneumatic shock test platform. The results of the test and evaluation are shown in Figure 9 and Table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>Input of shock environment</th>
<th>Shock response of anti-shock elastic floor</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Maximum velocity (m/s)</td>
<td>Time to reach maximum velocity (ms)</td>
</tr>
<tr>
<td>1</td>
<td>maximum acceleration is</td>
<td>2.64</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>82G, maximum velocity is 4.2m/s, duration is 8.1s</td>
<td>2.71</td>
<td>53</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>2.76</td>
<td>53</td>
</tr>
</tbody>
</table>

Figure 9 and Table 1 show that the shock maximum velocity of elastic floor output is 2.76 m/s less than the kickoff velocity limit of 3 m/s, the maximum average acceleration is 52.8 m/s² less than the safety acceleration limit of 130~140 m/s², the maximum force of load bearing is 4065 N less than the tolerance in the lower limb tibia of 5400 N, and the attenuation rate of the shock acceleration load is 93%. The performance comparison with the human shock protection measures men-
tioned above is shown in Table 2. The anti-shock elastic floor shows excellent shock protection effect, and can provide a safe anti-shock environment for areas at staffs concentrate or severe shock environment.

<table>
<thead>
<tr>
<th>No.</th>
<th>Protection type</th>
<th>Protection measures</th>
<th>Protection part</th>
<th>Protection effect (Attenuation rate of the shock acceleration load)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Contact protection</td>
<td>Anti-shock helmet</td>
<td>Head</td>
<td>45%</td>
</tr>
<tr>
<td>2</td>
<td>Contact protection</td>
<td>Anti-shock shoes</td>
<td>Heel, calf</td>
<td>63%</td>
</tr>
<tr>
<td>3</td>
<td>Contact protection</td>
<td>Anti-shock seat</td>
<td>Pelvis (sitting)</td>
<td>36%</td>
</tr>
<tr>
<td>4</td>
<td>Non-contact protection</td>
<td>Anti-shock ground tiles</td>
<td>Areas at staffs concentrate or severe shock environment.</td>
<td>80%</td>
</tr>
<tr>
<td>5</td>
<td>Non-contact protection</td>
<td>Anti-shock elastic floor</td>
<td></td>
<td>93%</td>
</tr>
</tbody>
</table>

5. Conclusion

The research on the human protection in the shock environment is closely related to the shock environment, the distribution and the working condition of the staffs in different parts of the ship. The design limits and evaluation index of the human shock protection are given from the aspects of kick-off velocity, shock response acceleration, maximum velocity and endurance force of human tibiae, etc, based on the characteristic analysis of ship shock environment and injury mechanism to human body.

In order to further improve the anti-shock performance of staff, a new kind of anti-shock elastic floor was put forward. Then, the mechanical properties with variable stiffness, structure composition and design method were studied. Finally, test results show that the shock attenuation rate of the shock acceleration load was up to 93%, which is higher than the existing measures, and has a good human shock protection effect.

REFERENCES


