Non-contact measurement and experimental study on complex dynamic motion under high impact

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Abstract: The multiple impact equipment of short interval and multiple impact loading is the key equipment to verify the high impact resistance and initiation control strategy for multi-layer penetration fuze in laboratory, the motion law of the moving part under high impact has an important influence on the consistency of acceleration. In view of measurement problem of complex dynamic motion process under multiple high impact, a non-contact measurement method based on high-speed photography and image processing was presented, obtaining pixel coordinate of feature point of the moving part by background difference and feature point detection, combining with the sub-pixel algorithm, further improving the accuracy of measurement. The results of high-speed photography were verified by contrast experiment and dynamic simulation, proving that the method is reasonable and feasible for complex dynamic motion process measurement under high impact, providing support for optimal design of the multiple impact equipment, also enriching the existing methods of complex dynamic motion measurement.

Key words: multiple impact; complex dynamic motion; non-contract measurement; sub-pixel

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高冲击复杂动态运动的非接触式测量方法及试验研究

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摘　要: 具有短间隔连续冲击加载能力的多次冲击试验台是实验室验证多层侵彻引信高冲击性能和多层起爆控制策略的关键设备，其运动件在高冲击下的运动规律对过载加速度的一致性有着重要影响。针对连续高冲击加载下复杂动态运动过程测量的技术难题,研究了一种基于高速摄影及图像处理算法的非接触式测量方法,通过背景差分和特征点检测的方法获得了运动件特征点的像素坐标,结合亚像素处理算法,进一步提升了测量精度;通过对比试验和动力学仿真对高速摄影测量结果进行了验证,证明了该方法应用于高冲击加载下复杂动态运动过程测量的合理性与可行性,为多次冲击实验台的进一步优化设计提供了支撑,也丰富了现有的高动态运动过程测量手段。

关键词: 多次冲击； 复杂动态运动； 非接触式测量； 亚像素

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0 Introduction

In the process of penetrating multi-layer hard targets, the internal fuze and control circuit of the high-speed penetration ammunition will bear a multiple high impact loading, which may cause the displacement, deformation and even damage of the mechanism and the circuit module, leading to function failure of the fuze[1]. In addition, the multiple high−g overload perceived by acceleration sensor is also the key input parameters for the penetration fuze to realize the layer initiation control, accordingly, a large number of dynamic tests must be carried out in the process of development and production of the multiple penetration fuze. In the existing testing methods, the range test is the most accurate and reliable dynamic test method, but due to the high cost and the long cycle, it is difficult to implement batch testing, the traditional laboratory imitate method such as machete hammer, falling ball and air cannon are only of single impact, difficult to simulate multiple impact of penetrating multi-layer targets. In view of this problem, Nanjing University of Science and Technology designs a multiple impact equipment and applies to multi-layer penetration fuze testing, obtaining a good experiment result.

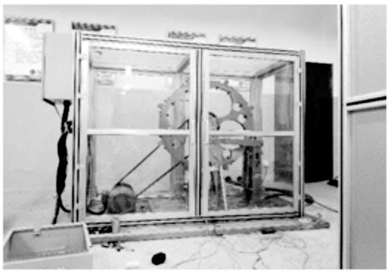
The designed multiple impact equipment produces high−g impact overload acceleration on test fuze by a series of impact components impacting the fixture which supported by the burthen spring, control the equivalent spring mass system to the balance position before each impact is an important guarantee for the good consistent of the impact overload acceleration[2], therefore, the accurate high dynamic motion of the moving part under impact loading is the key factor for the impact equipment. This kind of complex dynamic motion model under high impact loading is widely existing in production, but usually only can be analyzed by theoretical and simulation, lack of an effective measurement method. As the acceleration of the dynamic motion is far below than the acceleration of the impact process, conventional high −g acceleration sensor can meet the test requirement of high impact loading, but because of its own noise, it is insensitive to the dynamic motion after impact, the low−g acceleration sensor is hard to bear the initial high impact loading; therefore, it cannot be applied to the measurement of dynamic motion process; moreover, due to the complexity of high impact dynamic motion process, the impacted object contains not only motion along impact direction, but also complex deflection and swing, so the laser vibration based on single point also has a large error.

