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Research on drop tower technology for simulating explosive impact load

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Abstract. When military vehicles are subjected to a mine blast, the vehicles will be damaged and the occupants will be injured. The main objective of this paper is to study the feasibility and accuracy of the drop tower to simulate the response of the vehicle body under the actual explosion condition. The equivalent damage method of impact waveform simulation was studied, and the feasibility of the equivalent damage principle of impact waveform based on change in velocity was verified. By analyzing a large number of data of simplified seat impact simulation, the mechanical model of the drop tower was analyzed. Through the correlation study of the parameters of the drop impact load, the relation formula of the drop height required by the target load was constructed, and the customization of the impact load was realized. The response simulation of the protective seat in the explosion was completed in the drop tower, which verifies the accuracy of the drop tower in simulating the explosion impact load. In addition, the results provide a good basis for the follow-up research.

1. Research background and significance

In recent years, bottom explosion has become one of the most common causes of casualties among soldiers [1].The transient vertical acceleration and deformation of the vehicle body caused by the huge energy of the explosion impact load cause a threat to the safety of the occupants, especially causing serious damage to the spine. As for ensuring the safety of occupants in armored vehicles, it has attracted increasing attention as a frontier research topic in multiple interdisciplinary subjects [2]. Therefore, it is of great practical significance to carry out research on protective seats in an explosive environment to improve the occupant protection level of my country's armored vehicles.

At present, there is no perfect industrial standard in the field of performance evaluation of the protective seats. As a complex system, protective seats need a perfect closed loop of design-production-test to continuously optimize their performance [3]. Therefore, in order to study and evaluate the damage of the explosion environment to the occupants, the explosion protection tests at the bottom of the vehicles based on NATO AEP-55 with protective seats and dummies are usually carried out. However, in the research process, the vehicle explosion protection tests have the disadvantages of too high cost, large contingency and non-repetition, while the protective seat drop tower tests have low requirements for the test site, can effectively simulate the impact on the seats and occupants in the explosion environment, and can effectively verify the buffering and energy absorption effect of the protective seats.

Simulating the explosion environment is essentially simulating the impact conditions in the explosion, the impact test devices are used to test the ability of protective seat to protect the safety of occupants under a certain impact load. According to the structural differences of the impact devices and the characteristics of impact load required for testing, impact test devices can be divided into many types, mainly including impact test machine, Hopkinson compression bar device, Machett hammer, air cannon, etc [4]. Among them, the Hopkinson pressure bar device, Machett hammer, and air cannon are mainly used to generate horizontal impact and the size of the test piece is small, which cannot be adapted to the vertical load suffered by the protective seats. Common impact test machines used for vertical impact include drop type, pneumatic type [5], and electro-hydraulic type impact test machines, etc.

Typical drop tower impact test apparatus is shown in figure 1. The drop principle is that the drop platform is lifted to a certain height by mechanical, hydraulic and electric methods and then released. The drop platform makes an approximate free-falling movement, and the bottom of the platform collides with the pulse generator and receives an upward impact load in a short time.

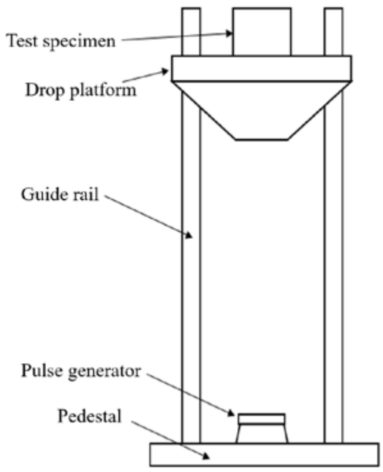


Figure 1. Model of the drop tower.