Aiming at the technical challenge for measuring complex dynamic motion process under high impact loading, this paper produces a non-contact measurement of high-speed photography based on the designed impact equipment, and carries out an experiment study on dynamic motion and motion acceleration under impact loading, obtaining pixel coordinate of the moving part by background difference and feature point detection, combined with sub-pixel algorithm, improving the accuracy of measurement. As it is difficult to measure the dynamic motion process directly under high impact loading, so the results of high-speed photography were verified indirectly by a single hydraulic feed and retract test, combining with the dynamic simulation of ideal spring mass system, which commonly verifies the feasibility of the measurement and provides basic support for the optimization design and performance improve of multiple impact equipment, moreover, the measurement method and image processing method can also be applied to the dynamic motion which cannot be measured directly, enriching the existing measurement method.

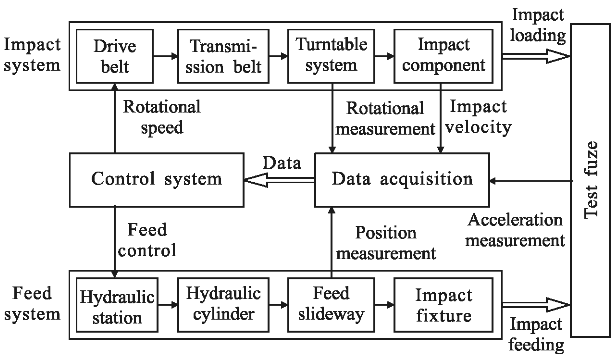
1 Experiment equipment and experiment design

1.1 Experiment equipment

This paper conducts relevant research based on the designed multiple impact equipment of penetration fuze, the main structure is shown in Fig.1 (a) and the principle is shown in Fig.1 (b). Its fundamental principle is: A plurality of impact components evenly distributed on the edge of the turntable, and the turntable of high-speed rotating driven by speed regulation motor through a belt, making the impact components of a certain impact kinetic energy; the test fuze is installed in impact fixture and the impact fixture is connected with hydraulic cylinder by a burthen spring. When the turntable reaches the experiment speed, controlling the hydraulic cylinder feeds the impact fixture to impact position, then the collision happened immediately between the impact component and the impact fixture, producing overload acceleration. After the impact, the impact fixture and test fuze of simple harmonic vibration in their equilibrium position as a whole, prepare for the next impact, if the multiple impact cannot happen in the equilibrium position, it will cause the inconsistent of impact state and result in poor consistency of overload acceleration, which is difficult to meet the experiment requirement.



(a) Multiple impact equipment



(b) Structure principle

Fig.1 Experiment device and principle

For the moving part of the overload acceleration generating mechanism, the high impact loading produced by impact component of high speed impact, provides an initial disturbance for its dynamic motion, after the impact, the moving part carries out a simple harmonic vibration in its equilibrium position, which can be simplified to a damping spring mass system of free vibration[3], the whole moving part has an equivalent mass of m, the stiffness coefficient of the spring mass system is k, and the system damping is c, its motion process satisfies the relationship:

$$m\ddot{x}+c\dot{x}+kx=0 \tag{1}$$

Equivalent to:

$$\ddot{x}+2\delta\dot{x}+\omega_0^2x=0 \tag{2}$$

where ω_0 is the natural frequency of the system, $\omega_0=\sqrt{k/m}$; δ is the damping coefficient, $\delta=c/2m$; since the system damping is less than the critical damping, so the solution of above equation is:

$$x=e^{-\delta t}(A\sin\omega_d t+B\cos\omega_d t)=Ce^{-\delta t}\sin(\omega_d t+\theta) \tag{3}$$

where A is the initial displacement of the system, expressed as x_0; B is the initial speed of the system, expressed as $\frac{\dot{x}}{\omega_d}=\frac{\dot{x}_0+\delta x_0}{\omega_d}$; C is the system amplitude, expressed as $C=\sqrt{A^2+B^2}=\sqrt{x_0^2+\left(\frac{\dot{x}_0+\delta x_0}{\omega_d}\right)^2}$; θ is the system initial phase, expressed as $\theta=\arctan\left(\frac{B}{A}\right)=\arctan\left(\frac{\omega_d x_0}{\dot{x}_0+\delta x_0}\right)$; ω_d is the natural frequency of damping system, expressed as $\omega_d=\omega_0\sqrt{1-\zeta^2}$.