Because the explosion impact load is an impact load with short pulse width and high amplitude, around these two characteristics, domestic and foreign scholars have done a lot of research on these vertical impact load test devices. Xiaojun Zou [6] studied the characteristics of different impact test devices and the impact environment they adapt to, providing a complete idea for the design of the impact test devices according to the performance requirements of the impact test devices; Pinghua Lv [7] designed and calculated the 100kg impact test devices according to the design and development work practice, analyzed and constructed the mechanical model of the test devices according to the drop principle, and studied the empirical formula of the drop height, pulse width and acceleration peak value; Ting Chen [8] finally produced a specific acceleration peak and pulse width in the drop tower through repeated pre-experiments; Cheng M [9] analyzed the feasibility of using drop tower to simulating explosion experiment, and it was found that with the increase of the drop platform mass, the DRI response value is closer to the dummy's DRI response value in explosion experiments; Kelly [10] carried out 12 protective seat drop experiments with different energy absorbing elements on the drop tower, and it was found that a specific drop height was required for a specific pulse amplitude, and the impact peaks were 200g and 350g corresponding to the two protection levels of the U.S. military; James [11] believed that the lack of a standard procedure for the drop tower for mine resistant means that the experiments will be carried out in the case of inconsistent test equipment tools, which will result in any given protective seats drop test performance report may not accurately reflect the protection degree for soldiers in the actual explosion events.

(a) (b)

Figure 2. Drop tower.

At present, the foreign research on the test methods is relatively rich, and different forms of attempts have been made in the design and test method of the drop tower. The influence of key factors of the drop tower, such as drop height, material, thickness and density of the pulse generator, on the drop impact load have been studied, and through the experiments to compare and evaluate the cushioning energy absorption effect of a variety of protective seats. However, there are few researches in China, and the researches in this field are only in the initial stage.

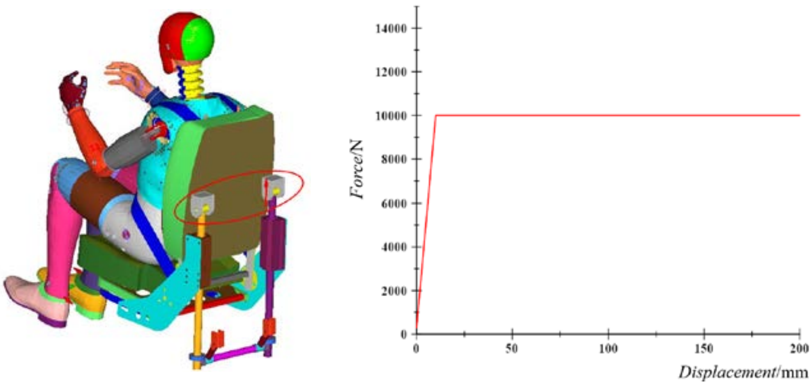
2. Research on equivalent damage of the explosion load

The core goal of this paper is to realize the simulation of the explosion impact environment through the drop tower. The bottom explosion experiments conducted according to NATO AEP-55 standard can obtain the actual explosion load waveform, and the ideal regular shape is adopted to represent the specific impact. Therefore, regular waveforms can be obtained through drop tower experiments to simulate the explosion load. At present, honeycomb aluminum, rubber or other elastomers are used as pulse generators for drop tower, which are easy to generate approximately semi-sine wave shape during drop impact, and the waveform is easy to realized and controlled [12]. Therefore, in the research of this subject, the approximate half-sine pulse generated by the impact pulse generator of the drop tower is used to complete the simulation of the explosion impact load.

At present, relevant scholars have proposed several explosive pulse loading parameters to represent and predict the severity of the explosion and the damage degree of the dummy. The most widely used parameters are peak acceleration G_{peak} and the change in velocity ΔV [13]. Similarly, for any given vehicle and explosion position, this acceleration peak and change in velocity can correspond to the explosion load expressed by the equivalent TNT in kilograms. The accuracy of these two parameters in predicting explosion damage will be discussed below.

2.1. Parametric simulation model

The simplified seat model is adopted to simulate the transient impact acceleration, and vertical upward acceleration pulse is given to the seat mounting points[14].The finite element model of the seat and the displacement-force curve of the seat energy absorbing element are shown in figure 3.



(a) (b)

Figure 3. Simplified seat model and force-displacement curve of the energy absorbing element.

The acceleration pulse waveform is a completely regular semi-sinusoidal waveform, and the relationship between the change in velocity ΔV of the semi-sinusoidal waveform, the acceleration peak G_{peak} and the pulse width T is：

$$\frac{2}{\pi} G_{peak} T = \Delta V \tag{1}$$

ΔV ranges from 12m/s to 1m/s (with 1m/s as the interval), pulse width ranges from 2.5ms to 60ms (a total of 13 different duration levels), and corresponding acceleration peak ranges from about 3g to 770g for parameter research. The 13 pulse widths are 2.5ms, 5ms, 10ms, 15ms, 20ms, 25ms, 30ms, 35ms, 40ms, 45ms, 50ms, 55ms and 60ms respectively. Figure 4 shows 12 simulation conditions when the pulse width is 2.5ms, and the other 12 simulation conditions are analogized.

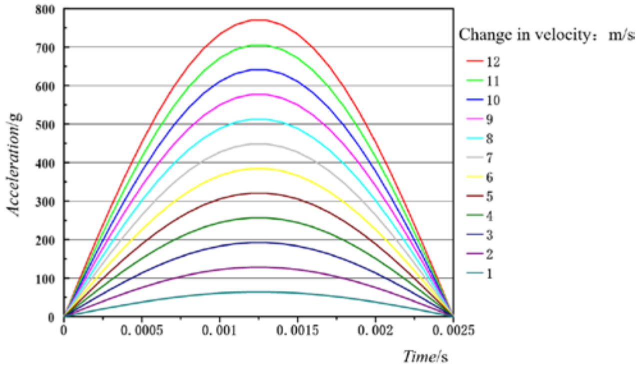


Figure 4. 12 simulation conditions when pulse width is 2.5ms.

2.2.Results analysis of the parameters research

After the simulation calculation was completed, the dynamic response index DRI_Z (pelvic dynamic response), HIC_{15} (head injury tolerance), axial force of the lumbar spine and axial force of the neck were extracted from each calculation result. As shown in figure 5, the change in velocity ΔV and the acceleration peak value G_{peak} are taken as the abscissa respectively, and the damage response of each part is taken as the ordinate, and each curve corresponds to a constant pulse width T.

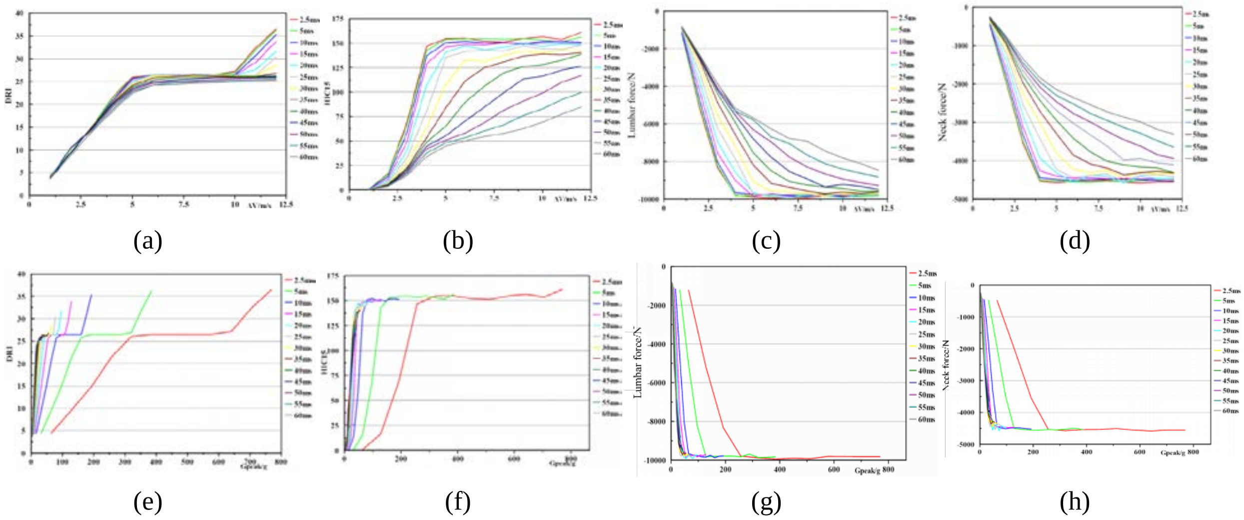


Figure 5. Occupant injury response curves.