Thus can obtain the motion cycle of the moving part:

$$T_d=\frac{2\pi}{\omega_d}\frac{2\pi}{\omega_0\sqrt{1-\zeta^2}} \tag{4}$$

The impact loading interval should be matched with the motion cycle of the moving part, allowing the system return to equilibrium position and maintaining the same direction of movement with each impact loading, which can ensure the consistent of the impact overload acceleration, that is to satisfy the relationship:

$$T=\frac{2k+1}{2}T_d=\frac{2k+1}{\omega_0\sqrt{1-\zeta^2}} \tag{5}$$

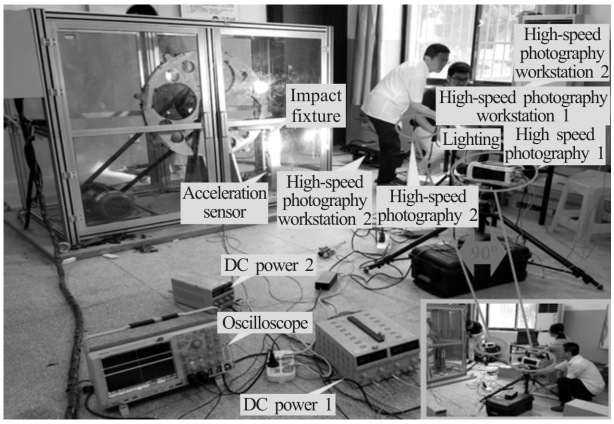
Since the actual continuous impact loading interval is usually set up by the impact requirement, therefore, by adjusting the damping, the system motion cycle can be adjusted to match the multiple impact loading interval, which guarantees the consistency of impact overload acceleration:

$$\omega_0=\frac{1}{T}\frac{2k+1}{\sqrt{1-\zeta^2}} \tag{6}$$

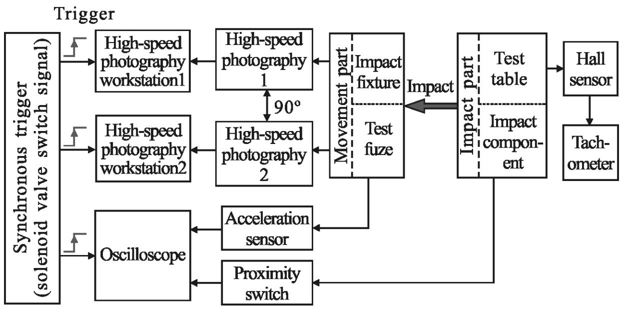
The above is the ideal dynamic motion process of the moving part, ignoring a series of factors such as friction and bump, in practice, the above parameters need to be corrected by the real motion measurement results, establishing a more accurate equation of motion model can effectively control the motion cycle and ensure the consistency of impact overload acceleration, at present, there is still lack of an effective measurement method for such complex dynamic motion under high impact loading. In recent years, with the development of electronic technology and image processing capability, the high-speed photography [4-7] gradually develop into an important method of modern optical measurement, which not only has the advantages of high adaptation, non-contact and globalization, but also provides detailed information about dynamic process and morphological changes, therefore, it is a good idea to introduce high-speed photography into dynamic motion process.

1.2 Measurement scheme

The site layout of the designed measurement system is shown in Fig.2 (a) and the schematic is shown in Fig.2 (b). The measurement system mainly consists of optical measurement device, acceleration sensor, lighting, auxiliary rotational speed measurement and impact velocity measurement. Aiming at the problem that the impacted object not only contains motion along impact direction, but also contains deflection and swing in other directions. We designed two optical measurements of 90° on horizontal plane, one is front shooting at the test fuze, another is side shooting at the impact fixture, this can obtain the dynamic motion process of the moving part in three directions, the coordinate paper is set up along the longitudinal direction of the impact bracket, in later data processing, conversion of the scale between the coordinate paper and pixel point, then can obtain the real displacement in any directions. Due to the short duration of the multiple impact process, in order to obtain detailed motion information, a higher frame rate is required, so it is necessary to provide a strong light source for the shooting area, parallel light is a good method of illumination compensation, but ordinarily it is difficult to obtain, so we introduce an ordinary high intensity spotlight front illumination, providing lighting to the shooting area from adjacent area of the camera lens. The acceleration sensor is installed directly on impact



(a) Site layout



(b) Measurement principle

Fig.2 Measurement scheme

fixture by threaded connection, to obtain impact overload acceleration, the output is inserted to the oscilloscope by shielding wire. In order to realize auxiliary observation of impact loading process, the hall sensor and the tachometer are introduced in the experiment to measure rotation speed, a high-speed proximity switch is also introduced at appropriate position of the impact bracket, when each impact component pass through, the sensor output a level transition, so transit time of each impact component can be measured based on this method, then the impact velocity and kinetic energy loss after each impact can be calculated, the output of the high-speed proximity is also inserted to the oscilloscope by shielding wire.