Taking DRI_Z as an example, the DRI_Z damage curves when the pulse duration is 2.5ms, 5ms and 10ms basically conform to the following functional relationship. When $\Delta V \geq 1$m/s, the DRI_Z value increases linearly; the DRI_Z curves maintain the platform phenomenon in the interval of 5m/s$\leq \Delta V <$10m/s. When 10m/s$\leq \Delta V <$12m/s, DRI_Z continues to increase linearly. When the protective seat experiences the same amount of the change in velocity, the pulse duration and acceleration peak value are different, but the degree of DRI_Z damage is very close.

$$DRI_Z = \begin{cases} 5.6\Delta V - 2 & (1 \le \Delta V < 5) \\ 26 & (5 \le \Delta V < 10) \\ 4.5\Delta V - 19 & (10 \le \Delta V < 12) \end{cases} \quad (2)$$

Therefore, within 10ms of the pulse width, when ΔV is taken as the influencing factor, the occupant injury curves are more concentrated. However, when G_{peak} is taken as the influencing factor, the occupant injury curves are very scattered. This shows that when the pulse width of the impact load is short (explosion impact can be simulated), the change in velocity ΔV has more potential than the acceleration peak G_{peak} in representing the explosion impact load level and predicting occupant injury, and the correlation between the change in velocity and the occupant injury is higher.

3. Research on technology of the drop tower

3.1.Mechanical model analysis of the drop tower

The basic method of the protective seat drop experiment is to use the lifting mechanism to lift the drop platform (including the protective seat and dummy on the platform) to a certain height and release it. The drop platform collides with the bottom pulse generator to generate acceleration pulse signals, so as to realize the approximate simulation of the acceleration impact load under the bottom explosion of armored vehicles. This system can be described by the following single degree of freedom vibration system, as shown in figure 6.

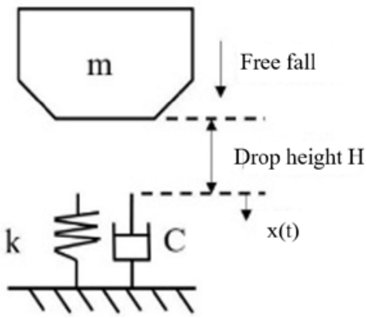


Figure 6. Schematic diagram of the drop tower.

The mechanical model is described as follows:

$$\mathrm{m}\frac{d^2x}{dt^2} + C\frac{dx}{dt} + kx = \begin{cases} \mathrm{mg} & (0 < t < T) \\ 0 & (t < 0, t > T) \end{cases} \quad (3)$$

m is the mass of the drop platform and the seat-dummy system; *k* and *C* are stiffness and damping values of the pulse generator respectively; *x(t)* is the deformation of the pulse generator; *T* is the acceleration pulse width.

The calculated acceleration amplitude is as follows:

$$\ddot{x} = (\frac{2Hk}{mg})^{-1} \quad (4)$$

Then the pulse width is as follows:

$$T = \frac{\pi}{\omega} = \pi(\frac{m}{k})^{-1} \tag{5}$$

The relationship between the drop height and the acceleration peak and pulse width can be obtained comprehensively:

$$H = \frac{g}{2\pi^2}(\ddot{x} \bullet T)^2 = 0.496(\ddot{x} \bullet T)^2 \tag{6}$$

The analysis shows that the acceleration peak is directly proportional to the drop height and the stiffness of the pulse generator, and inversely proportional to the drop mass. The pulse width is directly proportional to the drop mass and inversely proportional to the stiffness of the pulse generator.

3.2. Research on the correlation of drop impact load parameters

The relationship between acceleration peak value, pulse width and parameters of the drop tower has been analyzed according to the mechanical model. In this section, the correlation between acceleration peak value, pulse width and drop height will be further studied, and drop height will be customized according to the explosion impact load. In the analysis, because ΔV can be obtained by G_{peak} in a typical explosion, G_{peak} is taken as the specific research object of the impact load for convenience of the research.

In the previous section, the single degree of freedom mechanical model of the drop tower system revealed the functional relationship between the acceleration peak ,pulse width and drop height, the stiffness of the pulse generator and the drop mass, where the relationship between the drop height and the peak acceleration and pulse width is as in equation(6).