1.3 Synchronous trigger

The high dynamic characteristics of the impact experiment put forward higher requirement for signal acquisition, if the oscilloscope and the high-speed photography cannot be triggered immediately when the impact happened, it will be unable to obtain the synchronization acceleration and the dynamic motion picture. For the designed multiple impact equipment, the occurrence of the impact depends on the start of hydraulic station, which feeds the impact fixture to the impact position, so we select the switch signal of the solenoid valve as the synchronous trigger signal, one is introduced to the oscilloscope, the other is introduced to the high-speed photography, so can realize the synchronous acquisition of acceleration sensor and high-speed photography during the dynamic impact process.

2 Image data processing

2.1 Motion extraction

High-speed photography image contains information about all objects in the shooting area, analyzing these images directly will inevitably increase the workload of data processing. As the impact fixture and the test fuze keep synchronized movement, therefore, extracting any feature of the moving part can represent the dynamic motion process under the impact loading. This paper used the updated background difference method[8] to extract the motion information, the original image is shown in Fig.3(a), three frame foreground images of the moving part in high-speed photography sequence images are extracted as shown in Fig.3(b)–(d), Fig.3(b), (c) is the foreground image extracted from adjacent frames, Fig.3(d) is the foreground image extracted after a series of frames. It can be seen from the figure that, this method is well extracted the feature of the moving part in each frame, which basically filters out the background information, only a small amount of shadow exited on the edge of the moving part, may not affect the identification of the feature point.

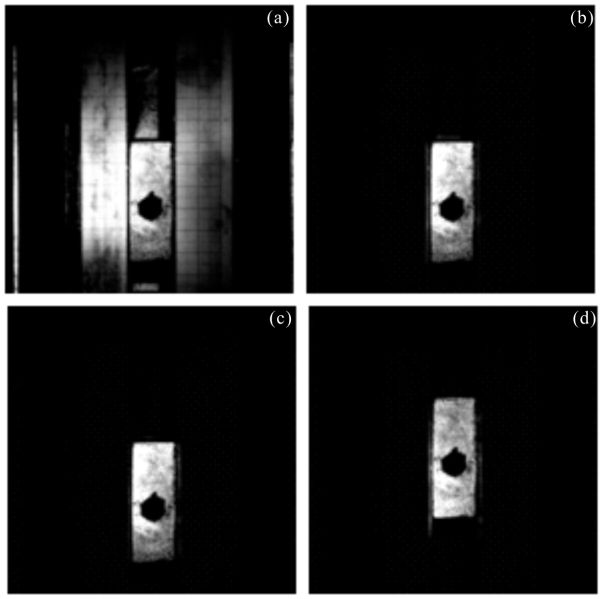


Fig.3 High-speed photography and moving part extraction

2.2 Feature point detection

After obtaining the foreground image only contains the moving part based on the background difference, the feature point of the moving part and its pixel coordinate can be identified by corner detection. In these corner detection algorithms, Harris algorithm[9] is an efficient and excellent corner detection algorithm, with a good suppression on the change of intensity and the shadow of the moving part caused by non-parallel light, suitable for the measurement of impact experiment. However, Harris algorithm can only obtaining corner coordinate of pixel level, but in dynamic measurement of the impact experiment, we hope to obtain a higher precision pixel coordinate, therefore, a sub-pixel optimization algorithm based on gradient in image data processing is further introduced[10], its basic principles are expressed as follows.

Because the high frame rate of high-speed photography, the moving part in sequence images only has a small displacement, respectively take the sub-region image before small displacement is $f(x,y)$ and the sub-region image after small displacement is $g(x',y')$:

$$f(x,y)=g(x',y')=g(x+u+\Delta x,y+v+\Delta y) \tag{7}$$

where u and v are the integer pixel displacement of the original points (x,y) along x direction and y direction; Δx is sub-pixel displacements along x direction and Δy is sub-pixel displacement along y direction. Expand the above formula of Taylor expansion and discard higher order minimum:

$$g(x+u+\Delta x,y+v+\Delta y)=g(x+u,y+v)+\Delta x g_x(x+u,y+v)+\Delta y g_y(x+u,y+v) \tag{8}$$

where g_x and g_y are the first-order gradient of the gray image after small displacement, $g_x=\frac{\partial g(x+u,y+v)}{\partial x}$, $g_y=\frac{\partial g(x+u,y+v)}{\partial y}$.

Assuming that the sub-region image is $m\times n$, the sub-pixel displacement Δx and Δy should make the minimum square distance correlation function to extreme value:

$$C(\Delta x,\Delta y)=\sum_{i=1}^{m}\sum_{j=1}^{n}[f(x,y)-g(x+u+\Delta x,y+v+\Delta y)]^2 \tag{9}$$

$$\frac{\partial C(\Delta x,\Delta y)}{\partial \Delta x}=0,\ \frac{\partial C(\Delta x,\Delta y)}{\partial \Delta y}=0 \tag{10}$$

Simultaneous the above formulas can obtain the sub-pixel displacement:

$$\begin{bmatrix}\Delta x\\ \Delta y\end{bmatrix}=\begin{bmatrix}\sum_{i=1}^{m}\sum_{j=1}^{n}g_x^2 & \sum_{i=1}^{m}\sum_{j=1}^{n}g_xg_y\\ \sum_{i=1}^{m}\sum_{j=1}^{n}g_xg_y & \sum_{i=1}^{m}\sum_{j=1}^{n}g_y^2\end{bmatrix}^{-1}\cdot\begin{bmatrix}\sum_{i=1}^{m}\sum_{j=1}^{n}[f(x,y)-g(x+u,y+v)]g_x\\ \sum_{i=1}^{m}\sum_{j=1}^{n}[f(x,y)-g(x+u,y+v)]g_y\end{bmatrix} \tag{11}$$

It can be seen that, the key to sub-pixel displacement solution lies in the first-order gradient of g_x and g_y. Pan Bing [11] compares the commonly used edge detection algorithms and concludes that the Barron algorithm is better than others in accuracy and stability, so this paper refer to the results directly and take the gray gradient as:

$$g_x=\frac{1}{12}g(x-2,y)-\frac{8}{12}g(x-1,y)+\frac{8}{12}g(x+1,y)-\frac{1}{12}g(x+2,y) \tag{12}$$

$$g_y=\frac{1}{12}g(x,y-2)-\frac{8}{12}g(x,y-1)+\frac{8}{12}g(x,y+1)-\frac{1}{12}g(x,y+2) \tag{13}$$

After obtaining the sub-pixel displacement of two adjacent frame images based on the above method, then the detected feature point coordinates can be obtained by correcting the sub-pixel coordinate, take the three frame images in Fig.3(b)-(d) as an example, the original results obtained by Harris corner detection and sub-pixel optimization are shown in Fig.4(a)-(c).