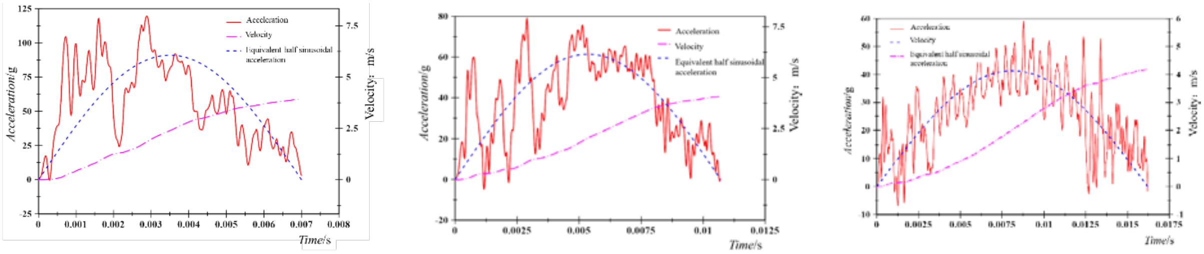
The formula is based on ideal conditions and ignores the energy loss caused by vibration and friction of the trestle, drop platform, guide rail, etc. Therefore, before the drop experiment is conducted to simulate the response of the protective seat and dummy in the explosion environment, the formula revealed by the above mechanical model must be verified through the test and confirm the rationality of the design of the drop tower, and for the equation(6), the formal modification shall be made.

Therefore, customization of the acceleration pulse in the explosion experiment can be quickly realized, and time and experiment cost can be saved.

As shown in figure 7, in order to eliminate the error in the experiment as much as possible, the drop experiment was carried out under the experiment condition without the protective seat and dummy system. In the experiment, the same Endevco piezoresistive acceleration sensor was used to measure the response of the drop platform. In each of the following experiment conditions, the acceleration shall be taken as the middle value, and the sampling time shall be the whole falling impact process. In order to facilitate observation of the difference of the change in velocity, only the waveform within the pulse width shall be presented.

Figure 7. Preliminary drop experiment.

3.2.1. The influence of the pulse generator thickness on drop impact load parameters. The rubber with the thickness of 30mm, 50mm and 100mm was used respectively, and the Shore hardness was Hs55. The drop mass was 373kg and the drop height was 0.5m. In the following data graphs, in order to facilitate observation and calculation of the change in velocity, the velocity starts from zero. The red line is the measured acceleration of the drop, the blue line is the change in velocity of the integral of the drop acceleration, the purple line is the equivalent ideal regular half-sine waveform at the same change in velocity, and the calculation of the acceleration peak also uses the equivalent complete regular half-sine peak.



(a) (b) (c)

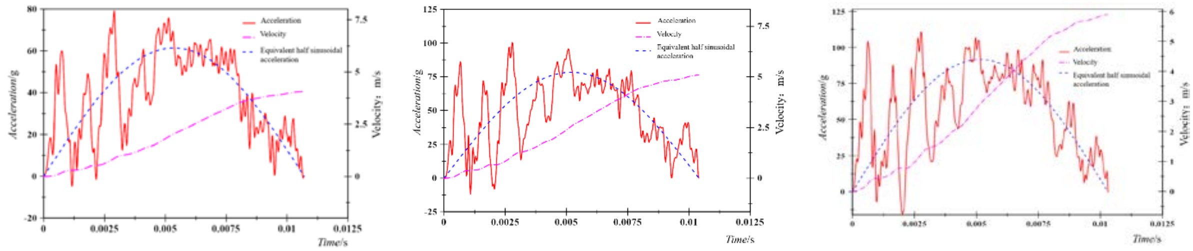
Figure 8. Pulse curves.

Table 1. Impact data statistics.

Rubber thickness (mm)	G_{peak} (g)	T (ms)	ΔV (ms^{-1})
30	90.20	7.00	3.94
50	61.40	10.60	4.06
100	41.20	16.20	4.17

Results as shown in figure 8 and table 1, the acceleration peak generated by 30mm, 50mm and 100mm rubber decreases in sequence 90.20g, 61.40g and 41.20g respectively, while the pulse width increases in sequence 7.00ms, 10.60ms and 16.20ms respectively. The experiment results conform to the laws revealed by the mechanical model formula, that is, the acceleration peak is inversely proportional to the rubber thickness, and the pulse width is directly proportional to the rubber thickness.

3.2.2. The influence of the drop height on drop impact load parameters. The drop height was 0.5m, 0.75m and 1m respectively. The same piece of rubber with a thickness of 50mm and a Shore hardness of Hs55 was adopted, and the drop mass was kept consistent at 373kg.



(a) (b) (c)

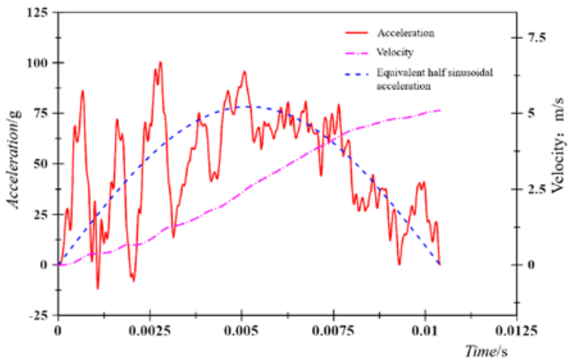
Figure 9. Pulse curves.