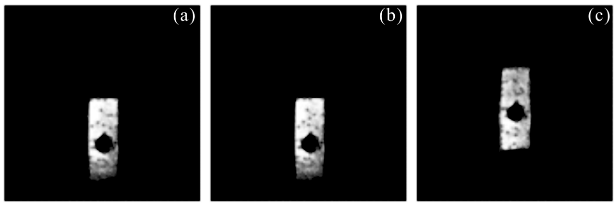


Fig.4 Original processing result

It can be seen from the figures that, affected by the imaging noise of high-speed photography itself and the spots and shadows by non-parallel light, the feature points detected by the algorithm not only contain the points of shape contour, but also contain the points produced by spots and noise. It can be seen by comparing Fig.4(a)-(c) that, when frame difference is small, the detected feature points are basically consistent, but when there is a large difference between two frames, the obtained feature points are of obvious difference. But for the hexagon hole at the center of the moving part, due to the obvious structural feature, of large contrast to the surrounding structure, the vertices can be well detected in all images, therefore, we choose the vertex of hexagon hole as the feature point to extract motion information. Because the main motion of the moving part is along the longitudinal impact direction, its lateral motion is limited by the guide rail and usually does not change significantly, therefore, when processing the coordinate data obtained by high-speed photography sequence images, the sub-pixel coordinates of feature points in each frame can be extracted by limiting the range of abscissa, take the three frame images in Fig.4(a)-(c) as an example, the feature points and their sub-pixel coordinates extracted by the above method are shown in Fig.5(a)-(c). In data processing, extract the sub-pixel coordinates of each feature point separately, obtained the displacement of each feature point according to the correspondence between the pixel displacement and the actual, then can average displacement of each feature point by arithmetic method, further improving the accuracy of high-speed photography.

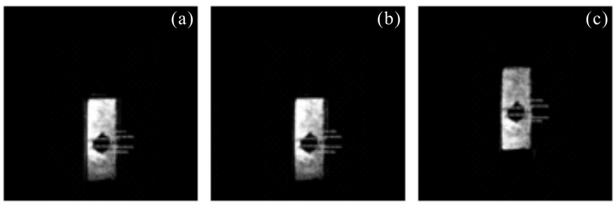


Fig.5 Feature point and sub-pixel coordinate extraction

3 Experiment results and analysis

In an impact experiment, we extract the sub-pixel coordinates of the feature points in each frame through the above method. Usually lens distortion is an influence factor that cannot be ignored in non-contact measurement of image vision, which mainly includes radial distortion, eccentric distortion and thin prism distortion[12-14], the radial distortion is usually the main source of measurement error, it is particularly obvious in measurement of short focal length and large viewing angle; for the professional fixed focal lens used in this experiment, its distortion is small, and the extracted moving part is located at the center of the image, also with small effect of lens distortion, this conclusion is also verified by the comparative analysis of multiple feature lines in shooting area, considering the above factors, we ignored the effect of lens distortion in this experiment and directly selected longitudinal displacement of the moving part as reference value to calculate the actual displacement corresponding to the pixel displacement, the longitudinal length of the moving part is 55.03 mm, occupying 16 pixels of the original image, then can obtain that actual displacement corresponding to each pixel is 3.44 mm. Considering that the frame rate of high-speed photography is 15 000/s, so the time interval for each frame is 1/15 000 s, taking the start time of impact fixture feeding as the coordinate origin, plotting the displacement-time curve of the dynamic motion process of the impact fixture along the impact direction, and the output of acceleration sensor is compared as a contrast, as shown in Fig.6.

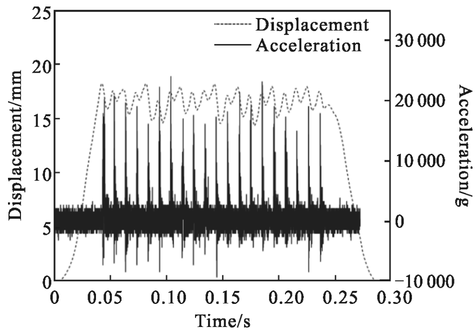
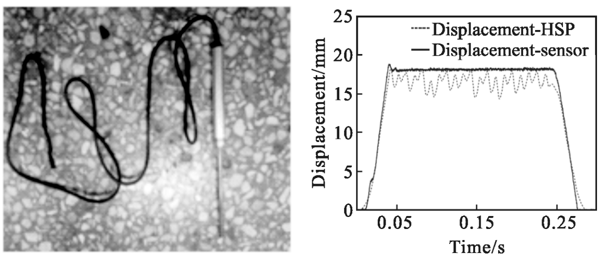


Fig.6 Impact overload acceleration and dynamic motion process

The solid curve in figure is output of the acceleration sensor, the dotted curve is displacement-time curve of the moving part obtained by the high-speed photography, it can be seen from the acceleration curve that, a total of 20 impact happens in 200 ms, although the curve clearly reflect the impact overload, but it is impossible to obtain the dynamic motion of the moving part after each impact.

However, the impact fixture displacement-time curve obtained by the image data processing of the high-speed photography can clearly reflect the dynamic motion of the moving part after impact, because of the impact loading cycle does not match with the motion cycle, lead to the inconsistent of overload acceleration and irregular of dynamic motion.