Table 2. Impact data statistics.

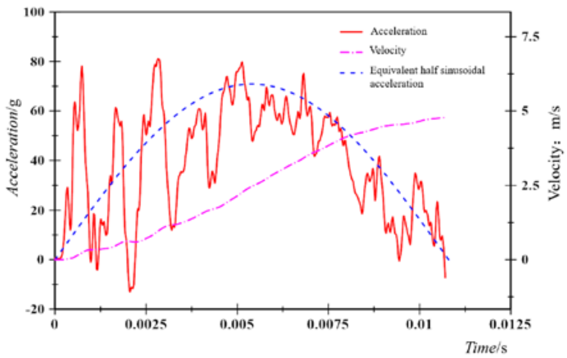
Drop height (m)	G_{peak} (g)	T (ms)	ΔV (ms^{-1})
0.50	61.40	10.60	4.06
0.75	78.30	10.40	5.08
1.00	91.60	10.30	5.89

The experiment results are shown in figure 9 and table 2.The acceleration peak caused by drop height of 0.5m, 0.75m and 1m increases successively, 61.40g, 78.30g and 91.60g respectively. The acceleration amplitude results conform to the laws revealed by the mechanical model formula, and the acceleration peak value is proportional to the drop height. With the increase of the drop height, the pulse width is 10.60ms, 10.40ms and 10.30ms respectively. The pulse width decreases continuously but the variation is small. The pulse width variation caused by drop height of 0.5m and 1m is 0.30ms, the relative error is only 2.80%. Therefore, when a pulse generator with the same thickness is used for experiment, the pulse width generated by the pulse generator has stability.

3.2.3. The influence of the drop mass on drop impact load parameters. The drop mass was 373kg and 500kg respectively, and 500kg was obtained by counterweight on the drop platform. The drop height was 0.75m.The thickness of the same piece of rubber was 50mm and the Shore hardness was 55.



(a)



(b)

Figure 10. Pulse curves.

Table 3. Impact data statistics.

Mass (kg)	G_{peak} (g)	T (ms)	ΔV (ms^{-1})
373	78.30	10.40	5.08
500	70.90	10.80	4.78

The experiment results are shown in figure 10 and table 3. As the mass of the drop platform increases, the peak acceleration decreases to 78.30g and 70.90g respectively, and the pulse width increases to 10.40ms and 10.80ms respectively. The experiment results conform to the laws revealed by the mechanical model formula.

3.2.4. Modification of the formula. The experiment results all verify the laws revealed by the drop mechanics model formula. The drop tower experiment results are reasonable and can be used to simulate the explosion impact load. The pulse width is most sensitive to the change of the rubber thickness, and the change in velocity is most significant with the change of the drop height.
According to the above data samples, the equation(6) will be modified and assume as follows:

$$H = \beta(\ddot{x} \bullet T)^2 \tag{7}$$

The values of β under the above experiment conditions are shown in table 4. According to the calculation results, the range of β is 1.122~1.279, and the relative error is 12.20%. It is found that the drop tower itself is a highly nonlinear system. The drop tower system is unstable in energy dissipation, but the error is within an acceptable range.

Table 4. Experimental value.

Mass (kg)	Thickness (mm)	Drop height (m)	G_{peak} (g)	T (ms)	β_{ideal}	$\beta_{experiment}$
	30	0.50	90.20	7.00		1.254
373	50	0.50	61.40	10.60	0.496	1.180
	100	0.50	41.20	16.20		1.122

	50	0.75	78.30	10.40	1.131
	50	1.00	91.60	10.30	1.123
500	50	0.75	70.90	10.80	1.279

The test value range of the β is 1.122~1.279. In order to realize the acceleration pulse (224g, 5.10ms) in the bottom explosion experiment of an armored vehicle, the required drop height is obtained according to the drop height formula as shown in table 5. The drop height ranges from 1.46 ~ 1.67m.

Table 5. The estimate of the drop height.