In impact experiment, due to the particularity of dynamic motion of the moving part under impact loading, the low−g acceleration sensor is hard to bear the initial high impact loading, and the laser interference will also contain a large error because the deflection and swing under impact loading, therefore, it lacks of an effective method to measure the complete impact dynamic motion process as a contrastive verification of high-speed photography. In view of this problem, we verified high-speed photography result indirectly by a single feeding and retracting process of hydraulic feeding system, ensure the same accumulator pressure with the aforementioned experiment, without impact loading, but only control the hydraulic feeding system of a feeding and retracting process, the displacement-time curve of feeding and retracting process are measured by the displacement sensor as shown in Fig.7 (a), compared the measurement results of displacement sensor and high-speed photography, as shown in Fig.7(b).

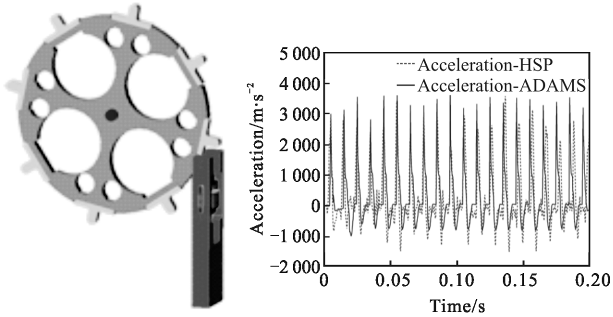


(a) Displacement sensor (b) Displacement-time curve

Fig.7 Single feeding and retracting experiment

The solid curve is the single feeding and retracting process displacement-time curve of the moving part obtained by the sensor, the dotted curve is the complete dynamic motion process displacement-time curve obtained by high-speed photography with image data processing. It can be seen from the figure, the maximum stroke of the feed motion is 18 mm, coincide with the design parameter, the rising and falling edges of the curve reflect the feeding and retracting motion of the moving part under hydraulic control, through duration and slope of the rising and falling edges of displacement sensor and high-speed photography we can see that, under the same pressure, the result of high-speed photography is basically consistent with the sensor, prove that the high-speed photography is feasible applied to the measurement of dynamic motion process. In the figure, because there is no impact loading during the single feeding and retracting process, so the displacement-time curve maintains a stable platform amplitude, but under impact loading, the dynamic motion of the moving part is much more complicated, because there is no control the system motion cycle match with the impact interval, result the impact happened when the moving part have not move to the balance position, cause inconsistent of the impact state, then lead to the inconsistent of the impact overload acceleration as shown in Fig.6.

In order to further verify the dynamic motion measured by high-speed photography, we established a dynamic simulation of multiple impact equipment, as shown in Fig.8 (a), the simulation parameters are set up according to the system parameters, obtained the motion acceleration of the moving part under impact loading through simulation, and compared with the motion acceleration obtained by high-speed photography, as shown in Fig.8(b).



(a) Dynamic simulation (b) Simulation result

Fig.8 Dynamic simulation verification

The solid curve in figure is the motion acceleration of the moving part obtained by simulation, the dotted curve is the motion acceleration obtained by high-speed photography, it can be seen from the figure that, the simulation result is basically in agreement with the high-speed photography result, proved the feasibility of high-speed photography. But in practice, due to the deflection, swing and other factors caused by impact loading, the actual external forces of the moving part are constantly changing, caused the changes of motion state, and the previous motion state will affect the next impact process and impact motion, lead to the deviation between the actual acceleration and the simulation acceleration increase when the impact times increased, it also reflect that the simulation analysis method of complex dynamic motion under impact loading is usually inaccurate, so it is still necessary to analyze the real motion process effectively through the actual measurement results.

4 Conclusion

This paper aiming at the measurement technical challenge of complex dynamic motion process under high impact loading, designed a non-contact measurement method of high-speed photography based on the designed impact equipment, realized visual measurement of dynamic motion under high impact loading; in image data processing, by background difference and feature point detection, combine with sub-pixel algorithm, obtain high track precision of dynamic motion about the moving part. Through indirect experiment of a single feeding and retracting process and dynamic simulation, proved that the proposed method is reasonable and feasible for complex dynamic motion process measurement under high impact loading, and the result also reflect that it is difficult to obtain the real dynamic motion process accurately through simulation, the experiment research in this paper provides support for the optimal design of the multiple impact equipment, and also provides reference for the observation of other similar high dynamic motion process.

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