Acceleration peak (g)	Pulse width (ms)	$\beta_{experiment}$	Drop height (m)
224	5.10	1.122	1.46
		1.123	1.47
		1.131	1.48
		1.180	1.54
		1.254	1.64
		1.279	1.67

4. Drop tower experiment and results analysis of the simulated explosion

Since the drop height ranges from 1.46 m to 1.67 m, a preliminary experiment is conducted to simulate the explosion load. The drop mass was weighted to the total mass of the drop platform, seat mounting frame, dummy seat system and connecting piece of 500kg. The protective seat was installed on the drop platform, and the installation method was completely in the form of a real vehicle, and drop experiments were carried out at four drop heights. Figure 11 is a drop experiment diagrams of the protective seat.

(a) (b) (c)

Figure 11. Experiment arrangement.

Table 6. Impact load parameters.

Drop height (m)	ΔV (ms^{-1})	Acceleration peak (g)	Pulse width (ms)
1.40	6.98	198	5.50
1.50	7.24	215	5.40

1.60	7.47	226	5.30
1.70	7.71	234	5.30
Explosion experiment	7.13	224	5.10

Table 6 shows the drop impact load and explosion impact load results at four heights. Analysis shows that when the drop height is 1.40m, the change in velocity of the drop impact does not reach the change in velocity of the explosion experiment. When the drop height is 1.50m, the change in velocity is 7.24m/s, which is greater than 7.13m/s of the explosion experiment, and the error between the peak acceleration 215g and the explosion environment acceleration peak 224g is 4%, within the error tolerance of 15%. Pulse width is within 5.10±0.50ms; when the drop height is 1.60m and 1.70m, the change in velocity is too large. Therefore, the drop height is 1.50m in the actual protective seat and dummy drop tower experiment.

The acceleration signal of the 1.50m drop tower experiment was extracted, the acceleration signal was low-pass filtered and the temperature effect was eliminated. The measured acceleration curve, integral velocity curve and equivalent semi-sinusoidal curve are shown in figure 12. The impact load of the drop tower experiment and the impact load of the bottom explosion experiment are shown in table 7.

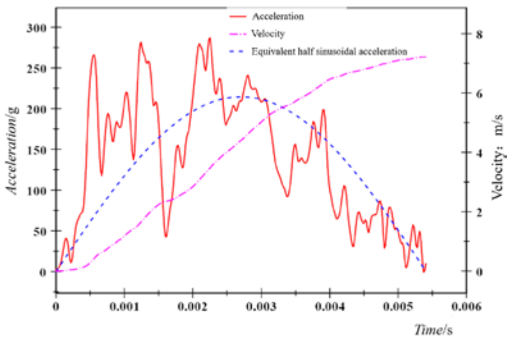


Figure 12. Curves of the drop tower experiment.

Table 7. Comparison of the impact load between the drop tower and explosion experiment.

	Equivalent semi-sinusoidal acceleration peak (g)	Pulse width (ms)	Change in velocity (ms^{-1})
Drop tower experiment	214	5.40	7.21
Explosion experiment	224	5.10	7.13

The results show that the change in velocity and pulse width in drop tower experiment are larger than those in bottom explosion experiment, but the error of the change in velocity in explosion experiment and drop tower experiment is smaller, 7.13m/s and 7.21m/s respectively, the pulse width is 5.10ms and 5.40ms respectively. The peak value 214g is within the tolerance range, and the error with the explosion experiment result is 4.50%.

To sum up, within the allowable range of the impact error, the drop tower system can simulate the movement response of the protective seat under the explosion condition.

5. Conclusion

In this paper, the theoretical analysis and simulation combined with the experimental research methods were used to study the explosive load simulation technology of the drop tower, and the following conclusions are obtained;

（1）When the pulse width of the impact load is short (explosion condition), the change in velocity ΔV has more potential in representing the explosion impact load level and predicting occupant injury, and the correlation between the change in velocity ΔV and occupant injury is also higher;

（2）The acceleration peak value generated in the drop tower is proportional to the drop height, inversely proportional to the rubber thickness and the drop mass, and the pulse width is proportional to the rubber thickness. The relationship between the drop height and the acceleration peak value and pulse width is deduced and corrected;

（3）Comparing the acceleration response and the protective seat response between the actual vehicle explosion experiment and the drop tower experiment, the feasibility and reliability of the drop tower technology to simulate the explosion impact load are verified.

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